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The diffusion of new technology: adoption subsidies, spillovers, and transaction costs.

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Abstract

We establish the relation between optimal subsidy rates and spillovers from the sequential adoption of a new technology, we find that they evolve in the same direction over time. We show that spillovers, hence the subsidy rates, need not be monotonic. We show that when subsidy rates are increasing, their growth rate has to be paced by the growth rate of the present cost of the adoption of the new technology. We also show that increasing subsidies rates cannot produce the desired effect of accelerating adoption if the social cost of public funds is relatively high; hence first-best subsidy adoptions are not always viable.

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1. Introduction

A new technology goes through two principal stages; the invention stage and the innovation stage. The invention stage is driven by firms' decisions to undertake research and development (R&D) efforts, the economic literature is abound with studies that attempt to understand and explain those decisions. Typically, R&D effort bears fruits only when research output is incorporated in the production process. A new technology is incorporated in the production process (innovation stage) only when tangible gains from its use are expected or have been demonstrated elsewhere. It is possible that between the invention stage and the innovation stage additional efforts are needed to accelerate the diffusion of the new technology. For instance, when inputs are particularly scarce, e.g. water and energy, the regulator may be inclined to encourage the early adoption of a new input-saving technology through subsidies, where the regulator underwrites part of the cost that each firm incurs upon the adoption of the new technology.

The diffusion of a new technology was studied by Reinganum (1981a,b), Fudenberg and Tirole (1985), and Quirmbach (1986) among others. Hoppe (2002) provides an extensive survey of the literature about the timing of adoption of a new technology; she distinguishes between: (i) certain vs. uncertain value and availability of a new technology, and (ii) between strategic vs. non-strategic adoption of a new technology. Reinganum (1981a,b) shows that although identical and fully informed, firms adopt a new technology sequentially. Fudenberg and Tirole (1985) outline the importance of the threat of preemption as a rent-equalizing factor in games of timing. They show that when preemption is possible, payoffs in a symmetric duopoly are equal in equilibrium and adoption is simultaneous; however, in an oligopoly that must not be the case. Hendricks (1992) studies the effect of uncertainty about the gains from a new technology and concludes that qualitatively the equilibrium with uncertainty and without adoption precommitment is the same as the equilibrium without uncertainty but with commitment to adopt.

In all of the above studies and those covered by Hoppe (2002) adoption subsidies were not considered. The properties of subsidies that promote the adoption of a new technology, the relation between adoption subsidies and the spillovers from adoption, or the effect of the social cost of public funds on adoption subsidies remain largely unresearched. In this paper we set up a fairly general model of timing of a new technology adoption with adoption subsidies. We establish the relation between subsidy rates and spillovers from the sequential adoption game and we show that they evolve in the same direction over time. While the intuition suggests that subsidy rates should be decreasing over time when the cost of adoption decreases over time, we show that this is not necessarily the case. Indeed, in our model spillovers from adoption hence subsidy rates are not always monotonic. We then show that when subsidy rates are increasing, their growth rate has to be paced by the growth rate of the present cost of the adoption. Last, we show that increasing subsidies cannot produce the desired effect of accelerating adoption if the social cost of public funds or transaction costs are relatively high. In the latter case, the regulator should only offer second-best subsidy rates or abstains from subsidizing the adoption if it implies an increase in the subsidy rate over time. This last point is particularly relevant for developing countries where adoption subsidies tend to be used indiscriminately to promote new and efficient technologies even though transaction costs are high.

Related to our work, Stoneman and David (1986) develop a model with adoption subsidies to show that subsidies may not always increase welfare and that their effect depends on the market structure in the supply of the new technology. However, in their model Stoneman and David did not allow for the subsidy to change over time and its level is exogenous to the model while in our model the subsidy rate is endogenously determined for each period where adoption occurs, and is function of the gains from adoption. Jaffe and Stavins (1994) present compelling arguments in favor of the use of adoption subsidies, such as the information value from the use of the new technology by some firms and its effects on spreading the use to other firms. Also, the use of adoption subsidies can be motivated by the existence of free-rider problems that reduce R&D efforts, the regulator's support through adoption subsidies to reduce the cost of adoption may be necessary to circumvent that. Conceptually, the diffusion of a new technology can be promoted through command and control instruments such as technology standards, those can be justified in the presence of negative externalities such as pollution; however, in addition to the possibility of choosing an unambitious or infeasible standard that approach is socially inefficient and tends to reduce incentives to innovate (Jaffe and Stavins, 1995).

The outline of the paper is as follows. In section 2 we introduce the general model, in section 3 we discuss the properties of the adoption subsidies for an oligopoly, in section 4 we discuss the properties of the subsidy rate, and then conclude.

2. The Model

Consider an industry where *N* firms produce a homogenous good using technology $v \in \{0,1\}$; an old technology denoted by 0 and a new technology denoted by 1. The new technology is made available at period zero and has the advantage of reducing the marginal cost of production. If the new technology is adopted at period *t* then its cost is $k(t)$, its present value cost is $L(t) = k(t)e^{-rt}$, with *r* being the discount rate. It is assumed that the cost of the new technology decreases with time, $\dot{k}(t) < 0$, but never reaches zero, $\lim_{t\to\infty} k(t) > 0$.[1]

When $n \le N$ firms adopt the new technology and a firm uses technology *v*, we denote its profit at every period by π_n^v with the stipulation that π_0^1 and π_N^0 do not exist. We assume that;

Assumption 1. *Firms realize positive profits,* $\pi_n^v > 0; \forall v, n$.

Assumption 2. *The adoption of the new technology is always more profitable than the non adoption and that a firm's profit decreases as more firms adopt the new technology,* $\pi_n^1 > \pi_{n'}^1 > \pi_0^0 > \pi_n^0; \forall n' \ge n$.

In static, we can set up a payoff matrix of the decision to adopt the new technology and find that the Nash equilibrium is that all firms adopt the new technology. However the introduction of dynamics leads to a different outcome. In the case of *N* firms, if a firm is the i^{th} to adopt the new technology, then it chooses the optimal period T_i of adoption by maximizing;

[1] We assume away incremental adoption of new technologies addressed by Lissoni (2005).

$$V_i\left(T_i\right)=\sum_{j=1}^{i-1}\int_{T_j}^{T_{j+1}}\pi_j^0 e^{-rt}dt+\sum_{j=i}^{n}\int_{T_j}^{T_{j+1}}\pi_j^1 e^{-rt}dt-L\left(T_i\right). \tag{1}$$

In the duopoly case, Reinganum (1981a) shows that there are two symmetric Nash equilibiria and conjectures that in an oligopoly there are $N!$ pure symmetric Nash equilibria; one equilibrium for each possible sequence of the firms' adoption of the new technology. Reinganum (1981a,b) also shows that the simultaneous adoption of the new technology is not an equilibrium; a diffusion process takes place although the firms are identical and operating in a full information environment, including in the case of an oligopolistic market (Reinganum, 1981b).[2] So in the remainder of this paper the following assumption holds.

Assumption 3. *Firms adopt the new technology sequentially*.

3. Technology Adoption Subsidies

When a firm adopts the new technology its marginal cost decreases, hence its output increases. At the aggregate level, the sequence of total outputs $\left\{Q_n\right\}$ is positive increasing and the sequence of consumers' surpluses $\left\{S_n\right\}$ is positive increasing. We define $\left\{w_n\right\}$ as being the sequence of social welfares – the sum of consumers' surplus and firms' profits. The aforementioned sequences are all assumed bounded above, hence convergent.

For the n^{th} firm to adopt the new technology at period T_n we define $s_n \equiv s(T_n)$, $L_n \equiv L(T_n)$, and $k_n \equiv k(T_n)$; then with $\lambda > 0$ the social cost of public funds (can also be thought of as transaction cost), the regulator maximizes the following program to determine the optimal subsidy rates $\left\{s_n\right\}$,

$$\max_{s(.)} W\left(s(.),T\right)=\sum_i \int_{T_i}^{T_{i+1}} w_i e^{-rt}dt-L(T_i)\left(1+\lambda s(T_i)\right) \tag{2}$$

s.t.

$$T_i \equiv \arg\max_{T_i} V_i\left(T_i\right)+s(T_i)L(T_i) \tag{3}$$

$$T_i \leq T_{i+1} \tag{4}$$

$$T_{i-1} \leq T_i \tag{5}$$

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[2] Reinganum (1981b) attributes the diffusion process to "purely strategic behavior" while Quirmbach (1986) attributes it to decreasing incremental benefits and adoption costs for late adopters. The introduction of adoption subsidies does not change the diffusion sequence, but has the potential of changing the adoption lags since, if positive, the subsidy makes the technology more affordable at an earlier date.

The two inequalities (4) and (5) imply that the optimal adoption time T_i should be constrained according to a predefined sequence (Assumption 3). The above problem is then solved as follow. First, the optimal adoption time T_i is determined from constraint (3), then taking into account these optimal adoption dates, the objective function is maximized with respect to subsidy rates $s(T_i)$.[3]

The first-order conditions of the above problem yield:

$$\begin{cases} -r\dfrac{dT_i}{ds(T_i)}\left[\left(w_{i-1}-w_i\right)e^{-rT_i}-L'(T_i)\left(1+\lambda s(T_i)\right)-\lambda L(T_i)s'(T_i)\right]=0 \\ \left(\pi_{i-1}^0-\pi_i^1\right)e^{-rT_i}+s'(T_i)L_i-\left(1-s(T_i)\right)L'(T_i)=0 \end{cases}, \tag{6}$$

When solved first for L_n and then for s_n, (6) gives the optimal subsidy rate for the n^{th} adopter:

$$s(T_i)=\frac{\left(w_n-w_{n-1}\right)-\left(\pi_n^1-\pi_{n-1}^0\right)}{\left(w_n-w_{n-1}\right)+\lambda\left(\pi_n^1-\pi_{n-1}^0\right)}, \tag{7}$$

From the above expressions of subsidy rates, we note that they are decreasing with respect to the social cost of public funds. Typically, countries with heavy bureaucracies and prevalent corruption have higher transaction costs. The subsidy rates depend directly on spillovers from the sequential adoption of the new technology; the spillovers refer to the gains to the rest of the economy when a firm adopts the new technology. We define the spillover ratio by:

$$\beta_n=\frac{S_n-S_{n-1}+\left(n-1\right)\left(\pi_n^1-\pi_{n-1}^1\right)+\left(N-n\right)\left(\pi_n^0-\pi_{n-1}^0\right)}{\pi_n^1-\pi_{n-1}^0}, \tag{8}$$

then the subsidy rate becomes (see appendix for a formal derivation),

$$s_n=\frac{\beta_n}{1+\beta_n+\lambda}. \tag{9}$$

With λ being a positive constant, the direction of the sequence $\{s_n\}$ in (9) is determined by the direction of the sequence $\{\beta_n\}$, where $ds_n/d\beta_n>0$. We summarize those finding in the following proposition.

Proposition 1: *The welfare maximizing subsidy from problem* (2)-(5) *is given by* (9). *The subsidy rate depends directly on the spillover ratio* β_n *and the cost of public funds* λ*, further the subsidy rate* s_n *and the spillover ratio* β_n *evolve in the same direction.*

[3] Notice that if the subsidy rate is equal to one all the firms adopt the new technology at period zero since all the costs are paid for by the regulator.

We now show that the spillover ratio is not monotonic, for that we need to establish the behavior of the sequences $\{S_n - S_{n-1}\}$, $\{\pi_n^1 - \pi_{n-1}^1\}$, $\{\pi_n^0 - \pi_{n-1}^0\}$, and $\{\pi_n^1 - \pi_{n-1}^0\}$ in the following lemmas.

Lemma 1. The sequence $\{S_n - S_{n-1}\}$ is positive decreasing.

Lemma 2. The sequence $\{\pi_n^1 - \pi_{n-1}^1\}$ is negative increasing.

Lemma 3. The sequence $\{\pi_n^0 - \pi_{n-1}^0\}$ is negative increasing.

Proof (similarly for Lemmas 1 and 2). Consider the sequence $\{\pi_n^0 - \pi_{n-1}^0\}$, then the series $\sum_{n=1}^{N} \pi_n^0 - \pi_{n-1}^0 = \pi_N^0 - \pi_0^0 < \pi_N^0$ is convergent, because $\{\pi_n^0\}$ is bounded, the infinite series theorem implies that $\lim_{\substack{n\to N \\ N\to\infty}} \pi_n^0 - \pi_{n-1}^0 = 0$. Since $\{\pi_n^0\}$ is a positive decreasing sequence then the sequence $\{\pi_n^0 - \pi_{n-1}^0\}$ is negative increasing. □

Lemma 4. The sequence $\{\pi_n^1 - \pi_{n-1}^0\}$ is positive, decreasing and convergent.

Proof. By assumption 2, we have $\pi_n^1 - \pi_{n-1}^0 > 0$. The sequence $\{\pi_n^1 - \pi_{n-1}^0\}$ is therefore positive, decreasing and convergent because as the number of firms who adopt the new technology increases the gains from the adoption of the new technology shrink, this implies that $\{1/(\pi_n^1 - \pi_{n-1}^0)\}$ is increasing. □

The following proposition summarizes the findings from lemmas 1 to 4.

Proposition 2. *The sequence of spillovers $\{\beta_n\}$ converges to zero but is not monotonic, therefore the subsidy rates sequence $\{s_n\}$ also converges to zero and is not monotonic.*

Proof. Let $\Delta_n = S_n - S_{n-1} + (n-1)(\pi_n^1 - \pi_{n-1}^1) + (N-n)(\pi_n^0 - \pi_{n-1}^0)$, then from the above lemmas we have $\sum_{n=1}^{N} \Delta_n < S_N + (N-1)\pi_N^1$ hence $\lim_{\substack{n\to N \\ N\to\infty}} \Delta_n = 0$. This implies that $\lim_{\substack{n\to N \\ N\to\infty}} \beta_n = 0$. Lemmas 1 to 3 show that $\{\Delta_n\}$ is not monotonic, therefore $\{\beta_n\}$ and $\{s_n\}$ are also not monotonic. □

4. Properties of the Subsidy Rate

In the previous section we established that the optimal subsidy rate is not monotonic but it converges to zero. In this section we establish the required conditions for subsidies to be effective in encouraging the adoption of a new technology. We also show that if the subsidy rate is increasing over time then it needs to be paced and that an increasing optimal subsidy rate is viable only when transaction costs and the social cost of public funds are low.

In order for subsidies to stimulate the adoption of the new technology they need to be positive. For the subsidy rate in (9) to be nonnegative it is necessary that either $\beta_n \geq 0$ or that $\beta_n < -(1+\lambda)$. The only case where the subsidy rate can be negative is therefore within a limited range, $-(1+\lambda) < \beta_n < 0$. The sign of β_n from (8) is determined by the effect that the adoption by one additional firm has on the rest of the economy; i.e. the balance of the gains in consumers' welfare and the decrease in the profits of all the other firms. If the regulator is encouraging the spread of the new technology and for some n we have $-(1+\lambda) < \beta_n < 0$ then the regulator may opt to not subsidize the n^{th} firm that adopts the new technology. If the regulator wants to discourage the adoption of the new technology and command and control instruments are not possible then a prohibitively high and constant adoption tax could be alternatively imposed at period 0. This would be more effective and easier to implement than setting up a dynamic adoption tax.

For a given firm, the first-order conditions for determining the adoption dates with and without subsidy, denoted respectively by $\hat{T}$ and $\hat{\hat{T}}$, are:

$$\begin{cases} \left(\pi_{n-1}^{0} - \pi_{n}^{1}\right) e^{-r\hat{T}} - \dot{L} = 0 \\ \left(\pi_{n-1}^{0} - \pi_{n}^{1}\right) e^{-r\hat{\hat{T}}} + \dot{s}L - (1-s)\dot{L} = 0 \end{cases}, \tag{10}$$

The first-order conditions (10) imply that:

$$\begin{cases} \pi_{n}^{1} - \pi_{n-1}^{0} = rk(\hat{T}) - \dot{k}(\hat{T}) \\ \pi_{n}^{1} - \pi_{n-1}^{0} = \dot{s}(\hat{\hat{T}})k(\hat{\hat{T}}) + \left(1 - s(\hat{\hat{T}})\right)\left(rk(\hat{\hat{T}}) - \dot{k}(\hat{\hat{T}})\right) \end{cases}, \tag{11}$$

In order for the firms to adopt the new technology at an earlier period than without subsidies, it is necessary that $\dot{s}k + (1-s)\left(rk - \dot{k}\right) < rk - \dot{k}$ (Figure 1). If the subsidy rate decreases over time, $\dot{s} < 0$, then there are no perverse effects to the subsidy. But if subsidy rate increases over time, $\dot{s} > 0$, then for the subsidy to encourage earlier adoption, the growth rate of the subsidy rate must be bound by the growth rate of the present cost of the adoption of the new technology, $\dot{s}/s < r - \dot{k}/k$.

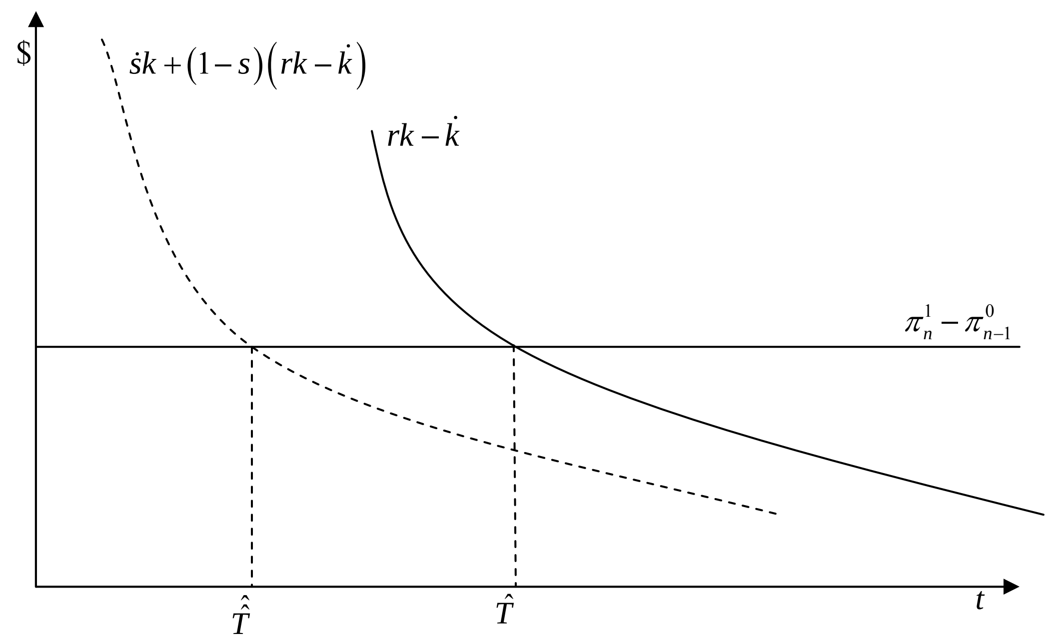

Figure 1. Effect of subsidies on the timing of adoption.

We now show that when the subsidy rate is increasing the condition $\dot{s}/s < r - \dot{k}/k$ can only be met when the social cost of public funds does not exceed a given level, beyond which a first-best optimal adoption subsidy should not be offered because it discourages and hence delays adoption. Let $\Delta w_n = w_n - w_{n-1}$ and $\Delta\pi_n = \pi_n^1 - \pi_{n-1}^0$, one can show that only with $\lambda \le \lambda_n$, where

$$\lambda_n = \frac{\Delta\pi_n \Delta w_{n-1} - \alpha_n \Delta w_n \Delta w_{n-1} - \Delta w_n \Delta\pi_{n-1}(1-\alpha_n)}{\Delta\pi_{n-1}\Delta w_n + \alpha_n \Delta\pi_n \Delta\pi_{n-1} - \Delta w_{n-1}\Delta\pi_n(1+\alpha_n)} \quad \text{and} \quad \alpha_n = r - \left(\frac{k_n}{k_{n-1}} - 1\right), \tag{12}$$

an optimal subsidy rate should be offered to all adopters of the new technology.

The implication of this is that if $s_n > s_{n-1}$ but the condition $\lambda \le \lambda_n$ is not met, then an optimal subsidy rate is not viable at period T_n, but a second-best subsidy rate such that $s' \le s_{n-1}$ could be offered. In fact, in that case even without a subsidy the firm would still adopt the new technology at period $\hat{T}_n \le T_n$. If $\lambda > \liminf_{\substack{n\to N \\ N\to\infty}} \lambda_n$ the regulator offers only non-increasing subsidy rates to all adopters, some of the offered subsidy rates are not optimal. We summarize the results of the discussion in the following proposition.

Proposition 3: *When adoption subsidy rates are decreasing the incentive to accelerate the adoption of a new technology is effective. But for increasing subsidy rates to be effective the following conditions must be met* $\dot{s}/s < r - \dot{k}/k$ *such that* $\lambda > \lambda_n$. *If* $\lambda > \liminf_{\substack{n\to N \\ N\to\infty}} \lambda_n$, *then adopters of the new technology are offered non-increasing subsidy rates that are not necessarily first best.*

5. Conclusion

Using a general model of technology adoption we looked into the optimal timing of the adoption of a new technology by firms in the presence of adoption subsidies. Adoption subsidies are a commonly used instrument to promote R&D effort and the use of new technologies. We have established the link between optimal adoption subsidies and spillovers from the sequential adoption of the new technology. The intuition suggests that the subsidy rates should be decreasing because the adoption cost is decreasing over time; contrary to the intuition we showed that in general spillovers and adoption subsidy are not monotonic and that when subsidy rates are increasing careful attention must be given to their growth rate and to the level of the social cost of public funds or transaction costs; otherwise, increasing subsidy rates may produce the undesirable effect of slowing down the adoption of the new technology.

In this paper it is assumed that all decisions are made under certainty, an obvious extension of the above model would be to include uncertainty about the gains from the new technology. This would affect the spillovers from adoption and adoption subsidies. Another possible extension would allow for the possibility of the appearance of a second new technology after the first new technology is made available. Such a new scenario would alter the gains from adoption and allow for the possibility of second mover's advantage eventually leading to a qualitatively different outcome as far as subsidy and spillovers are concerned. One would expect that delays in the adoption of the first new technology appear and possibly bring to a halt the adoption of that technology.

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Appendix

This appendix provides a proof of $s_n = \dfrac{\beta_n}{1+\beta_n+\lambda}$ in (9).

From (7), the subsidy rate can be rewritten as:

$s_n = \left(\dfrac{\left(w_n - w_{n-1}\right)}{\left(w_n - w_{n-1}\right) - \left(\pi_n^1 - \pi_{n-1}^0\right)} + \dfrac{\lambda\left(\pi_n^1 - \pi_{n-1}^0\right)}{\left(w_n - w_{n-1}\right) - \left(\pi_n^1 - \pi_{n-1}^0\right)} \right)^{-1}$, which can further be transformed to give $s_n = \left(\dfrac{\left(w_n - w_{n-1}\right)/\left(\pi_n^1 - \pi_{n-1}^0\right)}{\left(w_n - w_{n-1}\right)/\left(\pi_n^1 - \pi_{n-1}^0\right) - 1} + \dfrac{\lambda}{\left(w_n - w_{n-1}\right)/\left(\pi_n^1 - \pi_{n-1}^0\right) - 1} \right)^{-1}$.

We have $w_n = S_n + (n-1)\pi_n^1 + \pi_n^1 + (N-n)\pi_n^0$ and $w_{n-1} = S_{n-1} + (n-1)\pi_{n-1}^1 + (N-n)\pi_{n-1}^0 + \pi_{n-1}^0$; with $\beta_n = \dfrac{S_n - S_{n-1} + (n-1)\left(\pi_n^1 - \pi_{n-1}^1\right) + (N-n)\left(\pi_n^0 - \pi_{n-1}^0\right)}{\pi_n^1 - \pi_{n-1}^0}$, we have $\dfrac{w_n - w_{n-1}}{\pi_n^1 - \pi_{n-1}^0} = 1 + \beta_n$. This implies that $s_n = \left(\dfrac{1+\beta_n}{\beta_n} + \dfrac{\lambda}{\beta_n} \right)^{-1}$, therefore $s_n = \dfrac{\beta_n}{1+\beta_n+\lambda}$. □