The Effects of Learning-by-Doing on Product Innovation by a Durable Good Monopolist*

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Abstract

We analyze a durable–good monopolist's decision to adopt a new and more efficient technology that is readily available at very low or zero adoption cost. After an initial period of learning by doing, the new technology makes the good more attractive to consumers. Anticipating a better product, consumers delay their current purchases which lowers today's profits, but increases future profits since the monopolist can charge a higher price for the high quality good. We show that the effect on overall profit depends on variables such as the degree of innovation. For certain parameter values, the monopolist adopts the innovation even when it is not first best to do so. We also provide conditions under which the monopolist finds it optimal to continue using the inferior production technology even if the innovation is freely available. The latter result provides a possible rationale for a firm to hold on to a "sleeping patent" when its use is socially desirable.

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1 Introduction

Economists have long been skeptical about arguments in popular press according to which a monopoly acquires a patent to an innovation, only to subsequently put it away into a safe and never use it.[1] If the innovation improves the quality of the good that the monopolist sells or decreases her production costs, why would the monopolist not adopt it if she can do so at no additional cost? To shed more light on the incentives of a durable good monopolist to adopt an innovation that is readily available, this paper builds a two-period model in which a durable good monopolist decides whether to adopt a new technology that is readily available at very low or zero cost. Although our arguments apply equally to the case of an innovation that reduces the firm's cost of production, our primary focus will be on innovations that improve the quality of the firm's product.

Our results will be driven by two crucial assumptions. First, in line with much of the literature on durable good monopolies, our monopolist cannot commit to future prices, which gives rise to the well known time-inconsistency problem in pricing. The second key ingredient of our model, and one that is more novel, will be the assumption that when the new technology is adopted, an initial period of production is necessary before the full benefits of this innovation are realized in the subsequent period. This captures the notion of learning by doing, which we consider to be an essential part of any production process involving a new technology.

Our main result is that if there is a small cost associated with the adoption of the new technology, the monopolist sometimes adopts the innovation even if, from the social point of view, that innovation should be left unexploited (despite being superior to the old technology). This result has a relatively simple intuition: In the presence of learning by doing, the benefits of an innovation materialize mainly in the second period. But if the good is sold at the marginal cost, as is socially optimal, then the second period residual demand may not be high enough to warrant production in that period. This means that it may not be socially efficient to adopt the innovation if the adoption is not completely costless. In contrast, the inability to commit to a future price makes the monopolist's second-period output too high compared to what she would commit to in the first period if she could. Due to this high second period output, sometimes an innovation can be more

[1] "[R]umors long have circulated about the suppression of a new technology capable or enabling automobiles to average 100 miles per gallon or some new device capable of generating electric power at a fraction of its current cost..." (Flynn, 1998, p. 490). In fact, it is not that hard to find examples of companies that do not use technological innovations for which they own patents, although many of these may include cases where the companies cannot find a profitable use for their patents. According to the Business Week, "At most corporations, only about 3% of their patents are ever used" (Business Week Online, 2000). As two specific examples of companies that suppressed a superior technology, we mention the Universal Manufacturing Corporation and General Electric. Universal Manufacturing acquired a license for electronic ballasts for fluorescent light bulbs, but then suppressed that technology in favor of its traditional, less efficient electro-magnetic, carbon core ballasts (e.g., Chin, 1998). According to Dunford (1987, p. 516), "when fluorescent lighting was developed, its introduction was suppressed [by General Electric] because the company wished to saturate the incandescent market before releasing the new technology."

valuable to a monopolist than to a social planner, which can lead the monopolist to inefficiently adopt the new technology.

Pulling in the opposite direction to the above effect is the familiar 'Coase problem': The monopolist engages in intertemporal price discrimination, charging a lower price to those consumers who purchase the good later. However, as was argued by Coase (1972) and shown formally by subsequent researchers[2], the monopolist may be hurt by her own ability to price discriminate intertemporally – rational consumers correctly anticipate a future reduction in price and therefore postpone their purchases, which lowers the monopolist's overall profit. In our paper, adoption of a new technology in the presence of learning by doing can intensify the monopolist's time inconsistency problem. If the firm uses the quality improving technology, then learning by doing makes the units purchased today economically obsolete in the next period. This decreases the value that the consumers place on the units produced in the first period, which is reflected in the lower price they are willing to pay. This effect can make the adoption of the new technology less desirable, which leads to the second result of our paper: For some parameter values, the durable good monopolist shelves an existing innovation that is available to her at no cost[3], even though it would be socially efficient to adopt it. This result can provide a possible rationale for the existence of 'sleeping patents'.

1.1 Related literature

Our result that the monopolist can innovate too much compared to the social optimum makes the present paper related to the literature on innovation in the presence of network externalities, represented by Ellison and Fudenberg (2000) (see also Waldman, 1993, and Choi, 1994). Ellison and Fudenberg show that from the standpoint of social welfare, as well as from the standpoint of the monopolist's own profitability, the monopolist's incentives to introduce upgrades to her product are too high. However, the economics that drives their excessive innovation result is different from the logic behind our model. The result in Ellison and Fudenberg is driven by the assumption of positive network externalities and by the inflow of new consumers into the market in later periods, which are features that are not present in our model. As we have already mentioned, our excessive innovation result stems from learning-by-doing and the monopolist's inability to commit to future prices, because in the presence of learning-by-doing most of the innovation's benefits accrue in the second period, when the monopolist's output is greater than if she could commit to it in the first period. Moreover, in Ellison and Fudenberg the monopolist can never innovate too little, whereas in our framework the monopolist sometimes suppresses new and socially desirable technology.

[2] See, for example, Bulow (1982), Gul, Sonnenschein, and Wilson (1986), and Stokey (1981).

[3] Thus, in this part we are explicitly considering innovations that require no investments. One possible interpretation of this situation is that the monopolist has access to two different technological processes, as in Karp and Perloff (1996). Alternatively, the monopolist may have acquired a patent for the superior technology through an earlier race to innovate so as to prevent potential competitors from obtaining the patent (as in Gilbert (1981) and Gilbert and Newbery (1982)). We discuss the monopolist's R&D incentives later in the paper.

Our finding that a durable good monopolist may inefficiently ignore an existing, freely available innovation, is closely related to Karp and Perloff (1996). Karp and Perloff show that a monopolist may buy the rights to a superior production technology, only to subsequently suppress it and continue to use an inferior technology. They concentrate on cost-reducing innovations, as their explanation (building on a previous result by Kahn, 1986) is driven by the assumption of increasing marginal costs of production. Karp and Perloff demonstrate that the monopolist will sometimes keep using an old technology with a steeper marginal cost curve, rather than adopting a new technology which has a lower marginal cost, but for which the marginal cost curve is less steep. Consequently, their reasoning only works for cost-affecting technological innovations. Our approach applies to both product and cost innovations (although we focus on the former), because our results are driven by learning-by-doing, which can be present under both types of innovation.

Our analysis is also related to the extensive literature on product innovation and quality-improving R&D. The existing papers typically demonstrate that improving the product quality can help the monopolist mitigate the time-inconsistency problem. In contrast, we show that in the presence of learning-by-doing, product innovation can make the time-inconsistency problem more severe. Two models in this literature that we consider to be most closely related to our analysis are Waldman (1996a) and Lee and Lee (1998).[4]

The first of these papers, Waldman (1996a), investigates a durable good monopolist's incentive to invest in R&D that will improve the quality of the good in the second period. Waldman shows that the monopolist faces a time inconsistency problem in her second period R&D investment decision: she invests too much compared to her optimal level of investment, to which she would commit if she could. This is analogous to the standard time inconsistency problem identified by Coase, whereby a durable good monopolist produces too much in the second period. As Waldman shows, this high R&D investment level improves upon welfare, which is again analogous to the effect of the high second–period production in the standard Coase problem.

Our model differs from Waldman's in several respects. First, in addition to learning-by-doing, our results are driven by the monopolist's time inconsistency problem in pricing rather than in innovation decision. In fact, the time inconsistency problem in innovation analyzed by Waldman does not appear in the present model at all, due to different timings in the two models. In Waldman's model, the monopolist decides how much to innovate only after selling the first period production. She therefore does not internalize the effects of her decision on the first period profit. In the present model, the monopolist makes her innovation decision at the beginning of the first period, and therefore cares about the effect of this decision on her first period profit. Instead, the excessive innovation result is a consequence of the learning-by-doing feature of our model, which makes the

[4] See also Levinthal and Purohit (1989), who analyze alternative ways of selling a durable good when new and better units are being introduced onto the market.

monopolist's second period demand excessive compared to both her commitment level and the socially efficient level. Second, in Waldman's paper, the monopolist always innovates too much relative to her own optimum under commitment, but this level is second-best efficient from the social point of view. Our monopolist can innovate more, but also *less*, than what she would choose if she could commit to future prices. Moreover, she can innovate less than would be optimal in the second best scenario, which never happens in Waldman's framework. The last difference between our analysis and the model investigated by Waldman (1996a) is in the questions these papers are addressing: Waldman is not interested in the incentive of the monopolist to suppress an existing and freely available superior technology, while this is an important focus of our analysis, with the goal of demonstrating the possibility of 'sleeping patents'.

Finally, the second paper, due to Lee and Lee (1998), also builds a model in which a durable good monopolist invests in a quality-improving innovation that makes old units economically obsolete. Lee and Lee concentrate on a setting were there is no second-hand market for old units, which makes the consumers' valuations of new units dependent on their purchase history. Again, the main thing that distinguishes the present paper from Lee and Lee (1998) is a different research question. Lee and Lee do not investigate excessive innovation or the possibility of 'sleeping patents'. Instead, the focus of their model is on price discrimination by the monopolist, based on the consumers' purchase history.

The paper proceeds as follows. The model is presented in Section 2. Section 3 contains the analysis and our main results. We focus here on the quality-improving innovation, but also briefly discuss the case of a cost reducing innovation. In this section, we start by deriving the first best benchmark. We then analyze the monopolist's optimal technology choice and compare it with the first best and the second best outcomes. Section 4 concludes the paper. All proofs are in the appendix.

2 The Model

Consider a durable good monopolist that operates in two periods. The monopolist chooses her production level and prices so as to maximize the present value of profits. As in other papers in this strand of literature (e.g., Karp and Perloff, 1996), the monopolist in our model cannot commit to future prices to mitigate the time inconsistency problem. Similarly, she cannot use any other commitment device such as leasing, planned obsolescence, capacity constraint, and so on.[5]

At the beginning of the first period, the monopolist can choose between two known production technologies: the existing, old technology and a new one. Production with either technology incurs

[5] While we do not model this, in general the durability of a good depends on consumer maintenance effort, in which case there are moral hazard problems associated with leasing. Given this consideration, selling may be a more profitable marketing policy than renting (see Mann (1992)).

a marginal cost of $c < 1$ in each period; there are no fixed costs. If the monopolist adopts the new technology then the firm's product becomes more attractive to the consumers in the second period (and possibly also in the first period), as will be detailed later.

Throughout the most of the paper, we concentrate on the monopolist's incentives to adopt the new technology when it is already developed and freely available. Although it may have been costly to develop this new technology, there is no extra cost of adopting it once it is developed. We discuss the monopolist's incentives to invest in the development of a new technology in Subsection 3.2.6.

The production process with the new technology must be learned in the first period, before its full potential can be realized in the subsequent period. In particular, we assume that if strictly more than $q_{\min} > 0$ units are produced in the first period, then the new technology results in a quality improvement, otherwise it does not. This is a simple version of *learning by doing*.[6]

Each consumer lives for two periods and wishes to buy at most one unit of the good immediately, or after a one period delay. If a consumer purchases the good in the first period, he enjoys it for two periods or sells it at the secondhand market in period two.[7] A good produced in period 2 has only one period of economic life, although it may have two periods of physical life. Also, in period 1 there already exist q_o units of the good that were produced with the old technology in period 0.[8] These units are offered in the second hand market and become completely obsolete (worthless) at the end of the first period.

Consumers differ in their valuation for the good. If the good is produced with the old technology, then a representative consumer's one-period valuation of the good is θ, where θ is a valuation parameter that is distributed uniformly on $[0, 1]$. We will focus on a technological improvement that makes the good more attractive to consumers by raising their valuation for the good: in the first period to $s_1\theta$ and in the second period to $s_2\theta$, $s_2 \geq s_1 \geq 1$, where s_1 and s_2 measure the degree of quality improvement in the two periods respectively. The condition $s_2 \geq s_1$ reflects the learning-by-doing feature of our model.[9] Consumers know their valuations, but the monopolist only knows the distribution of θ. A consumer that does not make a purchase in any period gets zero

[6] Assumption 1 below guarantees that, in equilibrium, this minimum production requirement is non-binding.

[7] Alternatively, we could have assumed that there exists no secondhand market for the good. Both of these assumptions are used in the literature. For example, Sobel (1990), Lee and Lee (1998), and Chi (1999) do not allow for second hand markets, while Bulow (1982), Waldman (1996a), and Karp and Perloff (1996) do. We have checked that our qualitative results do not depend on this assumption.

[8] A more general model would allow for an infinitely lived monopolist, who can introduce gradual upgrades to its product in multiple periods. While the benefit of such a model would be a greater descriptive realism, this would come at a disproportionate cost of complicating the analysis substantially.

[9] Although we analyze quality improvements, we are not interested in a related question of durability choice. In our model, the good is perfectly durable (which is reflected in θ being constant over time), but has a physical life of 2 periods. As shown by other researchers (e.g., Bulow, 1986), the monopolist can use planned obsolescence to mitigate the Coase problem by building a lesser degree of durability into each unit. Basu (1988), Waldman (1996b), and Hendel and Lizzeri (1999) all analyze models in which a monopolist may choose to make the product less durable in order to better price discriminate between consumers. Finally, Chi (1999) shows that one way for the monopolist to alleviate the Coase problem is to make the good more attractive by choosing a higher (than optimum) quality in the first period, and lower the price–quality ratio in order to make high–demand consumers purchase immediately.

utility. Both the firm and the consumers are risk neutral and discount the future using a common discount factor $\delta \in (0, 1]$. The timing of events is summarized in Figure 1 below.

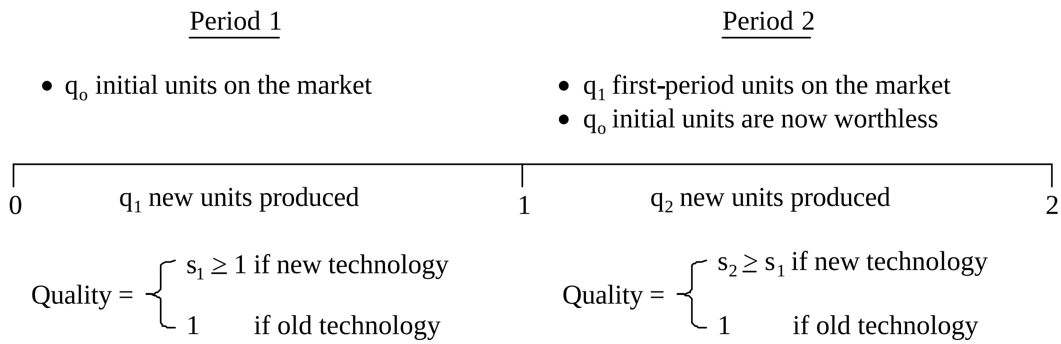

Figure 1. Timing of events

In order to reduce the number of cases that need to be analyzed, we adopt the following restrictions on the model's parameters:

ASSUMPTION 1. $q_{\min} \leq \frac{2[s_2 - c(s_2 - \delta)]}{4s_2(1+\delta) - 3\delta}$

ASSUMPTION 2. $c \leq c^{\max} \equiv \frac{2+\delta}{2+3\delta}$

ASSUMPTION 3. $q_o < 1 - \frac{s_2(s_1 - 1 - c) + c\delta s_1}{s_1[s_2(1+\delta) - \delta s_1] - s_2} \equiv \bar{q}_o$

If the first assumption is satisfied, then in equilibrium the monopolist's unconstrained first period output is always high enough for learning by doing to be effective. The second assumption guarantees that the second period output is positive, so that the setting does not collapse into a one-period model. Finally, Assumption 3 restricts the parameter space to those values for which the old q_o units are not in excess supply in the first period. This assumption allows us to exclude the less interesting parametrization, in which the first period price of the old, low quality units is zero.

3 The Analysis

3.1 The efficient technology choice

Our goal is to compare the monopolist's incentives to adopt the new technology with the socially efficient outcome. We begin by deriving the expression for the total surplus in this economy.

Suppose that the innovation is adopted and that q_1 units are produced in period 1 and q_2 in period 2. Then the total surplus, $W(s_1, s_2)$, is given by

$$W(s_1, s_2) = \int_{1-q_1}^{1} (s_1\theta - c)d\theta + \int_{1-q_o-q_1}^{1-q_1} \theta d\theta + \delta \int_{1-q_2}^{1} (s_2\theta - c)d\theta + \delta \int_{1-q_1-q_2}^{1-q_2} s_1\theta d\theta. \quad (1)$$

The first term above represents the consumer surplus from producing q_1 units in period 1 and selling them at marginal cost to high valuation consumers. The second term is the consumer surplus derived in period 1 from the transfer of old, period 0 units to those consumers who do not own the good at the beginning of period 1. The last two terms capture the corresponding surplus in period 2: the third term is the consumer surplus from producing q_2 of higher quality units in period 2 and selling them at marginal cost to high valuation consumers, while the last term is the consumer surplus that low valuation consumers derive in period 2 from the consumption of lower quality units at zero cost.

3.1.1 The first best benchmark

In line with the existing literature, we will consider two notions of social efficiency: The first best, where both the firm's technology and production level are chosen so as to maximize total surplus, and the second best, where only the firm's technology is chosen so as to maximize total surplus, while the prices and output are controlled by the monopolist, who maximizes her profit under the given technology. Here, we derive the first best benchmark; we will consider the second best benchmark later.

Maximizing (1) with respect to q_1 and q_2 yields the first-best outputs in periods 1 and 2 as

$$q_1^e = \frac{s_2(s_1 - c - q_o) + c\delta s_1}{s_1[s_2(1+\delta) - \delta s_1]} \quad \text{and} \quad q_2^e = \frac{(1+\delta)(s_2 - s_1) - c\delta + q_o}{s_2(1+\delta) - \delta s_1}, \tag{2}$$

respectively.[10] In order to focus on the most interesting parameterizations, we would like to restrict our attention to those initial output levels q_o for which the first period market is not completely saturated, i.e., $q_o + q_1^e < 1$. But this condition holds if q_o is less than $1 - \frac{s_2(s_1-1-c)+c\delta s_1}{s_1[s_2(1+\delta)-\delta s_1]}$, which is guaranteed by Assumption 3. The first best adoption of the innovation can then be characterized as follows:

Lemma 1. *(i) If the new technology does not improve the first period quality (i.e., $s_1 = 1$), then it is first-best efficient to adopt the innovation if and only if the second period quality improvement is sufficiently large, i.e., if and only if $s_2 > 1 + \frac{c\delta - q_o}{1+\delta}$.*[11]

(ii) If the new technology improves the first period quality ($s_1 > 1$), the first best outcome is to always adopt the innovation.

[10] Note that the total number of units on the market in the second period, $q_1^e + q_2^e$, may optimally be greater than one when s_2 is large. In such a case, the total surplus function should be written as $W(s_1, s_2) = \int_{1-q_1}^{1}(s_1\theta - c)d\theta + \int_{1-q_o-q_1}^{1-q_1} \theta d\theta + \delta \int_{1-q_2}^{1}(s_2\theta - c)d\theta + \delta \int_0^{1-q_2} s_1\theta d\theta$, instead of (1). This, however, affects neither the statements of our results nor their proofs.

[11] Strictly speaking, a social planner would be indifferent between adopting the technology or not in this case, because the new technology is free. However, whenever there is a cost, no matter how small, associated with adoption of the new technology, the social planner strictly prefers the old technology.

The intuition behind Lemma 1 is relatively simple. Note first that, from (1),

$$\frac{\partial W(s_2)}{\partial s_2} = q_2^e(1 - q_2^e). \tag{3}$$

This means that when the innovation does not improve the good's first period quality (i.e., $s_1 = 1$), then adopting it improves welfare only if the new technology is used for production in the second period, that is, $q_2^e > 0$. But second-period production is efficient only if the residual demand in that period is large enough, which is true if the condition in part (i) of the lemma holds. This condition says that the second period demand is large enough to warrant production in that period when the quality improvement, s_2, and the number of period 0 units, q_o, are relatively large, while the marginal cost, c, is relatively small (the effect of δ is ambiguous). The role of s_2 and c in ensuring that production is worthwhile in the second period is straightforward, but the role of q_o deserves a brief discussion. Suppose that the number of old units that are on the market in period 1, q_o, is relatively large. Then only a small amount of the (same quality) good needs to be produced in period 1 to ensure that all consumers with valuations greater than the marginal cost of production get the good in that period (as required by the first-best efficiency) – that is, the efficient q_1 is relatively small. But as the q_o units become worthless in period 2, the previous owners of these units enter the market for the good in the second period, which makes the second period demand relatively large, because q_o was large and the number of units that are traded on the second-hand market in period 2, q_1, is relatively small. An analogous argument shows that when q_o is relatively small, then also the second period demand is small. To sum up, if s_2 and q_o are small and c is relatively large, then in the second period there are no consumers left who would have high enough valuation for the new units to offset the cost of producing them. No production therefore takes place in the second period, which means that the innovation has no value.

Part (ii) of Lemma 1 says that if the new technology also improves quality in period 1, then it is always efficient to adopt it. The reason is that, by assumption, the number of period 0 units is sufficiently small to warrant production in the first period. But then the first period consumers benefit from the quality improvement, which improves efficiency if the adoption of the new technology is costless.

3.2 Technology choice under monopoly

We now provide an analysis of the monopolist's incentives to adopt the innovation, followed by a comparison of these incentives with the efficient adoption of the new technology. Using backward induction in the analysis of the monopolist's problem, we first take the share of consumers who purchased the good in the first period as given and derive the optimal second period output as a function of this share. We then find the optimal first period quantity produced under the equilibrium condition that the consumers' expectation of the second period price is correct. This also determines the equilibrium share of consumers who purchase the good in the first period.

3.2.1 The second period price and profit

Suppose that the monopolist adopts the innovation, and let q_1 be the quantity that was produced in period 1. Then if q_2 units of the good are produced in the second period, there will be q_1 old and q_2 new units offered for sale (recall that the q_o units produced in period 0 are completely obsolete by the beginning of period 2). Let p_2^L and p_2^H be the respective prices of old (low quality) and new (high quality) units in this period.

We start by deriving the monopolist's second period demand, then use it to determine her second period optimal output, and then derive the expression for her second period profit. We obtain the second period demand as a function of the first period output and the products' qualities (s_1, s_2) by finding the measure of consumers who will purchase a new unit in period 2. Since some consumers will purchase second-hand units, we determine the period 2 demand by identifying the consumer who is indifferent between an old and a new unit and then summing the units purchased by all consumers with valuation at least at this level. Formally, a consumer with valuation θ buys a new unit in period 2 if and only if $s_2\theta - p_2^H \geq s_1\theta - p_2^L$, whether or not he bought the good in period 1. If the reverse inequality is true, then the consumer buys an old unit in the secondhand market, as long as $s_1\theta - p_2^L \geq 0$. Let $\overline{\theta}$ be the valuation of a consumer who is indifferent in period 2 between buying an old unit and buying a new one. Then $\overline{\theta}$ is defined by $s_2\overline{\theta} - p_2^H = s_1\overline{\theta} - p_2^L$, so that $\overline{\theta} = \frac{p_2^H - p_2^L}{s_2 - s_1}$. Since the second period output is given by $q_2 = 1 - \overline{\theta}$, we have

$$p_2^H = p_2^L + (1 - q_2)(s_2 - s_1). \tag{4}$$

Thus, the price that the monopolist can charge for the new (upgraded) units produced in period 2 is proportional to the value of used units, and depends upon how much the quality of new units exceeds the first period level.

Similarly, let $\underline{\theta}$ be the valuation of a consumer who is indifferent between buying a used unit in period 2 and not buying at all. Then $\underline{\theta}$ will be given by $s_1\underline{\theta} - p_2^L = 0$. Clearly, $\underline{\theta}$ is also the measure of consumers with valuations below $\underline{\theta}$, who will not purchase the good in either period. Therefore, it must be that the total output over the two periods, $q_1 + q_2$, is determined by $1 - q_1 - q_2 = \underline{\theta}$. The second period price of low quality goods is then

$$p_2^L = s_1 \left(1 - q_1 - q_2\right). \tag{5}$$

Intuitively, the price of an old unit is proportional to its quality and to its valuation by the marginal consumer who buys it.

The monopolist's profit in period 2 is given by $\pi_2 = q_2(p_2^H - c)$, which, using (4) and (5), can be written as

$$\pi_2 = q_2 \left[s_1 \left(1 - q_1 - q_2\right) + (1 - q_2)(s_2 - s_1) - c\right].$$

The second period output that maximize this profit is given by[12]

$$q_2^*(q_1) = \frac{s_2 - s_1 q_1 - c}{2s_2}, \tag{6}$$

which allows us to express the second period profit as a function of the firm's first period output:

$$\pi_2^*(q_1) = \frac{1}{s_2}\left(\frac{s_2 - s_1 q_1 - c}{2}\right)^2.$$

3.2.2 The first period price and total profit

Using the second period profit function derived above, we now solve for the optimal quantity produced in period 1. The optimal q_1 will be the output level that maximizes the monopolist's overall profits. Recall that in the first period, there exists an initial quantity q_o of old units that were produced in period 0. Let p_o denote the price of these units in period 1 and let p_1 denote the first period price of the units produced in this period. We again start by identifying the consumer who is indifferent between buying a new and an old unit in this period. Summing up over all the higher valuation consumers will then allow us to derive the first period demand as a function of q_o and of the quality parameters s_1 and s_2.

A consumer with valuation θ buys a new unit (rather than an old unit) in period 1 if and only if

$$s_1\theta - p_1 + \delta E(p_2^L) \geq \theta - p_o, \tag{7}$$

where $E(p_2^L)$ is the consumer's expectation regarding the second period price of used units. This is because a new unit purchased in period 1 can be resold in the second-hand market of period 2. Similarly, a type θ consumer is willing to buy an old unit produced in period 0 if and only if $\theta - p_o \geq 0$, because this unit will be worthless by the end of the first period.

Now, let $\tilde{\theta}$ be the valuation of a consumer who is indifferent between buying a new unit in period 1 and buying an old one. Then $1 - \tilde{\theta}$ measures the number of consumers who buy new units in period 1, i.e., $q_1 = 1 - \tilde{\theta}$. Since (7) holds with equality for the consumer with valuation $\tilde{\theta}$, we have $\tilde{\theta} = 1 - q_1 = \frac{p_1 - p_o - \delta E(p_2^L)}{s_1 - 1}$. Combining this with the market clearing condition $p_o = 1 - q_o - q_1$ yields

$$p_1 = s_1(1 - q_1) - q_o + \delta E(p_2^L). \tag{8}$$

This highlights the fact that in the first period, the monopolist can increase the price of new goods by the amount for which the consumers expect to be able to resell them in the second period. Given

[12] Using q_1^* derived below, note that q_2^* increases in q_o; hence, q_2^* is positive for any q_o as long as $q_2^* > 0$ for $q_o = 0$. We have $q_2^* > 0$ at $q_o = 0$ if and only if $c < \frac{s_2[4(1+\delta)s_2 - (2+3\delta)s_1]}{2(1+2\delta)s_2 - \delta s_1} \equiv m(s_1, s_2)$. It is straightforward to check that $m(s_1, s_2)$ increases in s_2. Therefore, $c < m(s_1, s_2)$ if $c < m(s_1, s_1) = \frac{(2+\delta)s_1}{2+3\delta}$, which in turn holds if $c < \frac{2+\delta}{2+3\delta} = c^{\max}$. This is satisfied by Assumption 2.

that the consumers' equilibrium beliefs have to be correct, it must be that $E(p_2^L) = p_2^L$. Using (5) and (6), the first period price of new units can thus be written as

$$p_1 = (1 - q_1)(1 + \delta)s_1 - q_o - \delta \frac{s_1}{s_2} \left(\frac{s_2 - s_1 q_1 - c}{2} \right).$$

The monopolist's first period problem is then to choose q_1 so as to maximize her total profit over the two periods:

$$\pi(s_1, s_2) = \max_{q_1} q_1 \left[(1 + \delta)(1 - q_1)s_1 - \frac{\delta s_1}{s_2} \left(\frac{s_2 - s_1 q_1 - c}{2} \right) - c - q_o \right] + \frac{\delta}{s_2} \left(\frac{s_2 - s_1 q_1 - c}{2} \right)^2.$$

From this, the optimal first period output is obtained as

$$q_1^* = \frac{2\left[s_2(s_1 - c - q_o) + c\delta s_1\right]}{s_1\left[4s_2(1 + \delta) - 3\delta s_1\right]}. \tag{9}$$

Note that the first period output given by (9) is positive if $q_o < s_1 - c + \frac{c\delta s_1}{s_2}$, which holds by Assumption 3. This assumption also ensures that the total number of units available in period 1 is less than one, i.e., $q_o + q_1^* < 1$, which verifies that the old units q_o carry a positive price, as we have implicitly assumed when deriving (9).

Using the results obtained above, we are now ready to characterize the monopolist's incentives to adopt or suppress a freely available product innovation.

Lemma 2. *Suppose the initial supply of the old low quality units (q_o) is not too large, marginal cost of production (c) is relatively high, consumers and the firm are sufficiently patient, and the first period quality improvement (s_1) is relatively small. Then there exist s_2^* and s_2^{**} such the the monopolist optimally suppresses any innovation with $s_2 \in (s_2^*, s_2^{**})$. For all other parameter values the innovation is adopted.*[13]

This lemma says that in the presence of learning by doing, it may be a profit maximizing strategy for the monopolist to suppress a freely available quality-enhancing technology. The logic behind this result can be grasped most easily by comparing the effects of the second period quality enhancement, s_2, on the firm's first and second period profits. First, it can be verified that the optimal first period output, q_1^* (given by (9)) decreases in s_2. This is because the period 2 demand for the second hand units is lower the higher is the quality of new units in that period. This in turn implies that the equilibrium price of the second hand units in period 2 is lower when the innovation is adopted than when it is not, which means that the innovation induces more consumers to postpone the purchase of the good into the second period. Consequently, both the first period demand and optimal output are lower when the innovation is adopted than when it is not. On

[13] More formal statements of this and other lemmas and propositions, as well as the precise characterizations of the sets of parameter values for which they hold, can be found in their respective proofs in the Appendix.

the other hand, the higher is the second period quality, the larger is the demand for new units in that period. Thus, the innovation allows the monopolist to charge a higher price for the new units produced in period 2, which increases the firm's second period profit.

If the second period quality improvement s_2 is neither too small nor too large, the increase in second period profits arising from the firm's ability to charge a higher price in period 2 is more than offset by the decrease in first period profits caused by the delay in purchases. To see why s_2 needs to be from an intermediate range for the innovation to decrease the monopolist's profit, notice first that if s_2 is very large, then also the second period demand for new units, and consequently the present value of the firm's second period profit, is very large. This makes it optimal to adopt the innovation no matter how much it lowers the first period profit. On the other hand, suppose the second period quality improvement is no larger than the first period improvement, i.e., $s_2 = s_1$. Then adopting the innovation amounts to a proportionate increase in *both* the first and second period demands, which clearly increases the firm's total profit.

To illustrate the effects of the remaining parameters on the firm's decision to adopt the innovation, it may be helpful to provide a graphical representation of the firm's profit as a function of the second period quality enhancement. A closer inspection of the total profit function $\pi(s_1, s_2)$ reveals that it is convex, and that, when q_o is relatively small, it is first decreasing and then increasing in s_2, as represented in Figure 2 below. Consider first the effects of s_1. It can be checked that the firm's total profit from adopting the innovation increases in s_1 for any given s_2. As we explain in greater detail later, when discussing Proposition 1, this is because the most important impact of a rise in s_1 is that it boosts the firm's first period demand. Figure 2 illustrates the effect of an increase in s_1 from $s_1 = 1$ to $s_1 = 1.01$, when $c = 0.5$, $\delta = 1$, and $q_o = 0$. Due to this increase, the profit function $\pi(s_1, s_2)$ shifts up, which decreases the set of innovations the monopolist will optimally suppress (in other words, the range of s_2 such that $\pi(s_1, s_2) < \pi(1, 1)$ shrinks). The figure also suggests that for sufficiently large s_1, the profit function $\pi(s_1, s_2)$ is always above $\pi(1, 1)$, which means that adopting the innovation is always profitable. Hence, for suppression of the innovation to be optimal, the magnitude of the first period quality improvement has to be relatively small, i.e., $s_1 < s_1^*$.

The effects of the initial quantity, q_o, and of the discount factor, δ, are more subtle. As q_o increases, the market in the first period becomes more saturated, which forces the firm to produce less in that period and its overall profit decreases. This shifts the profit function $\pi(s_1, s_2)$ down, which by itself would increase the range of innovations that the monopolist will want to suppress. However, an increase in q_o also makes the slope of $\pi(s_1, s_2)$ less negative at $s_2 = s_1$ and for sufficiently large q_o this slope becomes positive, in which case $\pi(s_1, s_2)$ is always above $\pi(1, 1)$ and any innovation is adopted. The intuition for this is that although q_o decreases the monopolist's profit, it also makes her time inconsistency problem less severe, because this time inconsistency

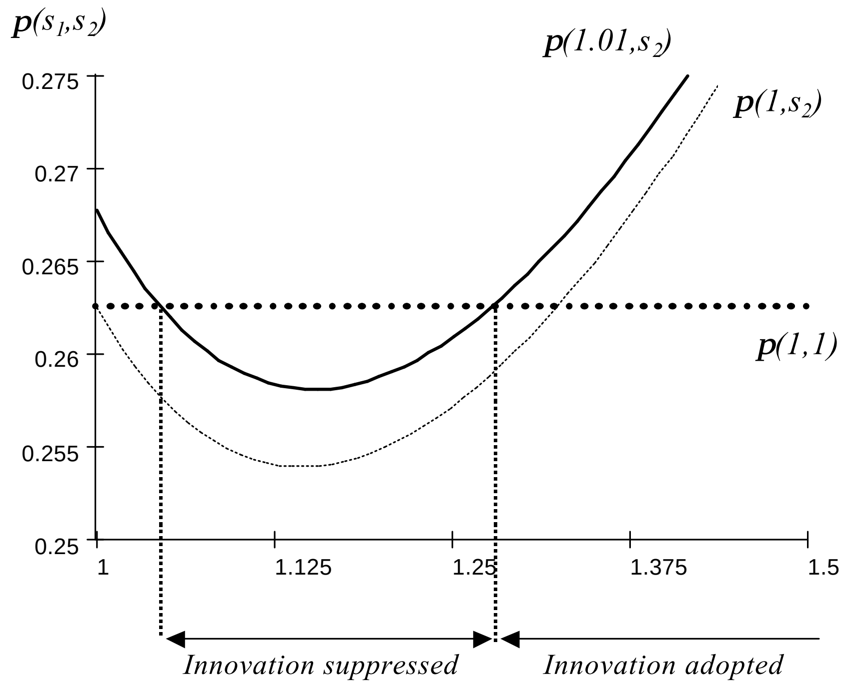

Figure 2. The dashed line depicts the firm's profit as a function of s_2, when $s_1 = 1$, $d = 1$, $c = 0.5$, and $q_0 = 0$. The bold line shows that an increase in s_1 to $s_1 = 1.01$ causes an upward shift in the firm's profit function $p(s_1,s_2)$, from $p(1,s_2)$ to $p(1.01,s_2)$. As a result, the range of innovations s_2 for which it is optimal to suppress the innovation shrinks.

problem is due to the monopolist's inability to commit to a high second period price. However, when q_o is relatively large, then the firm's optimal first period output is small, which means that the residual demand in the second period is large, and so is the optimal second period price. For sufficiently large q_o, the time inconsistency problem in pricing ceases to affect the monopolist's decision to adopt the new technology and the monopolist benefits from any innovation.

The effect of δ is explained as follows. The time inconsistency problem matters for the monopolist's decision to adopt or suppress the innovation only to the extent that the firm cares about its second period profit. If δ is small, then the present value of the second period profit is but a small fraction of the firm's overall profit, so that the time inconsistency problem becomes less important. Moreover, with a smaller δ, consumers are less patient and therefore less prone to postponing their purchase to the second period. For δ sufficiently small, the firm's first period effective cost of adopting the innovation, caused by the deviation from the one period optimal price, is therefore negligible relative to the profit increase that it generates in the second period, and it becomes worthwhile to adopt the innovation.

3.2.3 Technology choice under monopoly when commitment is possible

We have argued that the monopolist faces a time inconsistency problem in her pricing decisions, which affects her incentives to adopt the quality enhancing innovation. This is because, if the innovation is adopted, the first period goods become economically obsolete in the second period, and therefore consumers will only be willing to pay a lower price for them in period 1. The resulting reduction in first period prices, coupled with the inability to commit to prices in periods 1 and 2, is what leads the monopolist to suppress the superior technology.

Thus, before we proceed with the comparison of the monopolist's choice of technology with the first best outcome, it will be helpful to briefly investigate a benchmark case in which, at the beginning of period 1, the monopolist is able to commit to the second period output, q_2 (which, together with the first period output, q_1, uniquely defines the second period prices). As in the case of no commitment, the monopolist's profit in period 1 is again $\pi_1^{com} = q_1[s_1(1+\delta)(1-q_1) - \delta s_1 q_2 - (q_o + c)$ and the profit level in period 2 is $\pi_2^{com} = q_2[s_1(1-q_1-q_2) + (1-q_2)(s_2-s_1) - c]$. The monopolist thus commits in period 1 to quantities q_1 and q_2 that maximize

$$\pi^{com} = \pi_1^{com} + \delta\pi_2^{com}. \tag{10}$$

The solution to this problem is given by

$$q_1^{com} = \frac{s_2(s_1 - c - q_o) + c\delta s_1}{2s_1\left[s_2(1+\delta) - \delta s_1\right]} \quad \text{and} \quad q_2^{com} = \frac{(1+\delta)(s_2 - s_1) - c\delta + q_o}{2[s_2(1+\delta) - \delta s_1]}. \tag{11}$$

Note that Assumption 3 again guarantees that $q_o + q_1^{com} \leq 1$ and $1 - q_1^{com} - q_2^{com} \geq 0$.

It is now easy to see that the efficiency of the monopolist's decisions, relative to the first–best, depends on the monopolist's ability to commit to future prices. As can be seen by comparing equations (11) and (2), a commitment to future prices mitigates the delay in purchases by consumers: whenever q_1^e and q_2^e are positive, then q_1^{com} and q_2^{com} are also positive. We thus have:

Lemma 3. *When the monopolist can commit to future prices, she adopts the new technology if and only if it is first-best efficient to do so.*

Lemma 3 demonstrates that a necessary condition for any deviation from the efficient choice of technology is that the monopolist is not able to commit to future prices and quantities.

3.2.4 Excessive innovation and 'sleeping patents'

Having analyzed the social planner's decision to adopt a quality–enhancing technology, as well as the monopolist's optimization problem, we can now investigate the welfare implications of the monopolist's decisions. A comparison of Lemmas 1 and 2 reveals that without the possibility of a pre-commitment to future price, the monopolist in general deviates from the first-best choice of technology. In particular, for some parameter values she innovates too much, while for other parameter values she fails to adopt a free innovation that is socially desirable.

Proposition 1. *Suppose the monopolist cannot commit to future prices and let s_2^* and s_2^{**} be as in Lemma 2.*

(i) If the initial supply of old low quality units (q_o) is relatively large, marginal cost of production (c) is relatively small, consumers and the firm are not very patient, and there is no first period quality improvement ($s_1 = 1$), then there exists a set of second period quality improvements s_2 for which the monopolist inefficiently adopts the innovation, even though it would be first–best efficient to suppress it.[14]

(ii) If the initial supply of old low quality units (q_o) is not too large, marginal cost of production (c) is relatively high, consumers and the firm are sufficiently patient, and the first period quality improvement (s_1) is relatively small, the monopolist optimally suppresses any innovation for which $s_2 \in (s_2^*, s_2^{**})$, even though it would be first–best efficient to adopt it.

(iii) For all other parameter values, the monopolist adopts the innovation whenever it is first-best efficient to do so.

To see the economics behind this proposition, it is helpful to compare the effects of the innovation on the monopolist's profit when she can commit to future prices and when she can not. Using (8) and (4), the monopolist's total profit over the two periods can be written as

$$\pi(s_1, s_2) = q_1 \left[s_1(1 - q_1) - q_o + \delta p_2^L - c - q_o \right] + \delta q_2 \left[p_2^L + (1 - q_2)(s_2 - s_1) - c \right], \tag{12}$$

where $p_2^L = s_1 (1 - q_1 - q_2)$ is the second period price of used units, as given by (5).

Start with the effect of a small first period quality improvement, s_1, brought about by the new technology. Using the Envelope Theorem, a straightforward differentiation of the firm's profit function (12) with respect to s_1 yields

$$\frac{\partial \pi(s_1, s_2)}{\partial s_1} = q_1 \left[(1 - q_1) + \delta (1 - q_1 - q_2) \right] - \delta q_2 q_1 - \delta q_1 s_1 \frac{\partial q_2}{\partial s_1}. \tag{13}$$

Ignoring for the moment any effects due to the adjustment in the second period optimal output (captured by the last term above), (13) illustrates that an increase in s_1 has two opposite effects on the monopolist's profit. The first term represents an increase in the first period profit due to the higher demand and price in that period. The second term shows that an increase in s_1 decreases the firm's second period profit, because if s_2 is held fixed, an increase in s_1 decreases the quality premium for the new units in the second period, as can be seen from expression (4). However, the overall effect of these first two terms on the monopolist's profit is always positive. Formally, this is

[14] The same caveat applies here as in Lemma 1. Again, whenever there is a small cost, ε, associated with the adoption of the new technology, the social planner *strictly* prefers the old technology while the monopoly still prefers the new one if ε is small enough.

because Assumption 3 (non-saturation of the market) guarantees that $1 - q_1 - \delta q_2 > 0$. Intuitively, the reason is that the decrease in the quality premium that the monopolist can charge for the new second period units, caused by a higher s_1, is partly offset by the increase in the price of used units in that period, from which the quality premium is measured. This makes the second effect smaller in magnitude than the first one.

Finally, accounting for the effects of s_1 on the second period output does not change the conclusion that s_1 increases the firm's overall profit. An increase in s_1 makes the used units in period 2 more valuable, which decreases the demand for new units in that period, and hence also the optimal second period output. However, the Envelope Theorem implies that this decrease in q_2 does not have a first order effect on period 2 profit, while in the first period, a decrease in q_2 increases profit because it makes the first period units even more valuable by increasing the valuation of the marginal buyer, as can be readily seen from (5). Hence, s_1 increases the firm's profit, whether the monopolist can commit to the second period price and output (in which case the last term on the RHS of (13) vanishes) or not (in which case the term is positive). An increase in s_1 therefore always encourages *both* the monopolist and the social planner (by Lemma 1) to adopt the new technology. This means that any deviation from the first best incentives to innovate can only occur if s_2 increases beyond s_1, which highlights the importance of learning-by-doing for our results.

In contrast to the effects of s_1, the net effect of s_2 on the monopolist's total profit very much depends upon her ability to commit to the second period quantity. If commitment is feasible, then the quantity q_2 is chosen optimally in period 1, which means that, by the Envelope Theorem, the change in q_2 due to an increase in s_2 only has a second order effect on the firm's profit. Hence, differentiating the profit function (10) derived in section 3.2.3, we have

$$\frac{\partial \pi^{com}(s_1, s_2)}{\partial s_2} = q_2(1 - q_2),$$

which illustrates that if the monopolist has the ability to commit, the improvement in the second period quality only affects the firm's profit through an increase in the price that it can charge for the new units in the second period. This unambiguously increases the total profit whenever the second period output is positive, just like in the first best case, where the effect of s_2 on total surplus is given by (3). This, combined with the effects of s_1 discussed above, demonstrates that when commitment is possible, the monopolist's incentives to innovate coincide with those of a social planner in the first-best scenario, as we have already shown in Lemma 3.

When commitment is not feasible, the change in s_2 affects the firm's total profit also through the second period output, because the firm now chooses q_2 so as to maximize the second period profit, rather than total profit. Thus, in this case the monopolist's incentives to adopt the innovation generically differ from the first-best incentives. In particular, if $\frac{\partial \pi(s_1, s_2)}{\partial s_2} < 0$ when evaluated at $s_2 = s_1$, which holds for the parameter values given in Lemma 2, then an increase in s_2 has an adverse effect on the firm's overall profit, which, for small values of s_1, can lead to suppression of socially efficient innovation (part (ii) in the proposition). The intuition is as explained in the discussion following Lemma 2: The new technology tends to decrease the first period price (provided that s_1 is not too large), because the first period units will be obsolete in period 2, when most of the benefits from learning–by–doing are realized. This lowers the monopolist's first period profit, which can deter her from adopting the innovation where it would be socially desirable to exploit it.

The logic for the result in part (i), which says that sometimes the monopolist adopts an innovation that is not socially desirable, is also simple. The output in the second period is higher under monopoly with no commitment power than it is in the first best scenario, because when the monopoly chooses its output in the second period, it ignores the effect of this choice on the resale value of used units in that period. The low resale value of used units in turn decreases the first period demand and hence the price the monopolist can charge for these units, which prevents her from internalizing all the benefits brought about by the innovation. Therefore, the monopolist sometimes produces new units in the second period when there should be no production from the efficiency point of view. But the new technology is valuable only if there is production in the second period. This means that a monopolist can sometimes consider the innovation to be more valuable than a social planner would.

A specific example might be helpful here. Suppose that $s_1 = 1$, $q_o = 0$, $\delta = 1$, and s_2 is small (close to 1). Assume also that the quantity produced in the second period is positive, i.e., $q_2 > 0$ (otherwise, the innovation is worthless because $s_1 = 1$).[15] Then, using equation (1), the net surplus from adopting the innovation is approximately given by[16]

$$W(1, s_2) - W(1, 1) = \int_{1-q_2}^{1} (s_2 - 1)\theta d\theta - \int_{1-q_1-q_2}^{1-q_1} \theta d\theta.$$

The first term represents the increase in the second period utility for the high valuation consumers who, instead of a good of quality $s_1 = 1$, get to consume a good of quality $s_2 > 1$. However, the q_2 units produced in period 2 are not available for consumption in period 1. This decreases the first period consumer surplus, which is captured by the second integral. (To get the exact net benefit of the innovation, we would also have to account for the optimal adjustment of the first period output when the innovation is adopted. We ignore this quantity adjustment effect here, because it is of second order magnitude when s_2 is small, by the Envelope Theorem). Clearly, when s_2 is sufficiently close to one, the utility increase from the new second–period units is more than offset by the first period loss of surplus and it becomes optimal to produce all units in the first period and suppress the new technology.

[15] As explained in footnote 12, q_2^* is always strictly positive under monopoly, by Assumption 2. Under first-best, (2) implies that for the parameter values assumed here, $q_2^e > 0$ if and only if $c < 2(s_2 - 1)$.

[16] This is obtained under the assumption that $1 - q_1 - q_2 > 0$; otherwise, $W(1, s_2) - W(1, 1) = \int_{1-q_2}^{1} (s_2 - 1)\theta d\theta - \int_{0}^{1-q_1} \theta d\theta - c(q_1 + q_2 - 1)$. This, however, does not affect the reasoning here.

This is not true for the monopolist if c is small. For $s_1 = 1$, $q_o = 0$, and $\delta = 1$, it can be shown from equation (12) that the difference between the monopolist's profits when the innovation is adopted and when it is not is given by

$$\pi(1, s_2) - \pi(1, 1) = \left(\frac{1}{s_2}A^2 - B^2\right) - q_1^* \left(\frac{1}{s_2}A - B\right), \tag{14}$$

where $A \equiv \frac{s_2 - q_1^* - c}{2}$, $B \equiv \frac{1 - q_1^* - c}{2}$, and $q_1^* = \frac{2[s_2(1-c)+c]}{8s_2 - 3}$ (from equation (9)). The term $\frac{1}{s_2}A^2 - B^2$ represents the increase in the firm's second period profit if the innovation is adopted, while the term $q_1^* \left(\frac{1}{s_2}A - B\right)$ is the decrease in the first period profit, due to the lower price the monopolist has to charge in that period. Now, simple algebraic manipulations (where we use $s_2^2 > s_2$) reveal that a sufficient condition for this profit difference to be positive is that both $\frac{1}{s_2}A - B > 0$ and $\frac{1}{s_2}A + B - q_1^* > 0$. Letting c approach zero, we see that $q_1^* \to \frac{2s_2}{8s_2 - 3}$, so that $\frac{1}{s_2}A - B \to \frac{s_2 - 1}{8s_2 - 3}$ and $\frac{1}{s_2}A + B - q_1^* \to \frac{5s_2 - 4}{8s_2 - 3}$, which are both strictly positive for any $s_2 > 1$. This shows that, unlike the social planner, the monopolist will find it optimal to adopt the new technology if c is sufficiently small. Intuitively, a small marginal cost of production mitigates the negative impact of the new technology on first period profit, since the monopolist is able to charge a lower price which encourages consumers to purchase the good in the first period, rather than postpone the purchase until the second period, when the improved units become available. Hence, as c approaches zero, the first term on the right hand side of (14) dominates the second term.

3.2.5 A second best analysis

In our first-best analysis, we assumed that the social planner has the ability to both choose the degree of innovation, as well as to determine the firm's output levels and prices. However, this is not the only reasonable benchmark one can imagine; an alternative approach used in the literature (see, e.g., Waldman, 1996a) involves a comparison with the behavior of a social planner who can choose the monopolist's technology but nothing else, that is, outputs are set by the monopolist. Since the main focus of the paper is whether the monopolist adopts the innovation when such adoption is efficient, it could be argued that this alternative comparison provides more direct insights into whether or not the monopolist has proper incentives concerning which technology to adopt. Moreover, for some industries, such a second best benchmark may be quite realistic. For example, a regulatory body may decide not to grant a license to produce a certain drug if the quality does not meet a required standard, or a firm may be required to produce electrical appliances only if they meet a certain energy efficiency level. These situations are better approximated by a setting in which the social planner determines the degree of innovation, with output and price decisions left to the firm, rather than by a first best setting where the planner controls everything.

Thus, suppose that the monopolist's technology is chosen in the socially optimal way, but the monopolist then subsequently sets her outputs so as to maximize her profit. Then it is socially optimal to adopt the technology if and only if $W(s_1, s_2) > W(1,1)$, where both $W(s_1, s_2)$ and $W(1,1)$ are evaluated at q_1^* and q_2^* from equations (6) and (9). The second-best outcome is characterized by the following lemma.

Lemma 4. *Under assumptions 1-3, the second best outcome is to always adopt the new technology (s_1, s_2).*

The intuition for this result is relatively simple. Recall that our restrictions on the marginal cost and on the initial quantity of old units available in period 1 (assumptions 2 and 3) ensure that both q_1^* and q_2^* are positive. Given this, any improvement in the quality of the good raises the overall welfare, which makes it second–best efficient.

Comparing the second-best efficient technology adoption described in Lemma 4 with the monopolist's optimal technology choice described in Lemma 2 immediately yields the following result.

Proposition 2. *If the initial supply of the old low quality units (q_o) is not too large, marginal cost of production (c) is relatively high, consumers and the firm are sufficiently patient, and the first period quality improvement (s_1) is relatively small, then the monopolist optimally suppresses any innovation for which $s_2 \in (s_2^*, s_2^{**})$, even though it would be second-best efficient to adopt it. For all other parameter values, the monopolist adopts the innovation whenever it is second–best efficient to do so.*

Proposition 2 demonstrates that, unlike in the first best scenario (Proposition 1), the monopolist never adopts a product innovation that would be suppressed by a social planner who cannot influence the monopolist's prices. The reason is that if the social planner does not control the monopolist's prices and output, then the second period residual demand is the same as under monopoly. This makes the innovation at least as valuable to the social planner as to the monopolist.

More specifically, in our analysis we have restricted attention to the parameter values such that the monopolist produces a positive second period quantity if she adopts the innovation. Since the social planner in this case does not control the monopolist's output, the second best output in period 2 is also positive. But that means that the benefits of the innovation are always realized (even if the first period quality is not improved), which implies that, from the second-best point of view, the innovation should always be adopted. Consequently, it is not possible for the monopolist to innovate too much compared to the second-best.

To sum up, propositions 1 and 2 show that sometimes the monopolist suppresses a freely available, socially desirable innovation, and this is true in comparison to both the first-best and the second-best outcomes. In addition, compared to the first best outcome, the monopolist can sometimes adopt new technology that should efficiently be suppressed, although this is not true relative to the second best outcome.

3.2.6 Extensions

Before we conclude, let us briefly discuss two extensions of the model that demonstrate the robustness of our results.

First, our result that the monopolist may optimally suppress a superior technology naturally raises the following question: Why would the monopolist ever invest in the development of an innovation if she is going to shelve it once it is developed? It is fairly straightforward to incorporate costly development of innovation in our model. In particular, suppose that in period 0, before she has to make the technology choice, the monopolist can invest in R&D, which at the beginning of period 1 generates a new technology. However, ex ante, the monopolist cannot predict the exact degree of quality improvement that the new technology will result in; rather, this information becomes available only at the beginning of period 1, after the R&D investment is sunk. As we show formally in an earlier version of this paper (Kutsoati and Zabojnik, 2002), in this setting, the monopolist will find it profitable to undertake a costly R&D as long as the required investment is not too large. This is despite the fact that she knows that with positive probability, the quality improvement will fall within the range described in Lemma 2, in which case she will find it optimal to shelve the resulting innovation.

The second extension worth mentioning here is that, although in this paper we concentrate on a quality improving innovation, similar logic applies when the innovation decreases the monopolist's cost of production. In particular, suppose that the innovation does not affect the consumers' valuations (so that $s_1 = s_2 = 1$), but, instead, it decreases the marginal cost of production from c_1 in the first period (which would also be the marginal cost in both periods if the innovation were not adopted) to $c_2 < c_1$. Old units of the good therefore have the same per period value as new ones, but as before, they become economically obsolete after two periods. Analogous to part (i) in Proposition 1, it can be shown that if the first period marginal cost (c_1) is not too large, then for a range of second period marginal costs (c_2) the monopolist adopts the innovation even though the first-best outcome would be to suppress it.[17] The intuition is similar to that behind Proposition 1: If the marginal cost is already low even with the old technology, then the cost reduction due to the new technology cannot be large, which means that, from the first best efficiency point of view, it is not worth postponing the production (and consumption) of the good to the second period, when these cost savings can be realized. For the monopolist though, it is optimal to restrict the first period output compared to the efficient level, which increases her second period demand and makes production in the second period optimal even when this may not be first-best efficient. This makes the new technology more valuable to the monopolist than to a social planner.

On the other hand, the new technology has a negative impact on the monopolist's first period

[17] The reader interested in a more detailed analysis of this setting and more formal statements (and proofs) of the results described here is referred to an earlier version of this paper (Kutsoati and Zabojnik, 2002).

profit, as consumers postpone current purchases in anticipation of future lower prices, brought about by the lower second period production costs. Due to this effect, part (ii) in Proposition 1 also has an analogue in this alternative setting. In particular, if c_1 is relatively large, then the negative effect of the innovation on first period profits outweighs the increase in second period profits, as more consumers delay their purchases till the second period. Hence, unless it drastically reduces the second period production costs, the monopolist will find it optimal to suppress the cost-reducing innovation, even though the first best outcome would be to adopt it.

Finally, the conclusions in Proposition 2, regarding the comparison of the monopolist's incentives to adopt the new technology with the second best scenario readily extend to the case of cost-reducing innovation, as well.

4 Conclusion

Product and technological innovation under durable–good monopoly has been subject to a lot of research in the economics literature. In this paper, we approach this issue from a different point of view, and ask a slightly different question, than most other papers. First, we introduce learning by doing, which we believe adds more realism to the analysis. Second, for the most part we do *not* consider innovations that require investments. Rather, we concentrate on existing innovations that are available at no (or very small) cost and examine the monopolist's incentives to adopt or suppress such innovations.

There are two effects that influence a monopolist's incentives to adopt a new superior technology in the presence of learning by doing, and these work in opposite directions. First, owing to the presence of learning by doing, the gains from the innovation are realized mainly in the second period. But the inability to commit to future prices leads the monopolist to produce a higher second period output than she would if she were able to commit. Our first main result is that, due to this effect, the monopolist may view the innovation as more desirable than a social planner would, which can lead her to adopt a new technology that optimally should be suppressed.

The second effect is that, by adopting the new technology, the monopolist exacerbates her time inconsistency problem, which tends to discourage innovation. This effect can lead to situations where the monopolist suppresses a better product or a dominant technology in a socially inefficient way.

There are several ways in which our analysis could be extended. Probably the most interesting would be to investigate the effect of learning by doing on adoption of new technology by oligopolies. We leave this to future research.

Appendix

Proof of Lemma 1. (i) Let $s_1 = 1$. We will show that in this case the first best requires that the innovation is adopted if and only if $s_2 > 1 + \frac{c\delta - q_o}{1+\delta}$ Differentiate $W(s_2)$ with respect to s_2 and use the Envelope Theorem to get $\frac{\partial W(s_2)}{\partial s_2} = \delta \int_{1-q_2^e}^{1} \theta d\theta$. Thus, $\frac{\partial W(s_2)}{\partial s_2} > 0$ if and only if $q_2^e > 0$. But $q_2^e|_{s_1=1} = \frac{(s_2-1)(1+\delta)-\delta c+q_o}{s_2(1+\delta)-\delta}$, which is positive if and only if $s_2 > 1 + \frac{c\delta - q_o}{1+\delta} \equiv \hat{s}$. Since the welfare with the innovation is equal to the welfare without the innovation when $s_2 = \hat{s}$ (because $q_2^e = 0$ for $s_2 = \hat{s}$), the above analysis means that the innovation improves welfare if and only if $s_2 > \hat{s}$. Clearly, when $q_o > c\delta$, then this condition holds for all $s_2 > 1$. But for small values of q_o (in particular, $q_o \leq c\delta$), the innovation improves welfare only if it is substantial enough; i.e., $s_2 > \hat{s}$. Finally, it can be checked that the efficient level of output in the first period under the new technology satisfies our constraint that more than $q_{\min}$ units be produced in this period: $q_1^e|_{s_1=1} = \frac{s_2(1-c-q_o)+c\delta}{(1+\delta)s_2-\delta} > q_{\min}$.

(ii) Differentiate $W(s_1, s_2)$ with respect to s_1 to get $\frac{\partial W(s_1,s_2)}{\partial s_1} = \int_{1-q_1^e}^{1} \theta d\theta + \delta \int_{1-q_1^e-q_2^e}^{1-q_2^e} \theta d\theta$. Since $q_1^e = \frac{s_2(s_1-c-q_o)+\delta c s_1}{s_1[s_2(1+\delta)-\delta s_1]} > 0$, the innovation strictly increases welfare whenever it improves the first period quality. Finally, the efficient choice of output in the first period under the new technology satisfies the constraint $q_1^e > q_{\min}$, because $q_1^e > q_1^e|_{s_1=1}$. The last inequality can be checked by verifying that $\frac{\partial q_1^e}{\partial s_1} > 0$. Q.E.D.

Proof of Lemma 2. We first state the lemma more formally:

Lemma 2. *Let $q_o < \bar{q}_o$. There exist cutoff values $c^* \in (0, c^{\max})$, $q_o^*(c) > 0$, $\delta^*(c, q_o) < 1$, $s_1^*(c, \delta, q_o)$, $s_2^*(c, \delta, q_o, s_1)$ and $s_2^{**}(c, \delta, q_o, s_1)$, $s_2^{**} > s_2^* \geq s_1^*$, such that for any $c > c^*$, $q_o < q_o^*$, $\delta > \delta^*$, $s_1 < s_1^*$, and $s_2 \in (s_2^*, s_2^{**})$ the monopolist optimally suppresses the innovation (s_1, s_2). For all other parameter values the innovation is adopted.*

Proof: Rearrange $\pi(s_1, s_2, q_1)$ and plug in $q_1^* = \frac{2[s_1 s_2(1-q_o)-c(s_2-\delta s_1)]}{s_1[4s_2(1+\delta)-3\delta s_1]}$ to get

$$\begin{aligned} \pi(s_1, s_2, q_1^*) &= s_1 q_1^{*2}\left(\frac{3\delta s_1}{4s_2} - (1+\delta)\right) + q_1^* \frac{[s_2(s_1 - c - q_o) + c\delta s_1)]}{s_2} + \frac{\delta(s_2-c)^2}{4s_2} \\ &= \frac{[s_2(s_1 - c - q_o) + c\delta s_1]^2}{s_1 s_2\,[4s_2(1+\delta) - 3\delta s_1]} + \frac{\delta(s_2-c)^2}{4s_2}. \end{aligned} \tag{15}$$

The strategy of the proof is as follows. We will show that the profit function $\pi(s_1, s_2, q_1^*)$ is convex in s_2 throughout the relevant range of parameter values, approaches infinity in s_2, and its minimum (with respect to s_2) increases without bounds in s_1. Thus, for any given s_1, suppression of the new technology is optimal for some s_2 if and only if $\min_{s_2} \pi(s_1, s_2, q_1^*) < \pi(1, 1, q_1^*)$. We will show that this inequality holds for a range of parameter values c and δ when s_1 is small, but not when s_1 is large. We proceed in three steps:

Step 1. Using the Envelope Theorem, differentiate the expression for total profit in (2) with respect to s_2 to get $\frac{\partial \pi(s_2)}{\partial s_2} < 0$ if and only if

$$s_2^2 - (s_1 q_1^* + c)(3s_1 q_1^* + c) < 0. \tag{16}$$

It can be checked that q_1^* decreases in s_2, so that LHS of (16) increases in s_2. This means that $\pi(s_1, s_2, q_1^*)$ is convex in s_2 in the relevant range of parameter values. Also, from (15), $\lim_{s_2 \to \infty} \pi(s_1, s_2, q_1^*) = \infty$. Hence, for any given s_1, if

$$\min_{s_2 \geq s_1} \pi(s_1, s_2, q_1^*) < \pi(1, 1, q_1^*),$$

then there exists a non-empty interval (s_2^*, s_2^{**}), with $s_2^* \geq s_1$, such that $\pi(s_1, s_2, q_1^*) < \pi(1, 1, q_1^*)$ (i.e., the innovation is suppressed) for all $s_2 \in (s_2^*, s_2^{**})$, while for all other s_2 it must be that $\pi(s_1, s_2, q_1^*) \geq \pi(1, 1, q_1^*)$ (i.e., the innovation is adopted).

Step 2. It can be checked that $\pi(s_1, s_2, q_1^*)$ given in (15) is monotonically increasing in s_1 for all s_2. Hence, $\pi(s_1, s_2^{\min}, q_1^*)$ also increases in s_1, where $s_2^{\min} = \arg\min_{s_2} \pi(s_1, s_2, q_1^*)$. This, combined with $\lim_{s_2 \to \infty} \pi(s_1, s_2, q_1^*) = \infty$, means that $\min_{s_2 \geq s_1} \pi(s_1, s_2, q_1^*)$ increases in s_1, with $\lim_{s_1 \to \infty} \min_{s_2 \geq s_1} \pi(s_1, s_2, q_1^*) = \infty$. Therefore, there exists an $s_1^* \geq 1$ such that

$$\min_{s_2 \geq s_1} \pi(s_1, s_2, q_1^*) \geq \pi(1, 1, q_1^*)$$

for all $s_1 \geq s_1^*$, while $\min_{s_2 \geq s_1} \pi(s_1, s_2, q_1^*) < \pi(1, 1, q_1^*)$ if $s_1 < s_1^*$.

Step 3. To complete the proof, all we need to do is show that there exists a range of parameter values c, q_o and δ such that $s_1^* > 1$ and that for all other parameter values, $s_1^* = 1$. For this, it is enough to identify the parameter values under which $\frac{\partial \pi(s_2)}{\partial s_2} < 0$ when $s_1 = s_2 = 1$, because $\frac{\partial \pi(s_2)}{\partial s_2}|_{s_1 = s_2 = 1} < 0$ implies that $\min_{s_2 \geq 1} \pi(1, s_2, q_1^*) < \pi(1, 1, q_1^*)$.

Setting $s_1 = s_2 = 1$ and solving for q_1^*, we find that (16) holds for a positive q_1^* if and only if

$$q_1^* > \frac{1}{3}\sqrt{c^2 + 3} - \frac{2}{3}c. \tag{17}$$

Plugging in for q_1^*, this yields

$$\frac{2\,(1 - c - q_o + c\delta)}{4 + \delta} - \frac{1}{3}\sqrt{(c^2 + 3)} + \frac{2}{3}c > 0, \tag{18}$$

which for non-negative δ holds if and only if

$$c > \frac{1}{\sqrt{21}} \equiv \hat{c}_1 \quad \text{and} \quad \delta > \frac{-2c - 6 + 6q_o + 4\sqrt{(c^2 + 3)}}{8c - \sqrt{(c^2 + 3)}} \equiv \delta^*.$$

Now, $\delta^* < 1$ if and only if $q_o < \frac{5}{3}c + 1 - \frac{5}{6}\sqrt{(c^2 + 3)} \equiv q_o^*$, and $q_o^* > 0$ if and only if $c > \hat{c}_2 \equiv \frac{-4 + \sqrt{29}}{5} > \hat{c}_1$. Note that $\hat{c}_2 < c^{\max} = \frac{2 + \delta}{2 + 3\delta}$ for all $\delta \in [0, 1]$. Hence, if $c > c^* \equiv \hat{c}_2$, then $q_o^* > 0$, $\delta^* < 1$ for all $q_o < q_o^*$, and (17) holds for all $c > c^*$, $q_o < q_o^*$, and $\delta > \delta^*$. Q.E.D.

Proof of Lemma 3. First, applying the Envelope Theorem yields $\frac{\partial \pi^{com}}{\partial s_2}|_{s_1 = 1} = q_2^{com}(1 - q_2^{com}) \geq 0$, where the inequality follows because our assumptions guarantee that $q_2^{com} \in [0, 1)$. Next, differentiating with respect to s_1 and using $s_2 \geq s_1 \geq 1$, we obtain $\frac{\partial \pi^{com}}{\partial s_1} > 0$. Together with $\frac{\partial \pi^{com}}{\partial s_2} \geq 0$, this means that whenever the innovation improves the first period quality of the good, the monopolist finds it optimal to adopt it. Thus, the innovation can be possibly suppressed only when $s_1 = 1$. Setting $s_1 = 1$, we get $\frac{\partial \pi^{com}}{\partial s_2}|_{s_1=1} > 0$ if and only if $q_2^{com}|_{s_1=1} > 0$, which in turn holds if and only if $s_2 > 1 + \frac{c\delta - q_o}{1+\delta}$. Since this is the same condition as in Lemma 1, this shows that the monopolist's incentives to adopt the new technology coincide with the first best if she can commit to future prices.

Proof of Proposition 1. We again start with a more formal statement of the proposition:

Proposition 1. *Suppose the monopolist cannot commit to future prices.*

(i) If $s_1 > 1$, then for any $c > c^*$, $q_o < q_o^*$, $\delta > \delta^*$, $s_1 < s_1^*$, and $s_2 \in (s_2^*, s_2^{**})$, where c^*, q_o^*, δ^*, s_1^*, s_2^*, and s_2^{**} are as in Lemma 1, the monopolist optimally suppresses the innovation (s_1, s_2) even though it is first–best efficient to adopt it.

(ii) Suppose $s_1 = 1$, $q_o < c\delta$, and $s_2 \in (1, 1 + \frac{c\delta - q_o}{1+\delta})$. Then if either of $c < c^*$, $q_o > q_o$, $\delta < \delta^*$, or $s_2 \notin (s_2^*, s_2^{**})$ is satisfied, the monopolist adopts the innovation (s_1, s_2) even though it is first–best efficient to suppress it. The set of parameter values for which this holds is non-empty.

(iii) For all other parameter values, the monopolist adopts the innovation whenever it is first-best efficient to do so.

Proof: All the claims follow immediately by combining lemmas 1 and 2, except for the claim that part (ii) is not vacuous. This last claim is proved as follows. Lemma 1 shows that suppression is first-best efficient when $s_2 < 1 + \frac{c\delta - q_o}{1+\delta}$. On the other hand, Lemma 2 says that regardless of the value for s_2, the monopolist adopts the innovation for all $c \in [0, c^*)$, where c^* is as in Lemma 2. Consequently, the innovation is adopted by the monopolist even though from the efficiency point of view it should be suppressed whenever $\delta > 0$, $c \in (0, c^*)$, $q_o < c\delta$, and $s_2 < 1 + \frac{c\delta - q_o}{1+\delta}$, which is a non-empty set of parameter values. Q.E.D.

Proof of Lemma 4. The proof follows the same logic as the proof of Lemma 1. As in that proof, $\frac{\partial W(s_1,s_2)}{\partial s_1} > 0$. Moreover, differentiating $W(s_1, s_2)$ with respect to s_2 and using the Envelope Theorem, we get $\frac{\partial W(s_1,s_2)}{\partial s_2} = \delta \int_{1-q_2^*}^{1} \theta d\theta$, which is strictly positive because $q_2^* > 0$ by the assumption that $c < c^{\max}$. Hence, any new technology with $s_2 > s_1 \geq 1$ strictly improves welfare from the second-best point of view. Q.E.D.

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