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Leapfrogging: Time of Entry and Firm Productivity

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Leapfrogging: Time of Entry and Firm Productivity

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Abstract

We develop a model in which ex ante identical firms make endogenous entry and technology adoption decisions. We show that this model is capable of matching the stylized facts in which entry is dispersed over time and that, in many industries, it is the newest firms which are the most likely to exhibit high productivity growth and adopt new innovations (i.e., leapfrogging). We then derive the characteristics of those industries where such leapfrogging is likely to occur.

Keywords: entry, technology adoption
JEL Classification: L11

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1 Introduction

One of the more robust results of the product life cycle literature is that older (early entrant) firms are larger, more productive and have higher survival rates than later entrants (e.g., see Klepper and Simons (2000), Dunne, Roberts, and Samuelson (1989)). This correlation is typically explained by either selection effects (Jovanovic (1982)), convex adjustment costs (Klepper (1996) or Kamihigashi and Roy (2005)) or learning-by-doing (an early contribution is Arrow (1962)). However, recent entrants into a market exhibit advantages as well. Numerous papers have found that younger firms have higher growth rates (e.g., see Evans (1987), Dunne and Hughes (1994) and Farinas and Moreno (2000)). For example, in a study of innovation and productivity growth among Spanish firms, Huergo and Jaumandreu (2004) finds that entrant firms have higher than average productivity growth over the first several years of entry (before converging to the average growth rate). In addition, several studies have found that newer entrants (especially in technology intensive sectors) can have higher survival rates (e.g. see Agarwal and Gort (1996) and Agarwal and Gort (2002)) and technology adoption rates (see Klepper and Simons (2000) than incumbents.[1] Finally, a recent OECD working paper, Andrews, Criscuolo, and Gal (2015), found that, once one controls for capital intensity and size, younger firms are more likely to be on the global productivity frontier. The standard explanation for the advantages of younger firms is provided by Klepper (1996) in which the increasing competitiveness of the market results in a selection process in which only firms that are correspondingly efficient at innovation are willing to enter the market late. This paper provides a second explanation for the late entrant advantage. Specifically, in a model of industry evolution we show that, all else equal, new entrants have the greatest incentive to adopt the most recent technology. We then derive the characteristics of those industries where such leapfrogging behavior is more likely to occur.

To investigate the relationship between time of entry and firm productivity growth, we develop a model in which ex ante identical firms make endogenous entry and technology adoption decisions. One of the key stylized facts of the product life cycle literature is the birth of an industry is characterized, not by simultaneous entry of all firms at once, but rather by gradual entry which is dispersed over time.[2] Thus, we introduce a model that matches the stylized fact of gradual entry by assuming that the accumulation of knowledge over time will gradually reduce the costs of entering new markets. In the conventional product life cycle literature, gradual entry is derived by either assuming exogenous limitations on the number of potential entrants in a given time period (e.g., see

[1] Agarwal and Gort (2002) finds a U-shaped relationship between firm age and survival in which both the youngest firms and the oldest firms have the lowest hazard rates of exit. Agarwal and Gort (1996) finds that new entrants have higher survival rates than older firms in the 16 high-technology industries in their sample (high-technology products were those in industries with high ratios of R&D personnel to total employment). Meanwhile, Klepper and Simons (2000) finds a U-shaped relationship between firm age and technology adoption in which the youngest firms (as well as the oldest) are more likely to adopt new innovations.

[2] The pioneering papers in the empirical industry life cycle literature are Gort and Klepper (1982) and Klepper and Graddy (1990). Later contributions include Agarwal (1998) and Carroll and Hannan (2000).

Klepper (1996), Klepper and Simons (2000)) or gradual learning either about the conditions of the market or production processes (e.g., see Horvath, Schivardi, and Woywod (2001), Jovanovic and Lach (1989) or Kamihigashi and Roy (2005)). While our model differs, the mechanism by which we generate gradual entry is most similar to the learning models in that we assume technology advancement gradually reduces the costs of adopting the neccessary technologies for the production of the good. Thus, dispersed entry is generated by potential entrants trading off the higher revenues of early entry with the lower adoption costs of late entry (our particular framework is similar to those used in game-theoretic models of endogenous technology adoption (see in particular Götz (2002))). However, in contrast to other dispersed entry models, we also assume the possibility of a subsequent productivity-improving innovations. It is this introduction of additional technology improvements that allows us to analyze how the timing of entry (which introduces some degree of endogenous firm heterogeneity into our model) will impact firm decisions on technology adoption.

Our first main result is that, assuming firms are homogenous, new entrants into the market will have the greatest incentive to adopt the latest technology. Intuitively, this is because (in equilibrium) incumbent firms will be earning "excess" per-period profits to pay for the fixed costs of entry and adoption, and thus their marginal gain in profits to adopting a new technology will be lessened. As a result, our model typically generates two types of firms: incumbents (who enter early as low-tech firms and only later adopt the new productivity-improving innovation) and leapfroggers (late-entry firms that enter the market as high-tech firms prior to adoption by the incumbents).

Secondly, we show that leapfrogging does not always occur in equilibrium. Specifically, the presence of late-entering high-tech firms in an industry relies on certain market characteristics that allows for their profitable entry. First, and consistent with the empirical evidence that younger firms having advantages in high-tech industries, we show that leapfrogging firms are more likely in those industries where subsequent technology advances are both larger and occur earlier. In addition, we show that leapfrogging is more likely to occur in industries with greater competitive pressures (captured by a higher elasticity of demand). In contrast, changes in the sunk costs of entry seems to have little impact on the likelihood of leapfrogging.

In order to establish these results, the paper is structured as follows. In Section 2, we set up a model of endogenous entry and technology adoption and characterize the mechanics of the model. In Section 3, we consider the characteristics of industries in which new entrants are most likely to exhibit productivity advantages (i.e., leapfroggers). Finally, in Section 4, we utilize numerical simulations of our model to verify and demonstrate our results. Finally, Section 5 concludes.

2 Time of Entry and the Incentives to Adopt New Technology

In this section we present a model of industrial evolution that is driven by technology adoption. An industry is created at time $t = 0$ by the introduction of some basic technology, where the cost of adopting the basic technology (and hence entering the industry) is falling over time. We also assume the existence of a subsequent cost-saving innovation whose adoption is also costly. Entry

and technology adoption decisions are endogenized using a standard game-theoretic treatment of technology diffusion that dates back to the work of Reinganum (1981). In this section we follow Götz (1999) in considering a closed economy model with an industry characterized by monopolistic competition.[3]

2.1 Demand

We assume that the economy has two sectors: one sector consists of a numeraire good, x_0, while the other sector is characterized by differentiated products. The following intertemporal utility function defines the preferences of a representative consumer:

$$U = \int_0^\infty (x_0(t) + logC(t))e^{-rt}dt \tag{1}$$

where $x_0(t)$ is consumption of the numeraire good in time t and $C(t)$ represents an index of consumption of the differentiated goods. We assume a CES specification which reflects a taste for variety in consumption and implies a constant (and equal) elasticity of substitution between every pair of goods:

$$C(t) = \left[\int_0^{n(t)} y(z,t)^\rho dz\right]^{1/\rho} \tag{2}$$

where $y(z,t)$ represents consumption of brand z at time t and $n(t)$ represents the number of varieties available at time t. With these preferences, the elasticity of substitution between any two products is $\sigma = 1/(1-\rho) > 1$ and aggregate demand for good i at time t is:

$$y(i,t) = \frac{p(i,t)^{-\sigma}E}{\int_0^{n(t)} p(i,t)^{1-\sigma}dz} \tag{3}$$

where $p(i,t)$ is the price of good i in time t and E represents the total number of consumers in the economy.

2.2 Production Costs

All goods are produced in the economy using constant returns to scale technologies and a single factor of production, labor. Thus, production of any good (or brand) requires a certain amount of labor per unit of output. For simplicity, we assume that production of the numeraire good is defined by $l = x_0$ which ensures that the equilibrium wage is equal to unity.

Firms can enter the differentiated goods sector by paying a sunk entry fee of F_0. The basic (low-productivity) technology is available to any firm upon entering the industry, but requires an adoption cost of $L(t)$ where $L' < 0$ and $L'' > 0$. Thus, for initial entrants, the total cost of entry at time t is $F_0 + L(t)$. Production using the low-productivity technology is defined by $l(t) = y(t)$.

[3]By considering adoption in a setting of monopolistic competition we are following Götz (1999) and Ederington and McCalman (2008). However, neither of these papers address the issue of the time of entry.

We also assume that a subsequent cost-saving innovation is available at time $t = \underline{t} > 0$ (the emergent date), but requires an additional fee of $H(t)$ where $H' < 0$, $H'' > 0$ and $H(\infty) = \underline{H} \geq 0$. Production using the high-productivity technology is defined by $l(t) = y(t)/\varphi$, where $\varphi > 1$. Importantly, we assume that adoption of the high-productivity innovation requires that a firm has already adopted certain components of the basic technology. Thus, firms that have previously entered can adopt the new technology for cost $H(t)$, while new entrants must pay $H(t) + \alpha L(t)$ where $0 \leq \alpha \leq 1$. Thus, $\alpha = 1$ implies that new entrants must fully adopt the basic technology before upgrading, while $\alpha = 0$ suggests complete technological "leapfrogging" is possible were new entrants can simply skip to the latest technology.

2.3 Firm Behavior

In this model, firms have three choices to make: when to enter, what price to charge and when to adopt the new technology. Given Dixit-Stiglitz preferences, profit-maximizing firms use a simple mark-up pricing rule for given marginal costs. Thus, the prices set by the low-tech firms and high-tech firms respectively are:

$$p_L = \frac{1}{\rho} = \frac{\sigma}{\sigma - 1} \quad , \quad p_H = \frac{1}{\rho\varphi} = \frac{\sigma}{\varphi(\sigma - 1)} \tag{4}$$

Letting $n(t)$ represent the number of firms in the industry at time t, the operating profits of each firm can then be determined as a function of its own and rivals' behavior:

$$\pi_L(t) = \frac{(\frac{\sigma}{\sigma-1})^{1-\sigma} E}{\sigma \int_0^{n(t)} p(i,t)^{1-\sigma} dz} \tag{5}$$

$$\pi_H(t) = \frac{(\varphi^{\sigma-1})(\frac{\sigma}{\sigma-1})^{1-\sigma} E}{\sigma \int_0^{n(t)} p(i,t)^{1-\sigma} dz} \tag{6}$$

Let $q(t) \in [0,1]$ represent the fraction of firms that have already adopted the cost-saving innovation at a point in time. Then the price index is given by:

$$\int_0^{n(t)} p(i,t)^{1-\sigma} dz = (\frac{\sigma}{\sigma - 1})^{1-\sigma} ((q(t)\varphi^{\sigma-1} + (1 - q(t)))n(t)) \tag{7}$$

Substituting (7) into (6) gives profits as:

$$\pi_L(t) = \frac{E}{(q(t)(\varphi^{\sigma-1} - 1) + 1)n(t))\sigma} \tag{8}$$

$$\pi_H(t) = \frac{(\varphi^{\sigma-1})E}{(q(t)(\varphi^{\sigma-1} - 1) + 1)n(t))\sigma} \tag{9}$$

2.4 Initial Entry - Incumbents

First, we will focus on firms that initially enter the market before the emergent data of the high-productivity technology. By definition, these are firms that enter as low-tech firms and only subsequently adopt the new technology and we will refer to such firms as "incumbent" firms. Note that

an incumbent firm chooses it's entry date, T_e, to maximize the discounted value of total profits:

$$\Pi = \int_{T_e}^{T} e^{-rt}\pi_L(t)dt + \int_{T}^{\infty} e^{-rt}\pi_H(t)dt - L(T_e) - H(T) - e^{-rT_e}F_0 \tag{10}$$

where T represents the subsequent hi-tech adoption date and will be discussed in the following section (for incumbent firms $T > T_e$ by definition). These profits depend on both the firm's entry date, T_e, as well as the entry decisions of rival firms (which is summarized by the distribution function $n(t)$). Differentiating with respect to T_e yields the first-order condition:

$$\pi_L(T_e) = rF_0 - L'(T_e)e^{rT_e} \tag{11}$$

The above first-order condition demonstrates the trade-off faced by firms in the choice of when to enter. The left-hand side is the lost profits from waiting one more period to enter the industry while the right-hand side is the gain from the decrease in adoption costs from delaying entry another period. This optimal selection of adoption dates, in turn, can be used to solve for the equilibrium number of incumbent firms (at least in the early stages of industry life). Specifically, prior to the adoption of the hi-tech innovation (i.e., when $q = 0$), one can substitute profits given by (9) into this first-order condition to solve for $n(t)$:

$$n^*(t) = \frac{E}{[rF_0 - e^{rt}L'(t)]\sigma} \tag{12}$$

Given $L' < 0$ and $L'' > 0$, the RHS is slowly increasing over time and we have gradual entry into the industry. Intuitively, as adoption costs fall the number of firms within the industry will increase (and, thus, firm profits will fall) so that the first-order condition is satisfied.

2.5 Technological Adoption - Incumbent Firms

After the incumbent firms have entered the market, they must subsequently choose when to adopt the new productivity-improving innovation. The equilibrium distribution of technology at any point in time, $q(t)$, is determined by the firms' selection of their optimal adoption dates. A firm chooses the adoption date, T, to maximize the discounted value of total profits, given by (10). Differentiating with respect to T yields the first-order condition:

$$\pi_H(T) - \pi_L(T) = -H'(T)e^{rT} \tag{13}$$

The above first-order condition demonstrates the trade-off faced by firms in the choice of when to adopt. The left-hand side is the lost profits from waiting one more period to adopt the high-productivity technology while the right-hand side is the gain from the decrease in adoption costs from delaying adoption another period.

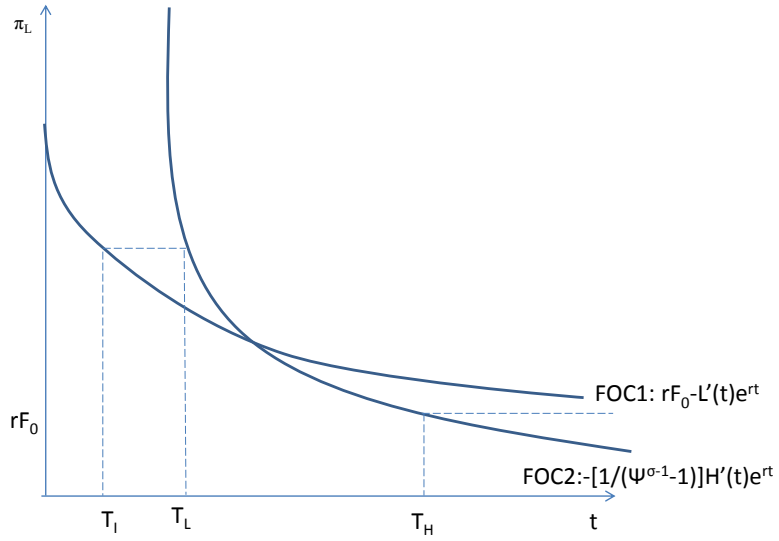

Figure 1: Process of entry and adoption: Incumbent Firms

To understand the dynamics of the model, it helps to consider the equilibrium in the presence of only incumbent firms (in section 3 we consider the conditions under which this will be the case). The process of entry is described by the line labeled FOC1 in Figure 1, which represents the first-order condition for optimal entry (11). Note that, after period 0, gradual entry will occur and the number of (low-tech) firms in the industry will increase at the rate defined by (12). As the number of firms increases, profits for a low-tech firm decrease (in line with the decrease in entry costs) so that the first-order condition for entry holds. Thus, FOC1 represents the decline in low-tech profits over time. Eventually, low-tech profits decrease to a point (defined by T_1) where a zero-profit condition holds and entry ceases (the zero-profit conditions will be discussed in more detail in the following section). In Figure 1, we assume that this point is reached before the diffusion of the new technology commences (i.e., $T_L > T_1$).

Second, from the fact that $\pi_H - \pi_L = \varphi^{\sigma-1}\pi_L$, one can rewrite the first-order condition for optimal adoption by incumbent firms (13) as requiring:

$$\pi_L(T) = \frac{-H'(T)e^{rT}}{\varphi^{\sigma-1} - 1} \tag{14}$$

Thus, in Figure 1, FOC2 represents (14): the first-order condition for optimal adoption.[4] Thus,

[4]Note that we have drawn Figure 1 such that FOC2 cuts FOC1 once from above. The later emergent date will typically result in FOC2 initially being greater than FOC1 and then eventually crossing as FOC1 is bounded by rF_0.

prior to T_L low-tech profits (and thus the profit differential) are too low to make the new technology commercially viable. However, at T_L adoption starts and, as adoption costs fall, more firms adopt the new technology, leading to a gradual diffusion of the new technology through the industry for periods $T_L \leq t \leq T_H$ (where the fraction of firms that have adopted at any point in time is given by $q^*(t)$). Indeed, from 13, one can derive the the equilibrium distribution function, q^*:

$$q^*(t) = \begin{cases} 0 & \text{for } t \in [0, T_L) \\ \frac{-e^{-rt}E}{H'(t)n^*\sigma} - \frac{1}{\varphi^{\sigma-1}-1} & \text{for } t \in [T_L, T_H] \\ 1 & \text{for } t \in (T_H, \infty) \end{cases} \tag{15}$$

Finally, all firms will have adopted the new technology by period T_H and firm profits are once again constant

However, this raises the question of what happens when model parameters are such that $T_L < T_I$ (i.e., diffusion of the new technology begins before entry is complete). In this case, as should be apparent, from Figure 1, the diffusion of the new technology will, in effect, cut-off entry.[5] Intuitively, the adoption of a new innovation causes low-tech profits to decline at a rate faster than the decline in the adoption costs of the base technology. Thus, firms will choose not to enter during the diffusion process (since they can earn higher profits by delaying entry until later). The nice aspect to this case is that it fits the empirical evidence that the period before the shakeout within an industry is characterized by a drop in the entry rate. An example of this can be seen in the automobile tire industry, where the rate of entry declines substantially before a subsequent increase in the exit rate. Several papers (i.e., Jovanovic and MacDonald (1994) and Ederington and McCalman (2009)) have shown how the adoption of a productivity improving technology force non-adopting firms to exit the market. Our model shows that the same technology adoption that generates exit will simultaneously deter entry of new firms, thus generating the industry shakeout along two dimensions.

2.6 High-Tech Entry - Leapfrogging Firms

After the emergence of the new high-tech innovation, firms also have the option of entering as a high-tech firm (with a combined entry cost of $F_0 + \alpha L(t) + H(t)$) - what we will refer to as "leapfrogging" firms. In contrast to the incumbent firms, a leapfrogging firm that enters as high-tech (at some optimal time period, T_e) will have present discounted profits of:

$$\int_{T_e}^{\infty} e^{-rt}\pi_H(t)dt - \alpha L(T_e) - H(T_e) - e^{-rT_e}F_0$$

Thus, differentiating with respect to T_e, the first-order condition for optimal adoption (and optimal entry) by leapfrogging firms is given by:

[5] This follows from the fact that FOC2 is steeper than FOC1 and thus, in the area after T_L when FOC2 holds $\pi_L < rF_o - L'(t)e^{rt}$ and thus entry will no longer occur.

$$\pi_H(T_e) = rF_0 - [\alpha L'(T_e) + H'(T_e)]e^{rT_e} \tag{16}$$

As before, the left-hand side is the lost profits from waiting one more period to enter the industry while the right-hand side is the gain from the decrease in adoption costs from delaying entry another period. The key question is how this first-order condition compares to the adoption decision of the incumbent firms (i.e., will leapfrogging firms begin to arrive before or after incumbent firms have begun to adopt). To see this, refer back to Figure 1. Note that, at the point where incumbent firms begin adoption (T_L) it is the case that

$$\pi_H - \pi_L = -H'(T_L)e^{rT_L} \quad and \quad \pi_L \geq rF_0 - L'(T_L)e^{rT_L} \tag{17}$$

The first-condition simply reflects that the first-order condition for optimal adoption by incumbent firms must hold at T_L. The second simply reflects that, since entry has stopped, incumbent firms are earning "excess" per-period profits to account for the fixed entry and adoption costs of production.[6] Thus, one can derive that:

$$\pi_H \geq rF_0 - [L'(T_L)e^{rT_L} + H'(T_L)]e^{rT_L} \tag{18}$$

which implies that

$$\pi_H > rF_0 - [\alpha L'(T_L)e^{rT_L} + H'(T_L)]e^{rT_L} \quad if\ \alpha < 1 \tag{19}$$

or that the first-order condition for optimal adoption by new leapfrogging firms will always be satisfied at an earlier time period than the first-order condition for incumbent firms. Thus, any late entrants will adopt the productivity improving innovation before the early entrant incumbent firms.

PROPOSITION 1 *If a firm enters the market as a high-tech firm (i.e., leapfrogging firms), it will adopt the productivity-improving innovation earlier than any incumbent firms.*

What is noteworthy about the above proposition is that it holds even when $\alpha \approx 1$ and thus technological leapfrogging is not possible (i.e., new entrants must adopt fully all previous technologies in order to produce the good).[7] Rather, this result is due to the fact that new firms have a greater incentive (on the margin) to adopt the latest technology. Intuitively, the gain from adopting the latest technology for incumbent firms is lessened since,in equilibrium, they must be earning "excess" per-period profits to pay for the fixed costs of entry and adoption. The so-called cannibalization

[6]Note that optimal adoption decisions prevent entry from occuring too rapidly and thus making $\pi_L < rF_0 - L'(T_L)e^{rT_L}$.

[7]In the following section we will show, however, that such leapfrogging firms cannot exist when $\alpha = 1$.

effect or, as Tirole (1988) calls it, the replacement effect is stronger than the higher cost adoption costs for leapfroggers stemming from the necessity to bear also the entry costs.

Proposition 1 also provides a theoretical foundation for the consistent finding in the product life cycle literature that there exist a group of late-entering firms that have higher productivity and adopt new technologies more readily than incumbent firms. For example, Huergo and Jaumandreu (2004) found that entrant firms have higher than average productivity growth over the first several years of entry, Andrews et al. (2015) found that younger firms were more likely to be on the global productivity frontier and Klepper and Simons (2000) found that new entrants exhibit some of the highest innovation and adoption rates. Klepper and Simons (2000) argued that the higher adoption rates of late entrants was due to an evolutionary self-selection process in the industry. That is, assuming some exogenous heterogeneity in firm innovative ability, as the market fills over time, only successively more innovative firms would be willing to enter the market. Thus, late entrants adopt more readily than earlier entrants because they are more likely to have higher ability. In contrast, our model shows that technology advantage of late entrants can occur even when firms are homogenous. Specifically, Proposition 1 suggests that, all else equal, new entrants into a market will actually have the strongest incentives to adopt the latest technology.

However, while this section demonstrates that *if* they enter, late-entrants will have the greatest incentive (on the margin) to adopt the latest technology, this does not establish that such late-entrants will actually exist in equilibrium. Thus, in the following section, we consider the characteristics of those industries where such late-entrant firms are most likely to enter and thus leapfrogging behavior is most likely to occur.

3 Determinants of Leapfrogging - Entry of High-Tech Firms

It is apparent that our model has two types of firms: incumbents (who enter as low-tech firms and only later adopt the new technology) and leapfroggers (who enter as high-tech firms). In the absence of fixed per-period costs of production, operating profits are positive in each time period and firms will choose to never exit the industry. Thus, in the absence of exit, all we are concerned about is whether leapfrogging entry will occur. Note that entry (by both incumbents and leapfrogging firms) will occur until the present value of lifetime profits of each firm is equal to zero. This zero-profit condition for incumbent firms is:

$$\int_0^{T_L} e^{-rt}\pi_L(t)dt + \int_{T_L}^{\infty} e^{-rt}\pi_H(t)dt - L(0) - H(T_L) - F_0 = 0 \tag{20}$$

Note that, given the first-order condition for gradual entry is satisfied, all incumbent firms make equivalent profits in equilibrium (regardless of their time of entry). Thus, without loss of generality we express the incumbent zero-profit condition for an incumbent firm entering at time period 0.

In contrast, a leapfrogging firm that enters as a high-tech firm (at the earliest optimal time period, T_e) will have present discounted profits of:

$$\int_{T_e}^{\infty} e^{-rt}\pi_H(t)dt - H(T_e) - \alpha L(T_e) - e^{-rT_e}F_0 \tag{21}$$

Since, we know from Proposition 1 that $T_e \leq T_L$, the condition that leapfrogging occurs (i.e., we have a mass of firms enter as high-tech firms) requires the present discounted profits of such entry to be positive. Thus, subtracting (20) from (21), one can show that leapfrogging firms exist when:

$$\int_{T_e}^{T_L} e^{-rt}\pi_H(t)dt + [L(T_1) - \alpha L(T_e)] + (1 - e^{-rT_e})F_0 > \int_0^{T_L} e^{-rt}\pi_L(t)dt + [H(T_e) - H(T_L)] \tag{22}$$

In the above condition, the LHS represents the relative gains to being a leapfrogging firm which includes higher profits in the period before incumbent firms adopt ($\int_{T_e}^{T_L} e^{-rt}\pi_H(t)dt$) and the gains from delaying entry costs ($[L(0) - \alpha L(T_e)]$ and $(1 - e^{-rT_e})F_0$). In contrast, the RHS represents the relative cost to leapfrogging which includes the foregone profits to early entry ($\int_0^{T_L} e^{-rt}\pi_L(t)dt$) as well as the extra costs of early adoption ($[H(T_e) - H(T_L)]$). Unfortunately, comparative statics on (22) prove to be complicated. Thus, in the following section (3.1), we provide some conjectures based on an intuitive analysis of condition (22) on what parameters should influence the probability of high-tech entry occuring (i.e., leapfrogging). We then more formally analyze these parameter changes in Section 4 using numerical simulations of our model.

3.1 Leapfrogging Technology: α

It is direct to see that a decrease in α (the fraction of previous technologies that must be adopted by leapfrogging firms) will directly increase the LHS of (22) and thus likely make high-tech late entry occur. Indeed, it is possible to show that $\alpha < 1$ is a necessary condition for leapfrogging firms to appear (i.e., technological leapfrogging is required for the existence of leapfrogging firms): To see the relationship between α and leapfrogging behaviour consider Figure 2 which adds the first-order condition for high-tech entry by leapfrogging firms (given by equation 16 and labeled FOC3) to Figure 1. As before, gradual entry occurs and profits decline along FOC1 which is the first-order condition for optimal entry for incumbent firms (defined by 11). At some point the zero-profit condition for incumbent firms (20) is satisfied and entry stops (at point T_1). Consistent with Proposition 1, after T_1 the first-order condition for leapfrogging firms (FOC3) will be satisfied prior to adoption by incumbent firms (FOC2) and thus, if exists in equilibrium, leapfrogging firms will begin to enter at T_e. Finally, entry by leapfrogging firms ends at T_2 and adoption by incumbent firms begins at T_L.

Note first that Figure 2 is drawn consistent with $\alpha = 1$ which implies that all three first order conditions intersect at the same point. The effect of decreasing α is to shift FOC3 to the left (and thus T_e occurs earlier). However, the important point to note from Figure 2 is that between time period 0 and T_e it is the case that $\pi_L \geq rF_0 - L'(t)e^{rt}$ (i.e., low-tech profits are equal to or greater than FOC1 for $t > T_1$) and thus:

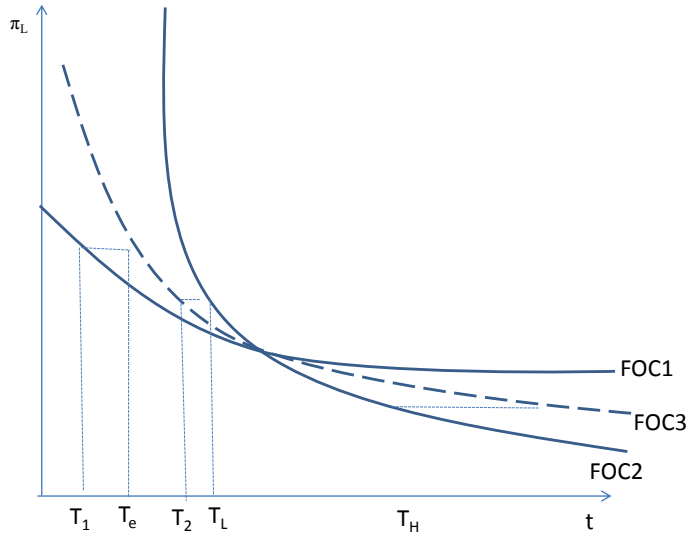

Figure 2: Leapfrogging: $\alpha = 1$

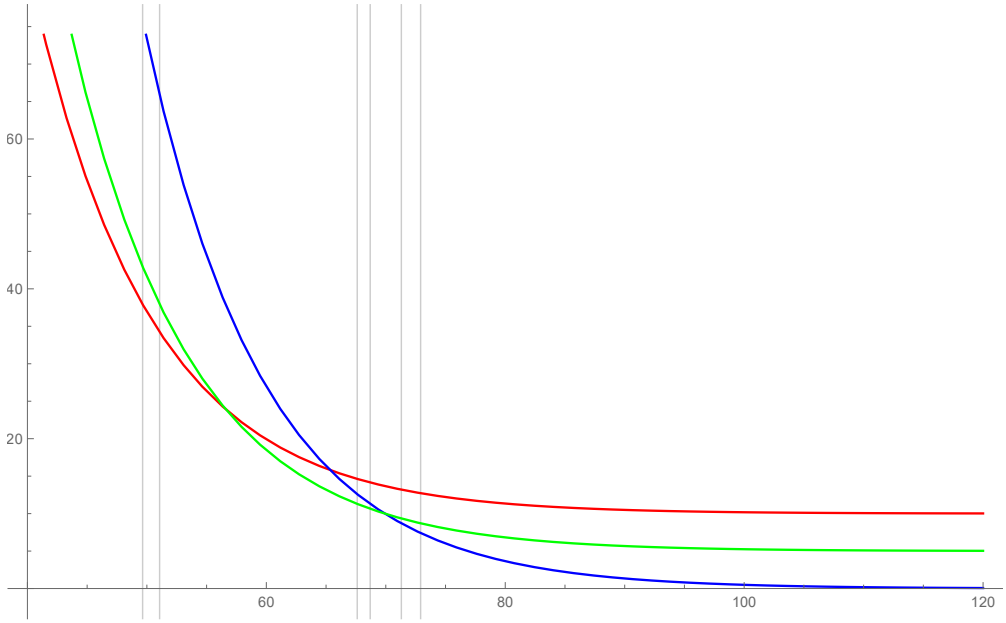

Figure 3: FOCs and first and last entry and adoption dates from simulation; $\alpha = 0$

$$\int_0^{T_L} e^{-rt}\pi_L(t)dt \geq [L(0) - L(T_e)] + (1 - e^{-rT_e})F_0 \tag{23}$$

In addition, note from Figure 2 that between time period T_e and T_L it is the case that $\pi_H - \pi_L \leq$

$-H'(t)e^{rt}$ (i.e., low-tech profits are less than FOC3) and thus:

$$\int_{T_e}^{T_L} e^{-rt}\pi_H(t)dt < \int_{T_e}^{T_L} e^{-rt}\pi_L(t)dt + [H(T_e) - H(T_L)] \tag{24}$$

However, note that if both (23) and (24) hold than, when $\alpha = 1$, the condition for the existence of leapfrogging firms (22) cannot be satisfied and we can state out second proposition.

PROPOSITION 2 *Regardless of the other parameter values, no leapfrogging firms will exist in equilibrium if* $\alpha = 1$ *(i.e., if new entrants must fully adopt the basic technology before upgrading).*

One can interpret Proposition 2 as suggesting that the fundamental gain to delaying entry and entering as a high-tech firm (leapfrogging) comes from the ability to skip previous technological requirements (i.e., $\alpha < 1$) and not from any decline in adoption costs or entry costs over time. Note, however, that even $\alpha = 0$ does not guarantee the existence of leapfrogging entry. As shown below even a large cost advantage is not sufficient if the new technology arrives too late in the market and enables the entry of a large number of low-tech firms.

3.2 Profit Differential: φ and σ

Note that one can rewrite (22) to derive that leapfrogging firms exist when:

$$\int_{T_e}^{T_L} e^{-rt}(\pi_H(t) - \pi_L(t))dt + [L(0) - \alpha L(T_e)] + (1 - e^{-rT_e})F_0 > \int_0^{T_e} e^{-rt}(\pi_L(t))dt + [H(T_e) - H(T_L)] \tag{25}$$

Thus, an increase in the profit differential $(\pi_H - \pi_L)$ will also directly increase the LHS of (22) and make the entry of leapfrogging firms more likely. Intuitively, one of the gains to being a leapfrogging firm is the extra profits one derives from adopting new technologies early. Recall that $\pi_H = \varphi^{\sigma-1}\pi_L$ and thus both the size of the new technology (φ) and the elasticity of substitution across varieties (σ) can affect the probability of leapfrogging. Indeed, 25 suggests two conjectures. First, that leapfrogging is more common in high-technology industries where new technological innovations are larger and more important (i.e., φ is larger). Intuitively, a larger φ increases the profit differential between high and low technology firms which (as can be seen from 25) will tend to directly encourage leapfrogging behavior. As discussed in the introduction, this is consistent with empirical evidence that new firms have the greatest advantages in high-technology industries.

Second, that leapfrogging is more common in industries where the elasticity of substitution is large (i.e., σ is larger). Intuitively, a larger σ will also increase the profit differential since now the price advantage from adopting the latest (productivity-improving) technologies has a greater impact on profits. Once again, this will encourage high-tech entry (leapfrogging). This result is of interest since it is commonplace to in the industrial organization literature to view the elasticity of substitution between product varieties as a proxy for the degree of product market competition

(since more competition allows consumers to more easily switch between suppliers). For example, Syverson (2004) measures the degree of product market competition across industries (and, hence, product substitutability) by using various measures of the size of trade barriers faced by geographically dispersed competitors. Thus, our conjecture is that greater product market competition (which increases the elasticity of demand faced by firms) can increase the probability of leapfrogging behavior.

3.3 Speed of Technology Diffusion: $L(t)$ and $H(t)$

Third, note from (22), that the speed of technology diffusion $[L(0) - \alpha L(T_e)]$ and $[H(T_e) - H(T_L)]$ also determines the probability of leapfrogging activity. Intuitively, a gain to leapfrogging is that it allows new firms to delay the cost of adopting the basic technologies (at least when $\alpha > 0$) and thus when low-tech adoption costs decline rapidly (i.e., $L(0) - \alpha L(T_e)$ is larger) it makes leapfrogging more likely. In contrast, a cost to leapfrogging involves the higher (early) adoption costs of the latest technology, and when these high-tech adoption costs decline rapidly (i.e., $H(T_e) - H(T_L)$ is larger) it provides a cost advantage to the incumbent firms which makes leapfrogging less likely. In the numerical simulations that follow, our basic method of adjusting the speed of technology diffusion is to adjust the emergent data of the high-tech innovation.

4 Numerical Simulations

Following Fudenberg and Tirole (1985) and Götz and Astebro (2006) we specify the entry and adoption cost functions as:

$$L\left(T\right) = L_0 e^{-(b+r)T} + \bar{L}$$

and

$$H\left(T\right) = L_0 e^{b(emergence-T)-rT} + \bar{L}.$$

The parameter b is a positive constant capturing the decrease in cost induced by either technical progress or learning. The entry cost $L(T)$ and the adoption cost function $H(T)$ are identical up to a 'time shift'. Note that we assume $H(T)$ to be infinite for $T < emergence$. $\bar{L}$ is the lower bound for L and H as T approaches infinity. As shown above (to be done based on Figure 2 and T_H) second generation leapfrogging entry eventually occurs after the adoption by all incumbents if $\bar{L}$ is 0. As becomes clear from the below results that kind of entry appears to be more like an artifact. For the parameter values employed below, values of $\bar{L}$ at $10^{-6}L_0$ are often sufficient to prevent that kind of entry. Typically we employ the respective values below. Concerning the parameters, we assume the following values in our benchmark case:

$$r = .1, L_0 = 20000, emergence = 10, b = .1, E = 1000, F_0 = 100, \varphi = 2, \sigma = 2$$

We start our discussion with the parameter α, that is the possible cost advantage of leapfroggers. In our simulation we consider the two extreme cases with $\alpha = 0$ and $\alpha = 1$, respectively. As shown

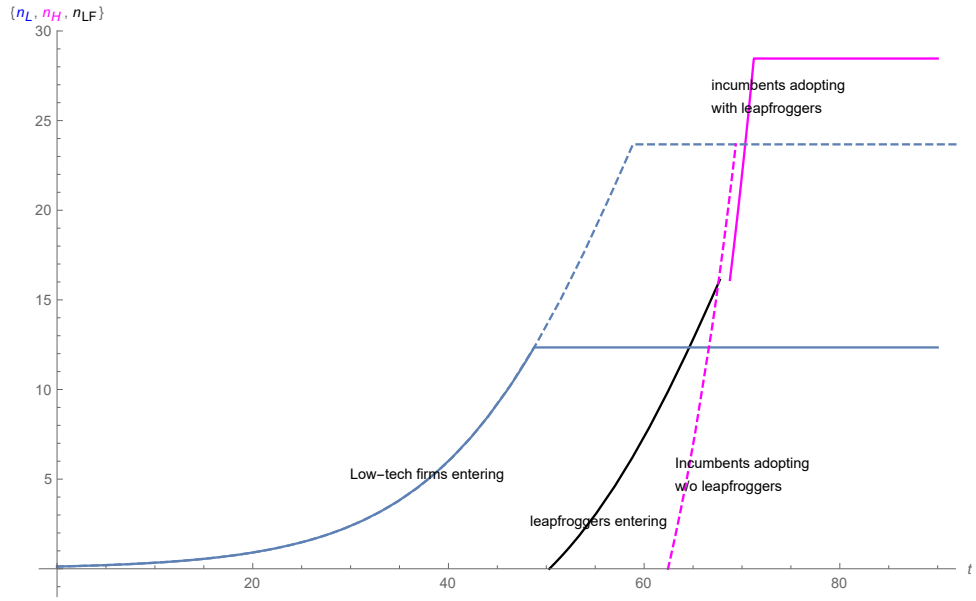

Figure 4: Entry and adoption patterns with and without leapfrogging

above there will be no entry by leapfroggers if $\alpha = 1$ and leapfroggers have to bear the full adoption cost $L(T) + H(T)$. This case serves as a benchmark to highlight the effect of leapfrogging. Figure 4 shows the entry and adoption patterns for both cases of α. The dashed lines depict the case without leapfrogging. They show that both entry and adoption are spread over quite some time. Furthermore, note that a gap exists between the last entry of a low-type firm and the first adoption of high technology. Due to the finite entry costs at time 0, there is an atom of entrants at $T = 0$. The respective firm number is .001, where the fraction is a consequence of our assumption of a continuum of firms.[8] We assumed that $\bar{L} = .026$, a value which guarantees in both cases that no second generation entry takes place.

Turning to the case of $\alpha = 0$ (the solid lines apply), the first thing to note is that leapfrogging occurs. After the entry of low-type firms and before those firms adopt the second generation, further entry occurs with firms employing the second generation. Leapfrogging, triggered by the lower costs of adoption of the second generation technology, speeds up productivity growth in the industry in the sense that the high productive technology is adopted earlier. At the same time leapfrogging reduces the number of low type entrants and therefore deters low-type entry. Due to the lower entry costs, however, the total number of firms increases. Technology adoption by incumbents is slightly delayed. Note that there are always gaps between last entry and first adoption dates. The number of low-type entrants as well as the number of leapfroggers is determined by the respective zero profit conditions. The remaining adoption dates to be determined derive from the first order conditions, given the firm numbers determined from the zero profit conditions.

Next we briefly discuss the effect of $\bar{L}$ on entry and diffusion patterns. As mentioned above

[8]The atom is more obvious, if we assume a lower L_0 such as $L_0 = 100$. In this case $n(0) = 23.8$.

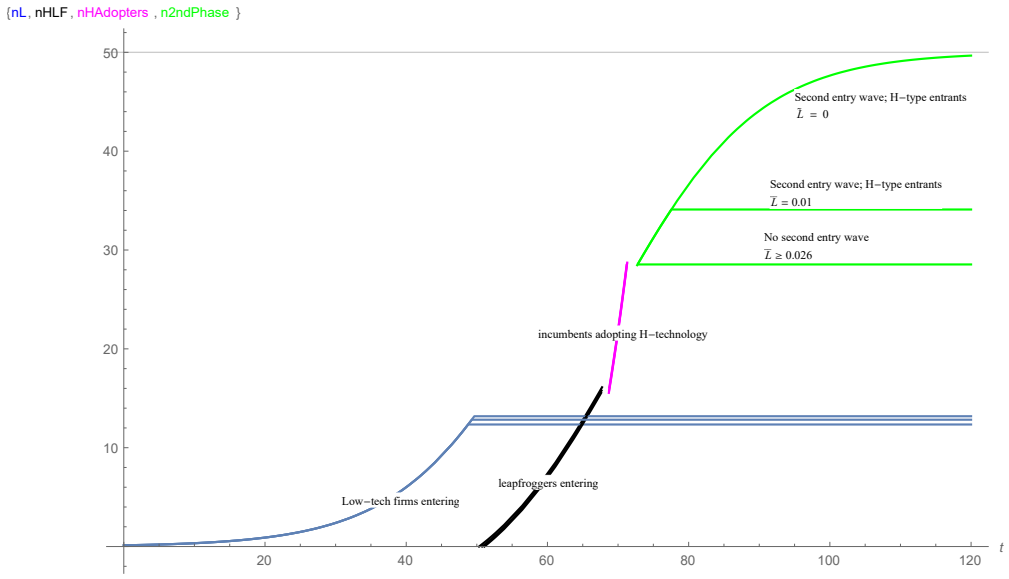

Figure 5: The effect of $\bar{L}$ on second generation entry

low values of this parameter are sufficient to prevent a second entry wave with the high technology. It immediately follows from Figure 3 that this type of entry occurs always latter than adoption of the high technology by the incumbents. Also the late entrants will always enter using the high technology. Both properties follow from Figure 3. The fact that, to the right of the intersection, FOC3 lies above FOC2 implies that further entry with technology underlying is FOC3, i.e. the high technology, is only possible once adoption by incumbents is finished. At the same time the profit from entering with the low technology must be insufficient compared to entry with the high technology as FOC1 lies above FOC3. Figure 5 shows the entry and diffusion patterns for the benchmark parameter set and for three values of $\bar{L}$: $\bar{L} = \{0, .01, .026\}$.

Probably the most surprising result is the extent of the second wave of high tech entry in the case of $\bar{L} = 0$. The number of firms increases by almost 75% from 28.7 to 50. Even though entry goes on forever as $L(t)$ approaches its lower bound only when t goes to infinity, the bulk of entry takes place at a comparatively high speed. The second surprising result is the strong effect even very small (positive) values of $\bar{L}$ have on the second high tech entry wave. A value of .01 already reduces the number of second wave high tech entrants by more than two thirds, a value of .026 cuts off that entry wave completely. These results underline how little leeway is for a second generation of high tech entrants given free entry by low-tech entrants and early leapfroggers. At the same time the different values of $\bar{L}$ have only a minor effect on both the extent of low-tech and leapfrogging entry and on the adoption pattern by incumbents. In the following comparative statics, we always assume values of $\bar{L}$ such that no second wave of entry oocurs.

Next we discuss the effect of the date of emergence of the new technology on the extent of leapfrogging. Starting from the benchmark parameter set defined above a decrease in the date of emergence has a straightforward effect. If the new technology emerges earlier, there will be more

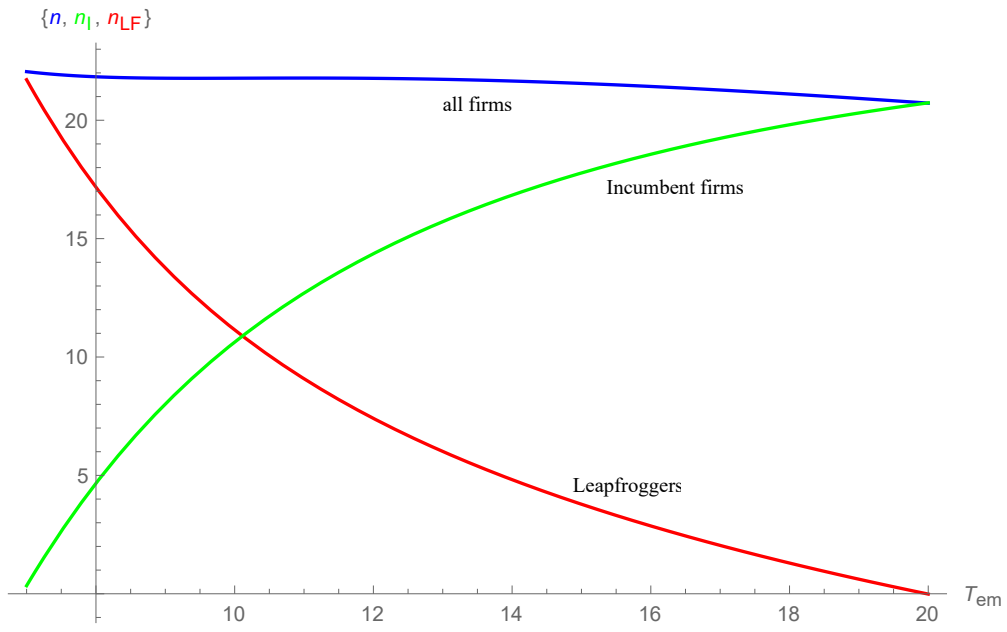

Figure 6: The effect of the emergence date T_{em} on entry of L-type firms and leapfroggers

leapfrogging and less low-tech entry. However due to the fact that the fraction of low-tech entrants can become arbitrarily small, leapfroggers cannot completely deter low-tech entry unless the the high technology also emerges at time 0. Given the benchmark parameter set, for emergence dates smaller than 6.96 there will be an atom of leapfroggers at the emergence date. Perhaps surprising is the effect of a later emergence date. If the new technology arrives at the market only at about $t = 23$, entry of leapfroggers will no longer occur. Even though leapfroggers have a strong cost advantage due to $\alpha = 0$, high-tech leapfroggers are crowded out by the large number of low-tech entrants, who can enter due to the late arrival date of the new technology. Sunk entry costs together with the fact that even firms with a cost disadvantage never stop producing deters high-tech entry. Figure 6 shows how the number of incumbents as well as of leapfroggers evolves as a function of the emergence date. The total number of firms is almost flat, while later emergence dates leed to a fast decrease in the number of leapfroggers and a corresponding increase in the number of low-tech entrants, which lateron adopt the new technology.

We illustrate the change current welfare and productivity associated with that development in Figure 7, which shows the current value of the consumption index $C(t)$ (see (2) for three different emergence dates. Note that $C(t)$ captures both the change in productivity over time as well as the change in the available product variety. While it is obvious that earlier emergence generally leads to a higher consumption index, Figure 7 reveals that a rather late emergence date (see the curve for $T_{em} = 18$) allows for more L-type entry and even leads to a higher value of the consumption index for some values of t.

Changes in the productivity parameter φ have largely similar effects than the change in the arrival date of the new technology. Increases in φ make the high technology and therefore leapfrogging more

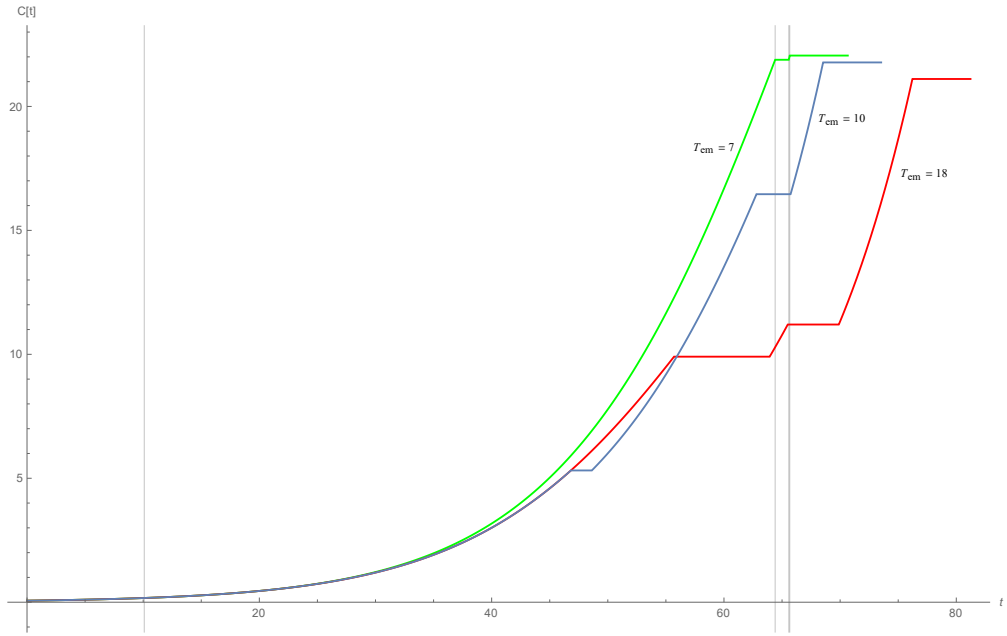

Figure 7: The effect of the emergence date T_em on the evolution of the consumption index $C(t)$

profitable. Decreases lead to more low-type entry and a smaller number of leapfroggers. Figure 8 shows in detail how the number of the different firm types depends on φ. If the productivity increase is too low, entry by L-type firms prevents leapfroggers from entering. The higher the productivity increase the more important are leapfroggers. The aggregate number of firms is clearly non-monotonic in the productivity increase. Note that welfare and productivity in the 'long run' adre rather different from the pattern shown in Figure 7 for T_{em}. While $C(t)$ is rather similar for high values of t (e.g. $t > 80$ in Figure 7), long run values of $C(t)$ differ by a factor similar to the the differences in φ. Finally note that leapfroggers can never completely crowd out L-type entrants as long as $T_{em} > 0$ for the reason stated above.

Changes in the intensity of competition, measured by the parameter σ, have a similar effect on the relation between operating profits associated with the two technologies as the productivity parameter. Larger values of σ, implying a higher elasticity of demand and of substitution, lead to lower markups and an increased intensity of competition. Firms employing the high technology are able to attract more customers from their low-productivity rivals. As a consequence, and comparable to the effect of a higher productivity increase, we find more leapfrogging in a more competitive industry. As Figure 9 shows, for values of σ close to the pure monopoly case of $\sigma = 1$, leapfrogging vanishes. If the intensity of competition increases high-technology leapfroggers (almost completely) drive out L-type entry. As the mark-up becomes smaller in this case, the aggregate number of firms also decreases.

Two further properties of the entry and adoption process as a function of σ are worth mentioning as can be seen from Figure 10. First, for low values of σ there is a discrepancy between the entry process and the diffusion of the second generation. While the former is rather extensive and takes

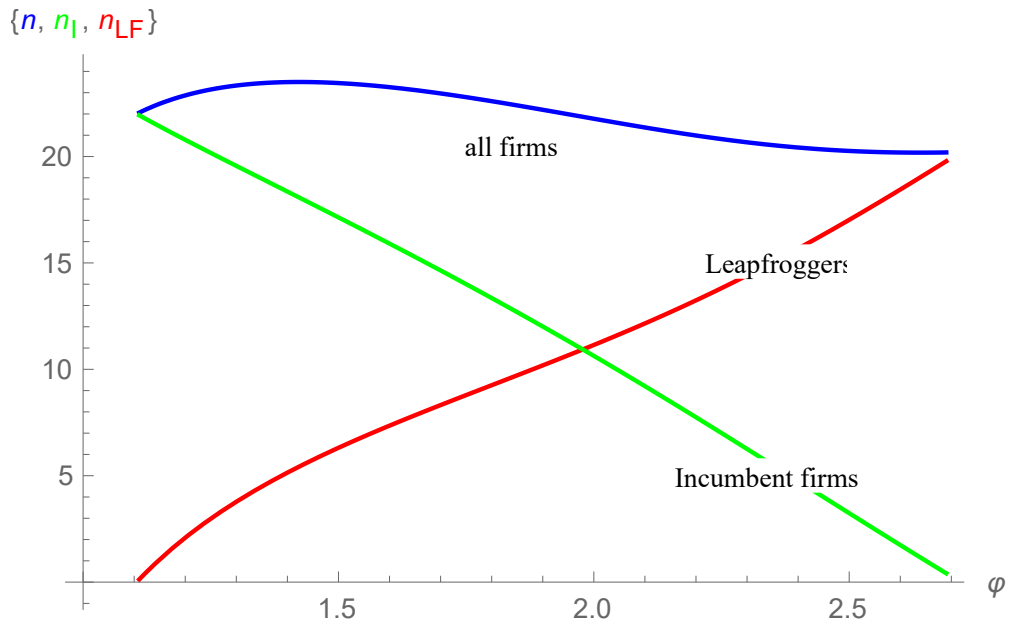

Figure 8: The effect of the productivity parameter φ on entry of L-type firms and leapfroggers

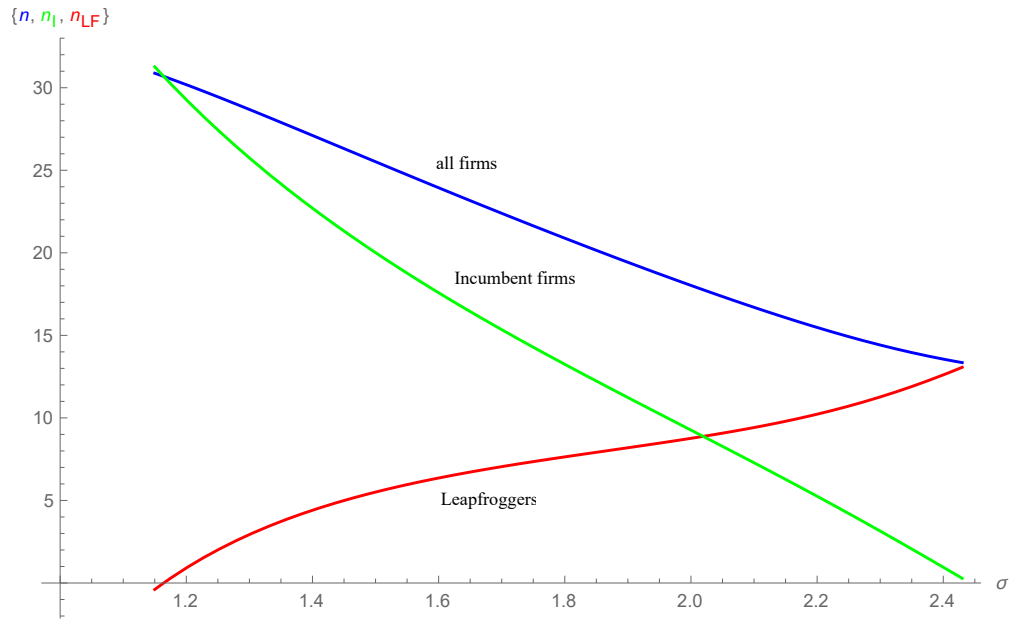

Figure 9: The effect of the demand elasticity σ on entry of L-type firms and leapfroggers

very long, the latter takes place almost simultaneously among all firms (compare the Ltype entry pattern with the adoption pattern of these firms for $\sigma = 1.17$) . Second, a more competitive industry, i.e. higher values of σ, leads to an expansion of the entry and diffusion process. This result is well-known from Götz 1999. A high elasticity of demand rewards early leapfroggers with large demand. But low markups prevent that all firms can follow such a strategy, leading to the expansion of the diffusion and entry process, respectively.

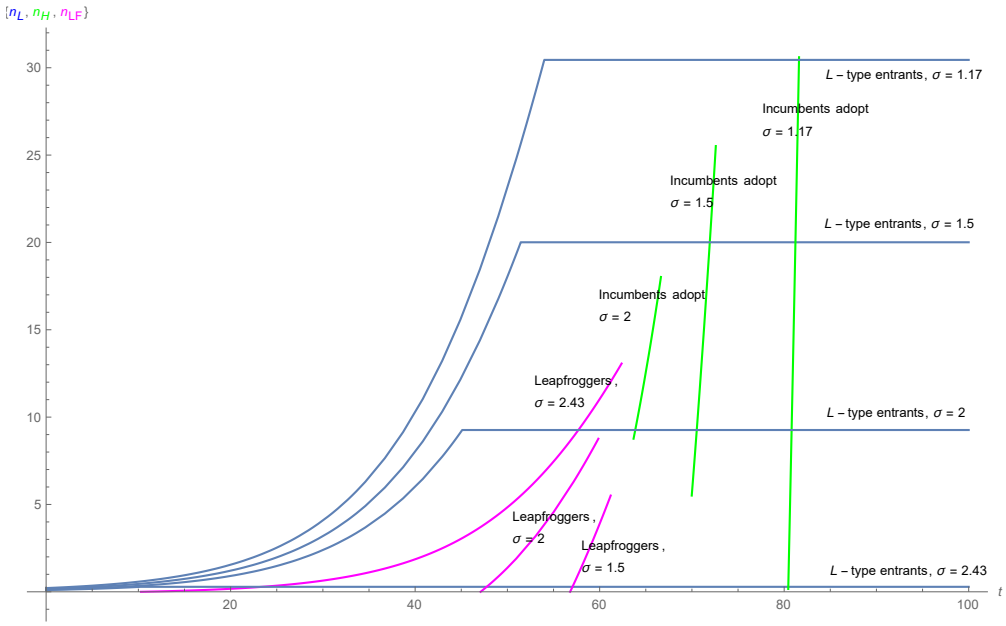

Figure 10: The effect of demand elasticity σ on the entry and adoption patterns.

Our specification of the entry as well as the adoption cost function allows for a straightforward examination of the effect of a change in the speed of technical progress or industry wide learning. The parameter b of the entry cost function $L(T)$ and of the adoption cost function $H(T)$ measures the speed with which these costs decrease over time. Theses costs are likely to differ greatly across industries, with high tech industries typically exhibiting much higher (negative) growth rates of these costs. Given the innovative step of the new technology, i.e. the productivity increase φ, and the arrival date of the new technology, an larger value of b, i.e. a higher speed of learning, leads to more entry of L-type firms. Figure 11 shows how faster learning translates into a larger number of incumbents. The effect of b on the number and entry dates of leapfroggers is much more involved. To see this note first that for $b = 0$, i.e. if there were no learning, entry would take place at $t = 0$ and $t = T_{em}$ for L-type firms and leapfroggers, respectively (or not at all). Note that for low values of b the difference in entry costs between the two technologies are small, given the productivity difference. This makes the high-technology, and therefore leapfrogging more profitable. As is apparent from Figure 12, leapfroggers enter rather early, namley at the emergence date of the new technology, when b assumes the lowest values covered in the figure. This early entrance renders entry all but unprofitable for L-type firms. Note that entry by leapfroggers takes a very long time span for this low values as the slow speed of learning causes a low speed of entry. An increase in b has a rather involved effect on entry by leapfroggers. As L-type entry bnecomes more profitable, early entry becomes less profitable. At the same waiting becames less profitable for later leapfroggers as the speed of learning is faster. These countervailing effects lead to a non-monotonicity in the number pf leapfroggers, which is increasing and then decreasing in b. As is apparent from Figures 11 and 12 the larger number of leapfroggers coincides with a reduced time span of their entry. For large

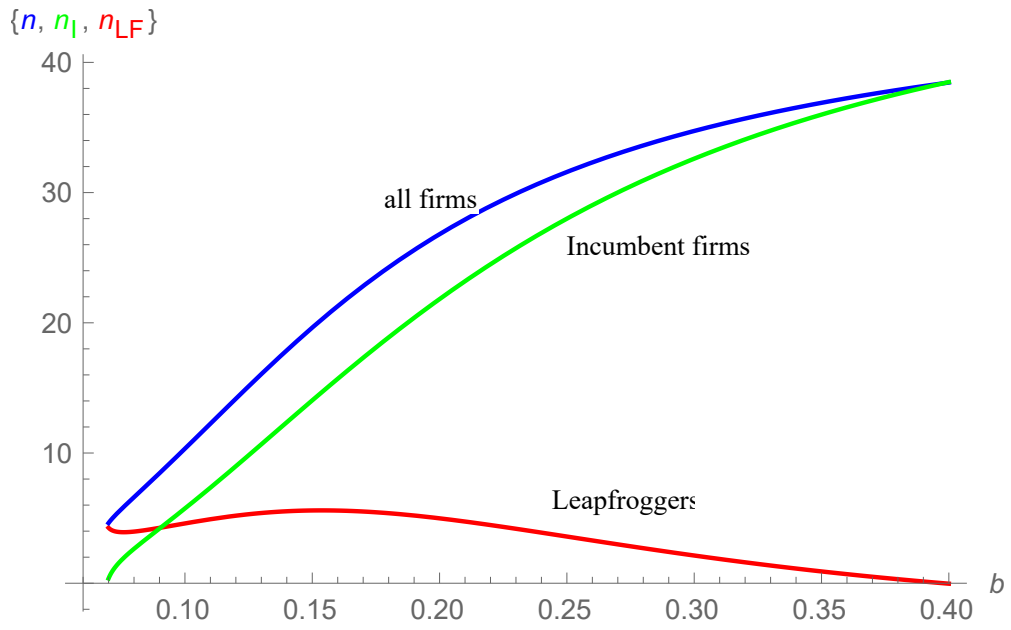

Figure 11: The effect of the speed of learning parameter b on entry of L-type firms and leapfroggers

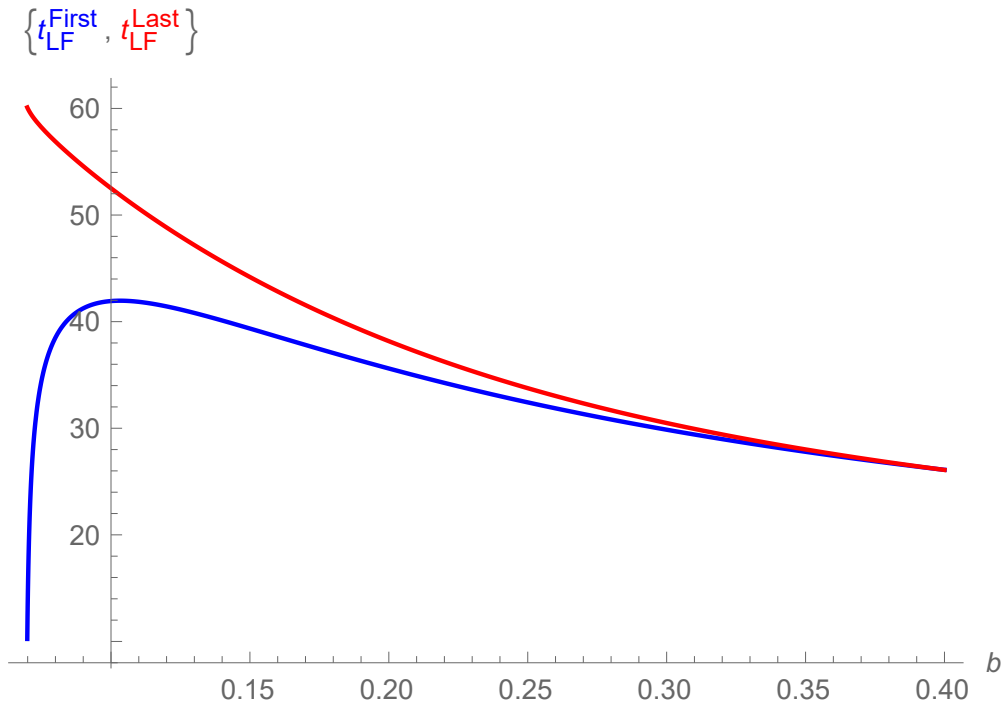

Figure 12: The effect of b on the first and last entry date of leapfroggers

values of b the fast decrease in entry costs leads to a large number of L-type entrants, which crowd out leapfroggers.

A straightforward effect arises in the case of changes in the market size parameter E, which denotes the number of consumers. Changes in E lead to proportional changes in the number of

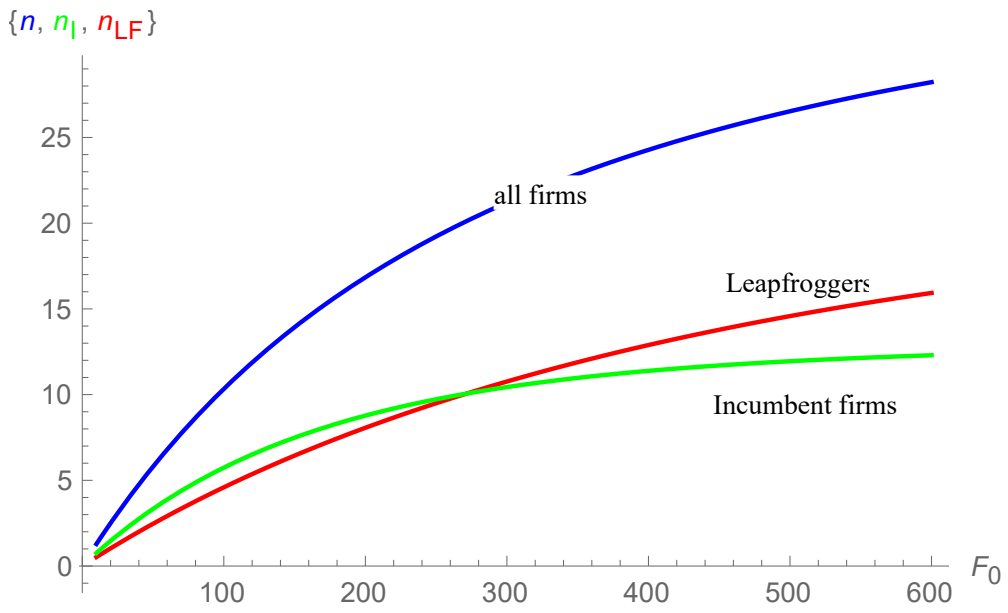

Figure 13: The effect of a proportional increase in both market size and entry costs on entry of L-type firms and leapfroggers (E/F_0 constant)

firms. As firm size stays constant, entry and adoption dates are not changed, only the number of firm active at each instant changes by the respective factor of proportionality. It is interesting to contrast the effect of market size parameter E with the effect of the sunk entry cost parameter F_0. In a static model (as well as in the long run of our model with $\bar{L} = 0$) the number of firms would also be (inversely) proportional to F_0. Nevertheless,due to the dynamic nature of the model the entry and the leapfrogging pattern changes with F_0 as can be seen for instance from the entry process of L-type entrants determined in 12. In order to isolate the effect of the dynamic structure with time dependant entry and adoption costs we keep the ratio of market size to sunk entry costs (i.e., E/F_0) constant. In a static model this would leave the number of firms and for instance $C(t)$ unchanged.[9] Figure 13 shows that a proportional increase in both market size and sunk entry costs has a huge effect on the number of firms. Larger markets allow for much more entry in a world where entry is dispersed over time even if they require higher entry cost. As Figure 14 shows, the short and long run welfare and productivity effects of such an equiproportionate increase in market size and sunk entry costs are enormous. Larger countries would profit greatly from their size even if a larger market size implies higher entry costs, due to, e.g., higher marketing costs.

[9]Note that we assume a value of $\bar{L} = 1$ in the simulation to not allow for a second wave of entry. As $\bar{L}$ also would imply entry costs, this would mean that in the simulation the long run ratio changes from 9.09 over 9.90 to 9.98. The total number of firms changes 1.28 over 10.33 to 26.52.

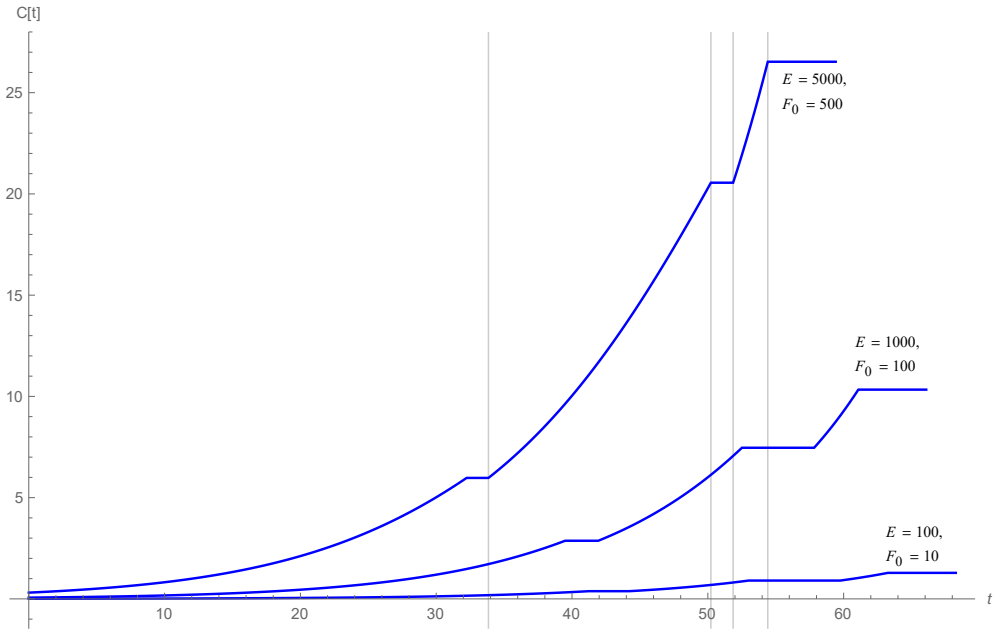

Figure 14: The effect of a proportional increase in both market size and entry costs on the evolution of the consumption index $C(t)$ (E/F_0 constant)

5 Conclusion

We develop a model in which ex ante identical firms make endogenous entry and technology adoption decisions. We show that this model is capable of matching the stylized facts in which entry is dispersed over time and that, in many industries, it is the newest firms which are the most likely to exhibit high productivity growth and adopt new innovations (i.e., leapfrogging). We then derive the characteristics of those industries where such leapfrogging is likely to occur.

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