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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 and adoption are 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 and show that leapfrogging can induce *reverse preemption* (i.e., forward-looking incumbent firms delaying entry and adoption due to leapfrogging behavior). As an application, we demonstrate how, in an industry conducive to leapfrogging, research subsidies can actually reduce short-run consumer welfare by discouraging firms from entering the market with a basic technology.

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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)).[1] However, in several industries, it is actually the newest entrants that exhibit market advantages. For example, numerous papers have found that younger firms have higher growth rates, at least over the first several years of entry (e.g., see Evans (1987), Dunne and Hughes (1994), Farinas and Moreno (2000) and Huergo and Jaumandreu (2004)). 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)).[2] Finally, numerous studies have found that newer firms are liable to have higher technology adoption rates (see Klepper and Simons (2000)) and are more likely to be on the global productivity frontier (see Andrews, Criscuolo, and Gal (2015)). Indeed, Bartelsman and Doms (2000) estimate that new entrants account for about a quarter of average TFP growth within an industry. Thus, it seems beneficial to have a better understanding of the link between entry and technology adoption decisions.

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 within a monopolistically competitive industry. Our particular framework is similar to those used in game-theoretic models of endogenous technology adoption (see in particular Reinganum (1981) and Götz (1999)) in which the cost of adoption is gradually declining over time. We assume that there are multiple technologies available to produce the good: a basic technology that is adopted on initial entry into the market and a cost-saving process innovation that only emerges later. What is unique about our approach is that we allow for the possibility of technological leapfrogging: that, after the emergence of the new technology, new firms can begin production without having to fully adopt the basic technology.

First, we show that (given endogenous entry) late entrants into the market will have the greatest incentive to adopt the latest technology. This result is actually independent of the degree of technological leapfrogging, but is instead a function of "cannibalization" effects. Intuitively, incumbent firms will be earning "excess" per-period profits to pay for the fixed costs of entry and adoption (in equilibrium), 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). Thus, our

[1]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)).

[2]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).

model is capable of matching many of the stylized facts of the life-cycle literature including gradual entry, gradual diffusion of new innovations and the fact that, in many cases, newer firms are the first to adopt new technologies.[3]

However, it turns out that technological leapfrogging is an important determinant of whether leapfrogging firms exist in equilibrium. Specifically, we show that at least a small amount of technological leapfrogging (new entrants having a cost advantage in only needing to partially adopt the basic technology) is necessary for the presence of late-entering high-tech firms. This raises the issue of what other market characteristics are conducive to profitable entry for leapfrogging firms. First, and consistent with the empirical evidence of 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 contrast, we show that a faster decline in technology adoption costs is not strongly correlated with leapfrogging entry. This suggests that the phenomenon of newer firms exhibiting productivity advantages (i.e., leapfrogging) should be more a prevalent in industries characterized by a high arrival rate of new innovations as opposed to the fast diffusion of existing innovations. Second, we show that leapfrogging is more likely to occur in industries with greater competitive pressures (captured by a higher elasticity of demand). Intuitively, in an industry characterized by greater product differentiation where the elasticity of demand is low, incumbent firms are less concerned about losing market share to new (low-cost) leapfrogging firms. As a result, there is more incumbent entry which "fills" the market and prevents late entry by leapfrogging firms.

It should be apparent that in discussing technology adoption decisions by both new firms and existing firms, our paper is related to a long-line of theoretical research in both the endogenous growth (e.g., see Segerstrom and Zolnierek (1999), Klette and Kortum (2004) and Acemoglu and Cao (2015)) and industrial organization (e.g., see Gilbert and Newberry, 1982 and Igami (2017)) fields. However, our approach allows us to endogenize the entry decisions of both new (leapfrogging) firms and existing (incumbent) firms. This allows us to derive some novel effects including what we refer to as reverse preemption: market characteristics that make leapfrogging entry more likely will also deter entry by forward-looking incumbent firms who fear being placed at a cost disadvantage. As an application, we demonstrate how research subsidies that speed-up the emergence of new cost-saving innovations can actually reduce short-run welfare by deterring early entry by incumbent firms.

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). In Section 4, we utilize numerical simulations of

[3]The standard explanation for the technology 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. We abstract from these selection effects by assuming ex ante identical firms.

our model to verify and demonstrate our results. Finally, Section 5 considers the short-run welfare implications of some policy changes in our model and Section 6 concludes.

2 Time of Entry and the Incentives to Adopt New Technology

In this section we present a dynamic 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.[4]

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.

[4]By considering technology 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 or successive technology innovations (and, hence, the potential for technology leapfrogging).

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 (l). 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 $l(t) = y(t)$.

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 $H' < 0$ and $H'' > 0$. Production using the high-productivity technology is defined by $l(t) = y(t)/\varphi$, where $\varphi > 1$ thus represents the size of the innovation. Note that, given the monopolistically competitive structure, we are investigating a situation of a non-drastic process innovation (i.e., price remains above cost for even the low-tech firms). Furthermore, we assume that $L(\infty) = H(\infty) = \bar{L}$where $\bar{L} > 0$ and is sufficiently large to prevent what we call third generation entry (this assumption is discussed later).[5] In order to guarantee a well defined entry and diffusion process, we assume that both $L(t)$ and $H(t)$ decrease with a speed greater than the discount rate, i.e. $d\left(-e^{rt}L'(t)\right)/dt < 0$ and $d\left(-e^{rt}H'(t)\right)/dt < 0$, resp.[6] 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 where 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

[5] As discussed in section 4, $\bar{L} = 0$ implies that another wave of entry would occur after all incumbents have adopted the high-tech technology simply as a result of the entry and adoption cost getting close to F_0. Simulations provided in the appendix show that values of $\bar{L}$ close to zero are sufficient to prevent that kind of entry.

[6] See Assumption 1 in Götz (1999) for a related assumption.

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 enter the market with the basic 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:

$$FOC1: \qquad \pi_L(T_e) = rF_0 - L'(T_e)e^{rT_e} \tag{11}$$

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 (8) into this first-order condition to solve for $n(t)$:

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

Given $L' < 0$, $L'' > 0$, and the above assumption that $d\left(-e^{rt}L'(t)\right)/dt < 0$, 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.

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.[7] 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. This description matches, e.g., the semiconductor industry rather well, where entry costs decline by 90% within the first three years and 50% of entrants still enter five years after the first entrant (see Liu, Siebert, and Zulehner (2013)).

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 Klepper (1996), Klepper and Simons (2000), Götz (2002)) 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 necessary 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. However, in contrast to other dispersed entry models, we also assume the possibility of 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.

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-

[7] 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).

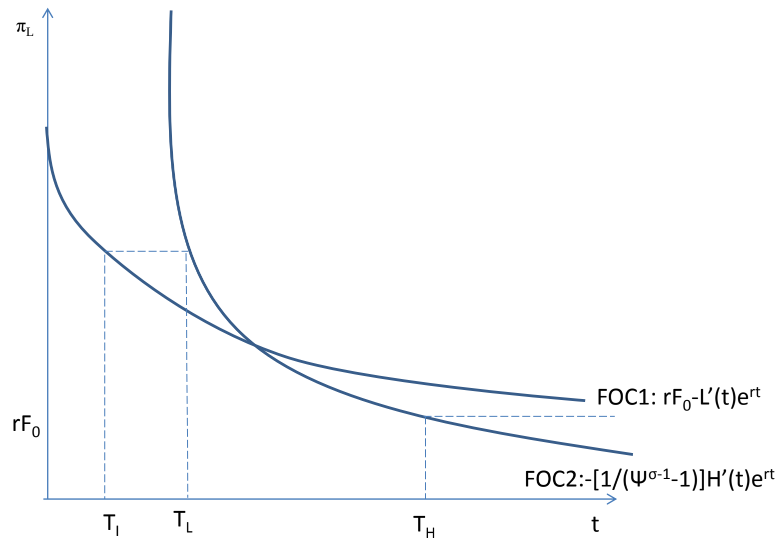

Figure 1: Process of entry and adoption: Incumbent Firms

productivity technology while the right-hand side is the gain from the decrease in adoption costs from delaying adoption another period.

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 continues to hold. Thus, the line labeled 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 entry 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., $T_L > T_1$).

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:

$$FOC2: \qquad \pi_L(T) = \frac{-H'(T)e^{rT}}{\varphi^{\sigma-1} - 1} \tag{14}$$

In Figure 1, the line labeled FOC2 represents (14): the above first-order condition for optimal adoption.[8] Thus, 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 $q^*(t)$).

Intuitively, gradual entry and adoption in the model are driven by preemption forces in which entry or adoption by a group of firms reduces the market share of competing firms and thus makes them less willing to pay the fixed costs of entry/adoption.[9] This generates gradualism as the remaining firms delay entry and/or adoption until more favorable market conditions (i.e., the decline in adoption costs) arise. Indeed, from (13), one can derive the equilibrium share of high-tech firms, $q^*(t)$, at any point in time:

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

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 $T_L < T_1$ (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.[10] Intuitively, the adoption of the new technology 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 high technology 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 can force non-adopting firms to exit the market. Our model shows that the same technology adoption that

[8] 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.

[9] For empirical evidence on preemption forces see Mulligan and Linares (2003) which finds that the adoption of chairlifts by a ski area reduces the likelihood of adoption by nearby competitors. In a more recent structural approach, Macher, Miller, and Osborne (2017) shows that the presence of nearby competitors also deters the adoption of a new cost-saving technology (the precalciner kiln) in the cement industry. However, it should be noted that Macher et al. (2017) model an oligopolistic industry in which firms engage in strategic preemption. In contrast, our framework is of a monopolistically competitive industry where it is adoption by a mass of firms that leads to (non-strategic) preemption.

[10] 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.

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:

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

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

$$FOC3: \qquad \pi_H(T_e) = rF_0 - [\alpha L'(T_e) + H'(T_e)]e^{rT_e} \tag{16}$$

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

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

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.[11] 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

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

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.

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

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).[12] 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. Thus, the gain from adopting the cost-saving innovation (i.e., the profit differential) is less for incumbent firms. This is the so-called "cannibalization" effect of Arrow (1962) or, as Tirole (1988) calls it, the replacement effect, in which incumbent firms are less likely to innovate since the new innovation is simply substituting for an existing innovation.[13]

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.

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

[13] In the literature, the cannibalization effect has also been typically applied to product innovations where the benefits of introducing new products are smaller for incumbent firms since, to the extent the old and new products are substitutes, they are simply replacing one source of profits with another. Indeed, in a recent paper Igami (2017) shows that cannibalization is a significant deterrent to incumbent innovation and can explain at least 57 percent of the incumbent-entrant innovation gap.

3 Leapfrogging - Late 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:[14]

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

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:

$$\int_{T_e}^{T_L} e^{-rt}\pi_H(t)dt + [L(0) - \alpha L(T_e)] + (1 - e^{-rT_e})F_0 > \int_0^{T_L} e^{-rt}\pi_L(t)dt + [H(T_e) - H(T_L)] \tag{22}$$

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 occurring (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 encourage leapfrogging (i.e., late entry of high-tech firms). Indeed, it is possible to show that $\alpha < 1$ is a necessary condition

[14] 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.

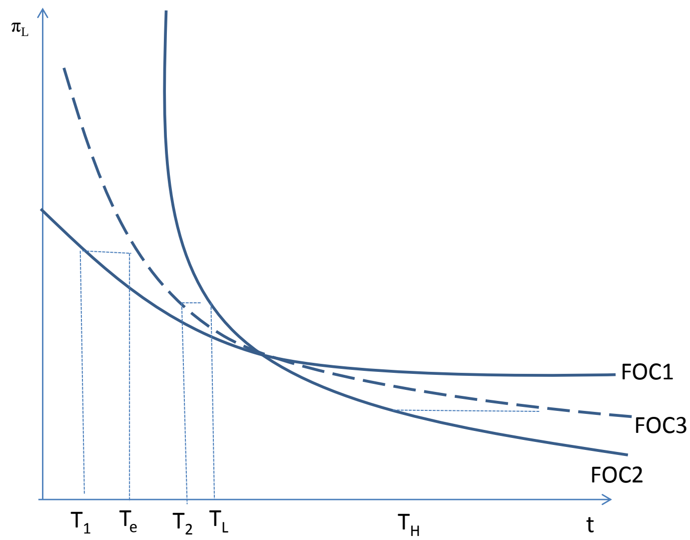

Figure 2: First order conditions: No leapfrogging for $\alpha = 1$

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 behavior 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.[15] 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). We will show next that leapfrogging cannot occur for the case drawn in Figure 2, where $\alpha = 1$.

The proof proceeds by contradiction and for the moment assumes that leapfrogging firms act according to their first order condition and begin to enter at T_e. Entry by leapfrogging firms will end at some point T_2 to the left of the intersection of the first order conditions. Adoption by incumbent firms begins at T_L. 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 $t > 0$) and thus:

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

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

[15]Figure 2 assumes $\alpha = 1$ and thus it can be shown that the three first order conditions intersect at the same point.

$-H'(t)e^{rt}$ (i.e., low-tech profits are less than FOC2) 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 our 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. However, it should be noted that the reverse is not true: even $\alpha = 0$ does not guarantee the existence of leapfrogging entry in all situations. Thus, in the following sections, we consider other parameters that influence the existence of leapfrogging.

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 $H(t)$

In addition to the profit differential, the speed of technology diffusion (in terms of both adoption cost of the original technology, $L(t)$ and subsequent technology improvement, $H(t)$) will also determine the probability of leapfrogging activity. Note, from (25) that high industry profits during the early time periods $[\int_0^{T_e} e^{-rt}\pi_L(t)dt]$ reduces the probability of leapfrogging. This is due to the fact that high early profits induces the entry of incumbent firms, which in turn crowds out later leapfroggers (note also that these foregone profits are the opportunity cost to delaying entry). Thus our conjecture is that faster technological progress which shifts forward these adoption dates (i.e., an earlier T_e) would reduce the number of incumbents and increase leapfrogging behavior. In the numerical simulations that follow we address how the speed of technology diffusion affects leapfrogging by adjusting both the emergent data of the new technology $t = \underline{t}$ and the speed at which adoption costs decline over time.[16]

4 Numerical Simulations

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

$$L(T) = L(0)e^{-(b+r)T} + \bar{L}$$

and

$$H(T) = L(0)e^{b(\underline{t}-T)-rT} + \bar{L}.$$

The parameter b is a positive constant capturing the decrease in cost induced by either technical progress or learning. The parameter $\underline{t}$ reflects the emergent date of the new technology. Note that the entry cost $L(T)$ and the adoption cost function $H(T)$ are identical up to a 'time shift' and that we assume $H(T)$ to be infinite for $T < \underline{t}$. $\bar{L}$ is the lower bound for L and H as T approaches infinity.[17] Concerning the parameters, we assume the following values in our benchmark case:

$$r = .1, L(0) = 20000, \underline{t} = 10, b = .1, E = 1000, F_0 = 100, \varphi = 2, \sigma = 2$$

[16] Specifically, we model changes this effect with an economy wide learning rate b, at which these costs decrease. Faster learning will speed up both the entry process of incumbents and their adoption of the new technology.

[17] As discussed later, third generation entry eventually occurs after the adoption by all incumbents if $\bar{L}$ is 0. However, this type of entry appears to be an artifact of the fact that entry costs converge towards 0 in the long-run and can be ruled out with even small positive values of $\bar{L}$.

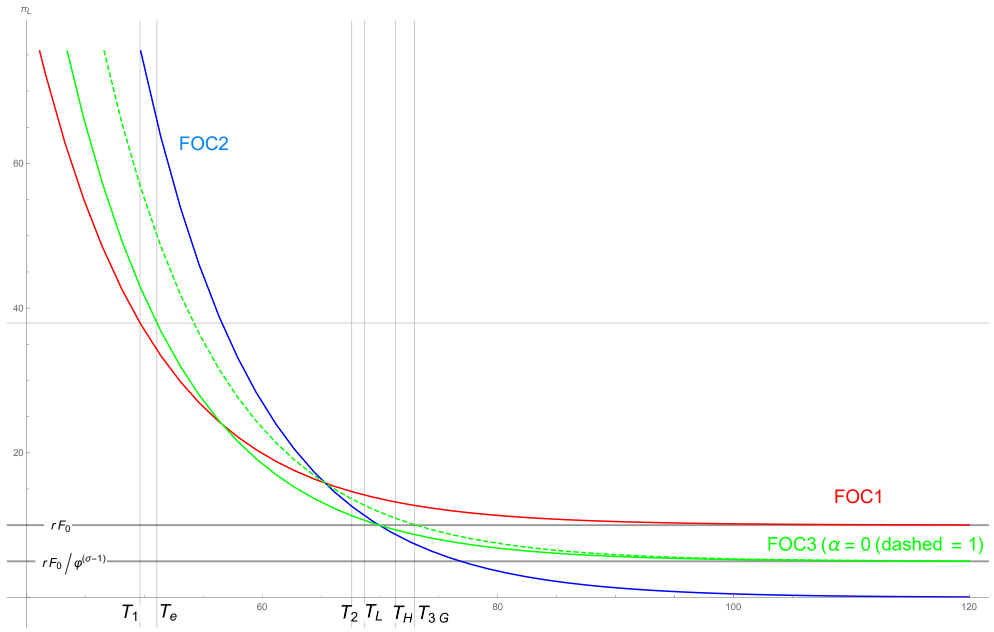

Figure 3: FOCs and first and last entry and adoption dates from simulation; $\alpha = 0$ and $\alpha = 1$, resp.

We start our discussion with the parameter α (the cost advantage to leapfroggers). In Figure 3 we plot the first-order conditions for two extreme cases: $\alpha = 0$ and $\alpha = 1$. To facilitate discussion of third-generation entry, Figure 3 is drawn assuming $\bar{L} = 0$. Note that the first-order conditions for incumbent entry (FOC1 from 11) and adoption (FOC2 from 13) are independent of α and achieve their lower bound at rF_0 and 0 respectively. In contrast, lower values of α imply a shift to the left of FOC3 (the first-order condition for optimal leapfrogging entry from 16) with a lower bound at $rF_0/\varphi^{(\sigma-1)}$). As can be seen, a shift to the left of FOC3 implies that leapfrogging occurs earlier in equilibrium (i.e., an earlier T_e).

Figure 3 also demonstrates the existence of third generation entry unless $\bar{L} > 0$ (i.e., late entry by hi-tech firms when the cost of adoption has declined to approximately zero). To see this note that FOC1 implies that, in equilibrium, $\pi_L \geq rF_0$ and thus $\pi_H = \varphi^{(\sigma-1)}\pi_L > rF_0$. However, this implies that firms can eventually profitably enter with the H-technology (regardless of α) once the costs of adoption ($L(t)$ and $H(t)$)have declined to approximately zero. Note that this third generation entry will always happen with the H-technology rather than with the L-technology as FOC3 is below FOC1 in the respective range and thus H-technology is more profitable. However, simulation exercises suggest that this type of entry is not robust and is prevented by even small values of $\bar{L}$. For example, for our benchmark parameter values, values of $\bar{L}$ at $10^{-6}L_0$ are sufficient to prevent third generation entry. Thus, for our benchmark case we will assume that $\bar{L} = .026$, a value which guarantees that no third generation entry takes place. We discuss the equilibrium dynamics when third-generation entry exists in the Appendix.

Figure 4 shows the entry and adoption patterns for both cases of $\alpha = 0$ and $\alpha = 1$. The dashed lines depict the case without leapfrogging (i.e., when $\alpha = 1$ and leapfroggers have to bear the full

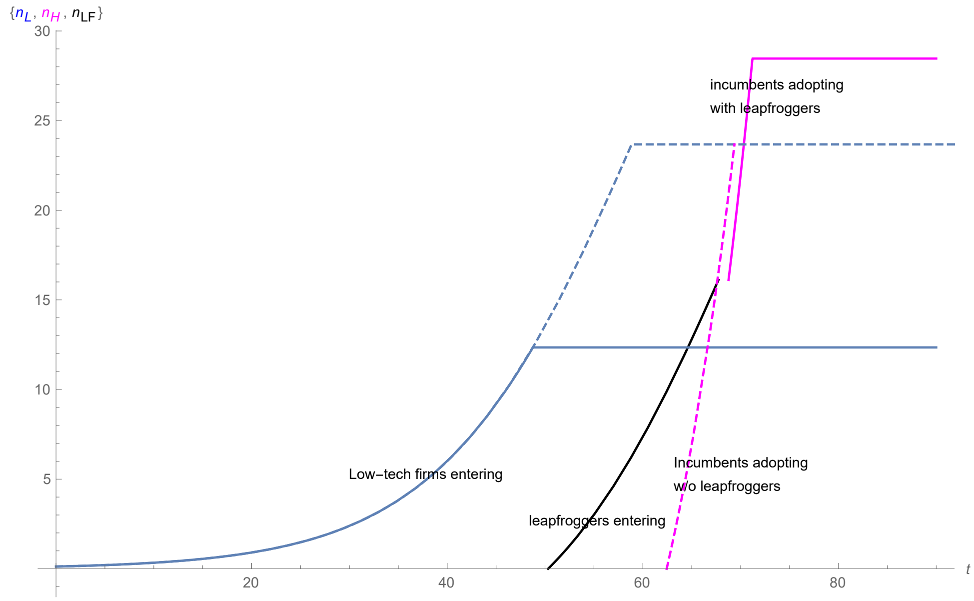

Figure 4: Entry and adoption patterns with and without leapfrogging

adoption cost $L(T) + H(T)$). First, concentrate on the entry decisions. As can be seen, in the absence of leapfrogging, entry is gradual over time with low-tech incumbent firms entering until $T_1 = 58.85$ and $n_L = 23.67$.[18] Turning to the case of $\alpha = 0$ (the solid lines), the first thing to note is that entry by leapfrogging firms occurs. Specifically, low-tech incumbents gradually enter until $T_1 = 48.77$ and $n_L = 12.35$. Then, after a slight delay, hi-tech leapfrogging firms enter from $T_e = 50.32$ until $T_2 = 67.74$ with the total number of leapfrogging firms equal to $n_{LF} = 16.11$. Note that leapfrogging deters entry by incumbents, however (due to the lower entry costs afforded by leapfrogging the original technology), the total number of firms actually increases in the long-run in the leapfrogging equilibrium.

Next, concentrate on the adoption decisions by firms. For the non-leapfrogging equilibrium, there is a gap between the last entry of a low-type incumbent firm ($T_1 = 58.85$) and the first adoption of the new technology ($T_L = 62.44$). The technology gradually diffuses through the industry until all incumbent firms have adopted by $T_H = 69.37$. In contrast, leapfrogging speeds up initial productivity growth in the industry in the sense that the high productive technology is adopted earlier by the new leapfrogging entrants beginning at $T_e = 50.32$. However, technology adoption by the incumbents is slightly delayed and now occurs from $T_L = 68.77$ to $T_H = 71.21$.

Having established the basic mechanics of our model, in the following sections we consider how changing parameter values impacts both the underlying dynamics as well as the importance of leapfrogging (i.e., the fraction of leapfrogging firms in the industry).

[18]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. The atom becomes more obvious as we lower $L(0)$. For example, when $L(0) = 100$, then $n(0) = 23.8$.

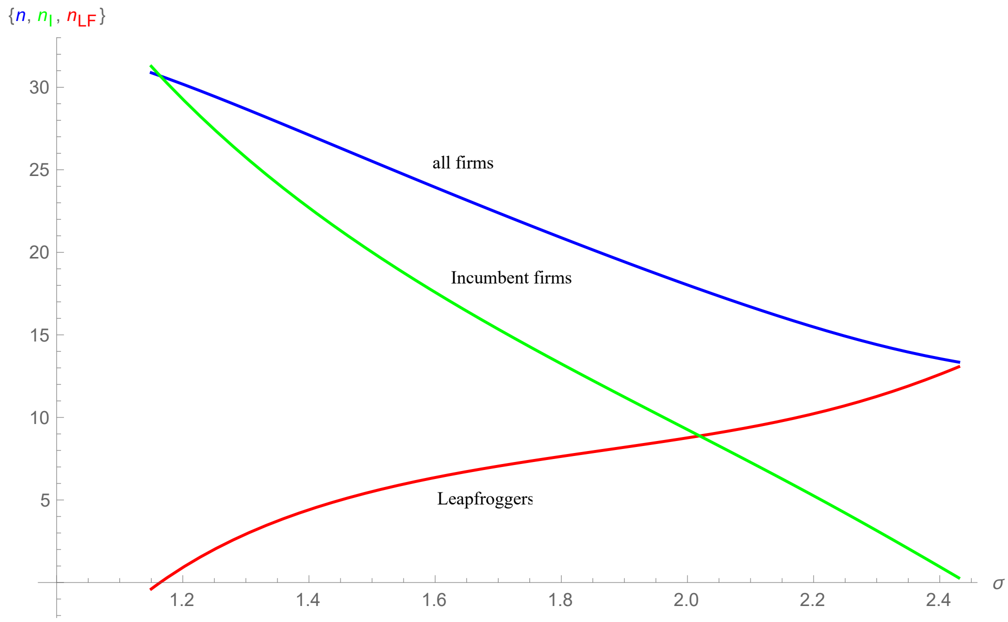

Figure 5: The effect of the demand elasticity σ on entry of L-type firms and leapfroggers

4.1 Determinants of Leapfrogging: Intensity of Competition (σ)

First consider a change in the intensity of competition within the industry, measured by the parameter σ (i.e., a a higher elasticity of demand and of substitution). Since leapfrogging firms employing the high technology are able to attract more customers from their low-productivity rivals, we conjectured that an increase in σ would result in more leapfrogging behavior. This mechanism is similar to what Aghion and Schankerman (2004) refer to as a restructuring effect in which firms have an increased incentive to reduce costs given greater competition intensity. Figure 5 plots the change in the number of incumbent and leapfrogging firms as σ is adjusted. As can be seen, for values of σ close to the pure monopoly case of $\sigma = 1$, leapfrogging vanishes. However, as the intensity of competition (σ) increases, the number of leapfrogging firms increases (and the number of incumbent firms declines). Thus, similar to Aghion and Schankerman (2004), intensified competition has a market selection effect in that it reduces the number of low-tech (incumbent) entrants and increases the number of hi-tech (leapfrogging) entrants. Indeed, for sufficiently high values of σ almost no low-tech incumbent firms are willing to enter the market.

Figure 6 plots both entry and adoption decisions over time for different values of σ and highlights the strong effect of the intensity of competition on the speed of both entry and technology adoption. A low intensity of competition (cf. $\sigma = 1.16$) provides a high margin for the incumbent firms and therefore leads to rather extensive low-type entry ($n_L = 30.69$). At the same time it both prevents leapfroggers from entering and retards the process of technology adoption (the date of first adoption is not until $T_L = 80.79$). As incumbents face little competition they delay adoption until adoption costs are very low and then adopt almost simultaneously.

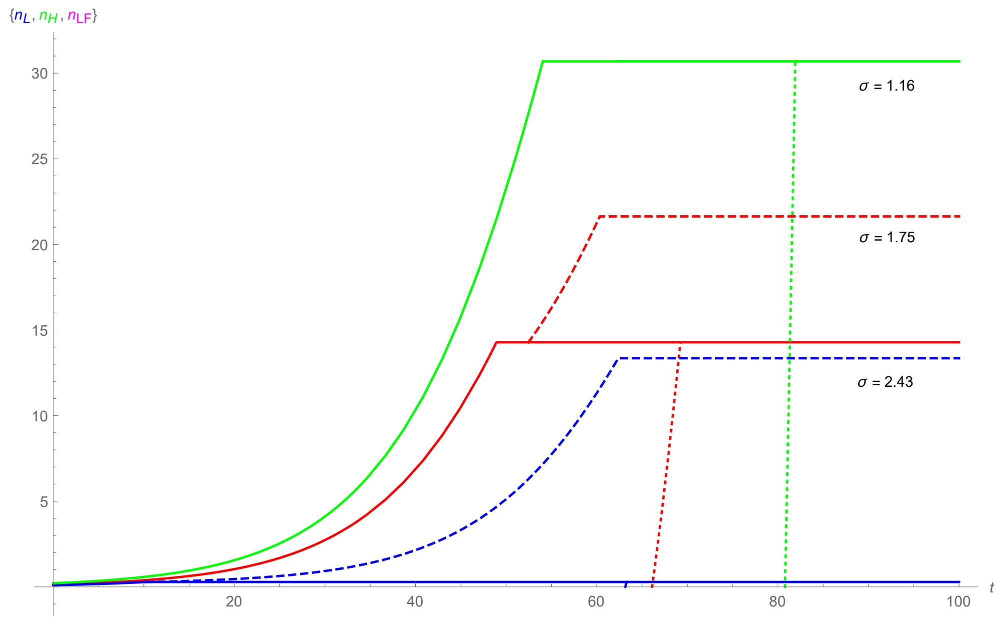

Figure 6: The effect of demand elasticity σ on the entry and adoption patterns.

As the intensity of competition is increased, (cf. $\sigma = 1.75$), there is less low-type incumbent entry (n_L declines to 14.28) and earlier entry of leapfroggers which speeds up the process of technology adoption drastically (i.e., now the date of first adoption is by leapfrogging firms at $T_e = 52.46$). Following the arrival of the leapfroggers, the new technology then diffuses rapidly through the incumbent firms, starting at time period $T_L = 66.12$.

Finally, when the intensity of competition is very high (cf. $\sigma = 2.45$) low-type incumbent entry has almost disappeared ($n_L = .28$). This is because the high elasticity of substitution among product varieties makes firms hesitant about entering as low-tech firms since they are liable to be priced out of the market by new hi-tech leapfrogging entrants. As a result, leapfroggers appear very early ($T_e = 10.29$), leading to rapid diffusion of the new technology (all firms have adopted the new technology by time period 63.00).

4.2 Determinants of Leapfrogging: Size of Technology Improvement (φ)

Changes in the productivity parameter φ have largely similar effects to the change in the intensity of competition. Consistent with our conjecture, increases in φ make adopting the new technology more profitable and therefore increase the number of leapfrogging firms. Figure 7 shows in detail how the number of the different firm types depends on φ. If the productivity increase is small, incumbent firms do not fear leapfrogging entry as it only places them at a small cost disadvantage. Thus, there is significant initial entry by L-type incumbent firms which in turn crowds-out entry by leapfroggers (i.e., forward preemption). However, increases in the size of the productivity jump (i.e., the importance of the technology improvement) increases the profit differential and, thus, the number of leapfroggers. This threat of early entry and adoption by leapfrogging firms in turn deters

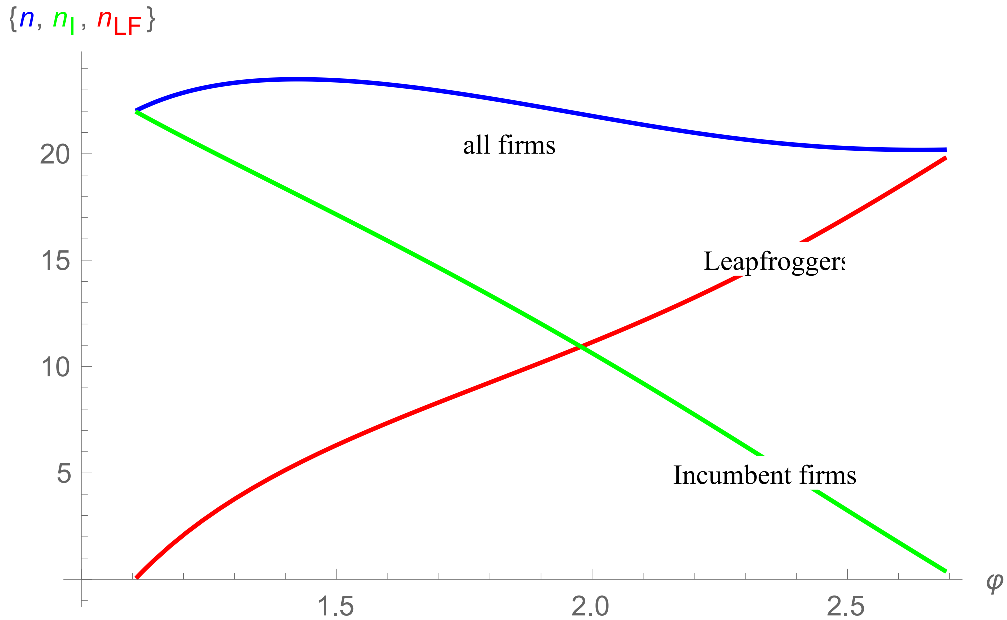

Figure 7: The effect of the productivity parameter φ on entry of L-type firms and leapfroggers

entry by forward-looking incumbents who fear being placed at a significant cost disadvantage. It is this negative feedback between the entry decisions of leapfrogging and incumbent firms (which we refer to as "reverse preemption") which leads to large changes in market structure as φ increases.

As mentioned previously, the above figure is consistent with the empirical evidence that leapfrogging firms (high-tech new entrants) are more common in high-tech industries. However, Figure 7 provides a more concise definition of the link between high-tech and leapfrogging: specifically that leapfrogging is more common in industries which are more susceptible to large innovations. As can be seen, industries where any new process innovations tend to provide only small cost savings are heavily dominated by incumbent firms. In contrast, industries more susceptible to radical innovations will see less entry by low-tech incumbents and thus a larger percentage of leapfrogging firms.

4.3 Determinants of Leapfrogging: Date of Emergence of New Technology ($\underline{t}$)

Our specification of the entry and adoption cost functions suggest two methods by which differences across industries in technological progress can be captured. First, faster technological progress could suggest an earlier data for the emergence of the new technology (i.e., $\underline{t}$). Notice that, by our specification, this is equivalent to a shift in the adoption cost function for the new technology. Second, the parameter b of the entry cost function $L(T)$ and of the adoption cost function $H(T)$ measures the speed with which adoption costs decrease over time. Notice that changes in b are more similar to a change in the slope of the adoption cost function. Theses costs are likely to differ greatly across industries, with high tech industries potentially exhibiting both earlier emergent dates (i.e., greater frequency of new innovations) and higher (negative) growth rates of adoption costs (i.e., faster learning about existing innovations). Thus, in this section we consider an earlier emergent data (decline in $\underline{t}$) and in the next section we consider a change in the speed of the decline in adoption costs (i.e., increases in b).

The effect of an earlier emergent date turns out to be rather straightforward: if the new technology emerges earlier, there will be more leapfrogging and less low-tech entry. Figure 8 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 lead to a fast decrease in the number of leapfroggers and a corresponding increase in the number of low-tech incumbent entrant. Note, that the first order conditions for both leapfroggers and for the adoption of the H-technology by incumbents would be satisfied for lower values of T (see 13 and 16) if the adoption cost function shifts to the left. As a result (and similar to our conjecture) this decreases the amount of time incumbent firms can earn early profits as low-tech entrants (the opportunity costs of delaying entry) and thus deters such low-type entry and encourages leapfrogging.

It should be noted that, 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 new technology emerges at time 0.[19] Of more interest is the effect of a later emergence dates on leapfrogging activity. Even when leapfroggers have a strong cost advantage (setting $\alpha = 0$), high-tech leapfroggers can be crowded out by the entrance of a large number of incumbents who are willing to enter the market due to the late arrival date of the new technology. Indeed, if the new technology arrives at the market at about $t = 23$ or after, entry of leapfroggers will no longer occur. Thus, our results are consistent with leapfrogging entry being more likely to occur in high-tech industries where new innovations are both larger (φ) and arrive more rapidly ($\underline{t}$).

4.4 Determinants of Leapfrogging: Decline in Adoption Costs (b)

Next, consider a increase in b (i.e., a higher speed of learning in which adoption costs decline at a more rapid rate). This more rapid decline applies to both adoption of the original technology ($L(t)$) as well as the new technology ($H(t)$), but is holding the emergence date ($\underline{t}$) constant. Figure 9 plots the number of incumbent firms and leapfroggers for our benchmark case as the speed of learning increases. Note, first, that faster learning translates into a larger number of total firms as well as the number of incumbents. This is a straightforward consequence of the assumption that the speed of technical progress affects both the entry costs for the low-type technology and the adoption cost for the high-tech technology. Thus, a higher speed of learning, leads to more entry of L-type incumbent firms.

The effect of b on the number and entry dates of leapfroggers is much more involved. Recall from (25) that the main benefits to leapfrogging are the higher profits during the time period before

[19] Given the benchmark parameter set, for emergence dates smaller than 6.96 there will be an atom of leapfroggers at the emergence date.

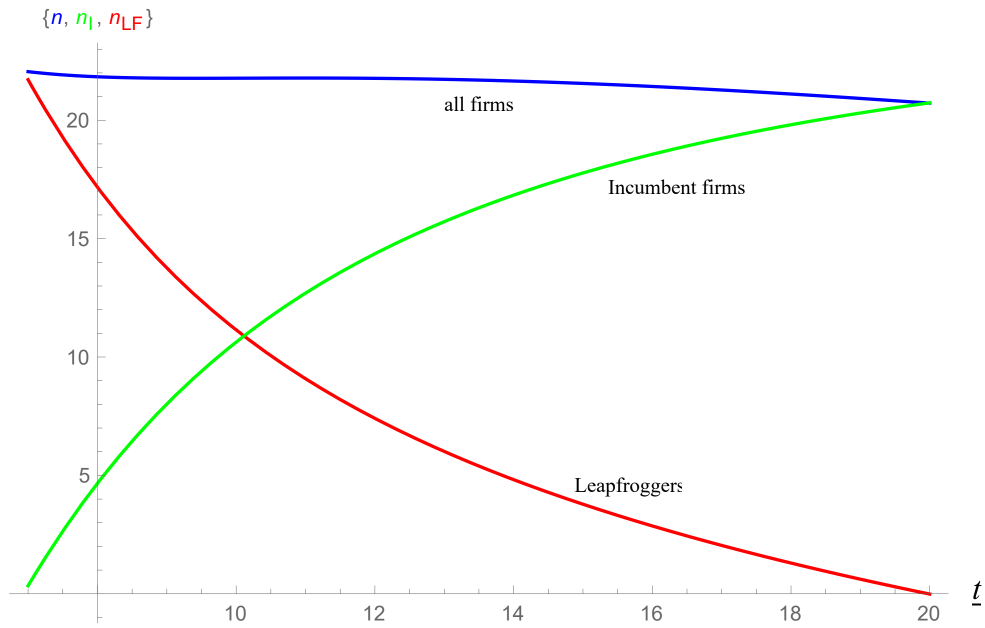

Figure 8: The effect of the emergence date $\underline{t}$ on entry of L-type firms and leapfroggers

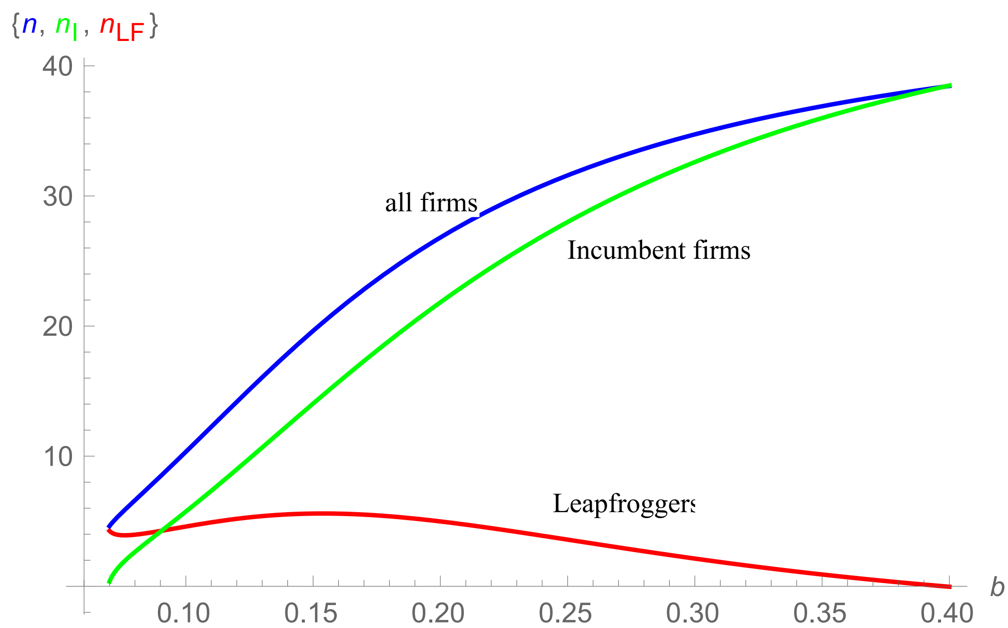

Figure 9: The effect of the speed of learning parameter b on entry of L-type firms and leapfroggers

incumbents begin to adopt (i.e., $\int_{T_e}^{T_L} e^{-rt}(\pi_H(t) - \pi_L(t))dt$) and being able to avoid some of the costs of adopting the original technology (i.e., $L(0) - \alpha L(T_e)$). However, faster learning tends to reduce these relative benefits to leapfrogging. Most directly, it reduces the time period between when leapfroggers enter (T_e) and when incumbents begin adopting (T_L) which directly decreases the relative advantage of delayed entry. This is made clear in Figure 10 which plots the time period of first entry by leapfroggers (T_e) and the time period of first adoption by incumbents (T_L)as the speed

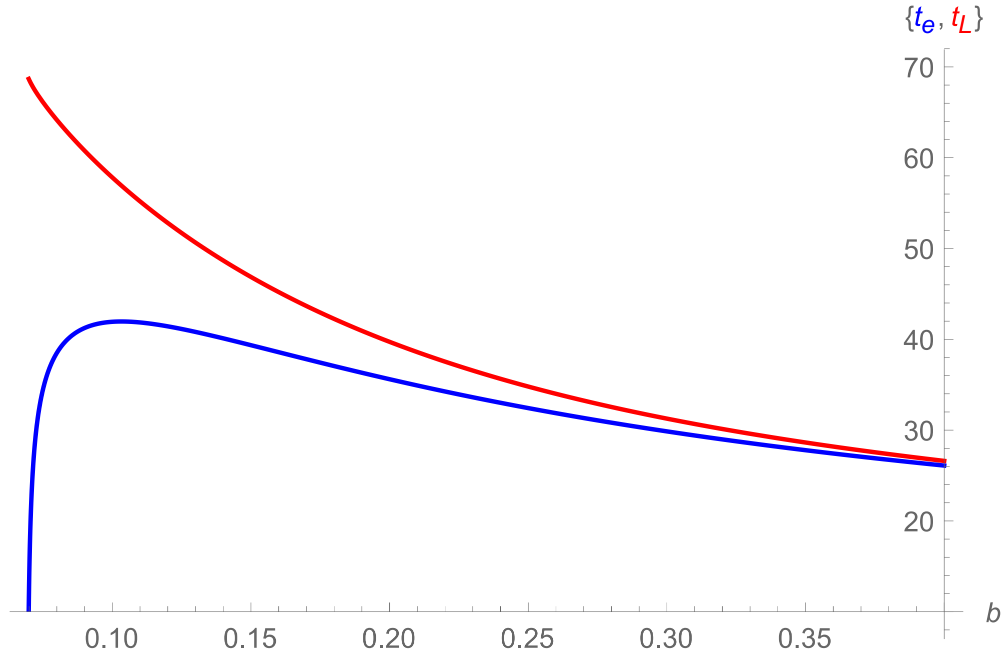

Figure 10: The effect of b on the first entry date of leapfroggers and incumbents, resp.

of learning is increased. As can be seen, as b increases, these two dates converge which reduces the incentive to to enter as a leapfrogger.

On the other hand it would seem that faster technological progress (through learning) would shrink the time period before entry by leapfroggers and thus reduce the profits to early entry (i.e., $\int_0^{T_e} e^{-rt}(\pi_L(t))dt$) similar to the decline in the emergent date. However, as is clear from Figure 10, the relationship between b and the time period of leapfrogging entry (T_e) is actually non-monotonic. Specifically, at extremely low levels of b (where learning is almost non-existent) there is very little incentive to delay either adoption or entry and thus leapfroggers enter early (close to the emergence date of the new technology). This early entry by leapfroggers crowds out incumbent entry and thus results in an equilibrium characterized by a small number of (primarily leapfrogging) firms. As the speed of learning, b, increases, the leapfrogging firms begin to delay entry to take advantage of the lower adoption costs. The cost advantages from such a delay both lead to a greater number of leapfrogging firms but also a greater number of incumbent firms (whose profits increase an the leapfroggers delay entry). However, as b continues to increase the time period between T_e and T_L shrinks drastically, leading to a strong shift shift from leapfrogging firms to incumbent firms. The time period of leapfrogging entry T_e also declines, but recall that the emergent date ($\underline{t}$) is held fixed which allows incumbent firms a period of early profits to compensate for earlier entry. Thus, our analysis suggests that the phenomenon of leapfrogging is tied more to the rapid emergence of new innovations ($\underline{t}$) and not to rapid learning about existing innovations (b).[20]

[20]Empirically, this suggests that leapfrogging would be more prevalent in industries characterized by a high arrival rate of new innovations, rather than industries characterized by the fast diffusion of existing innovations.

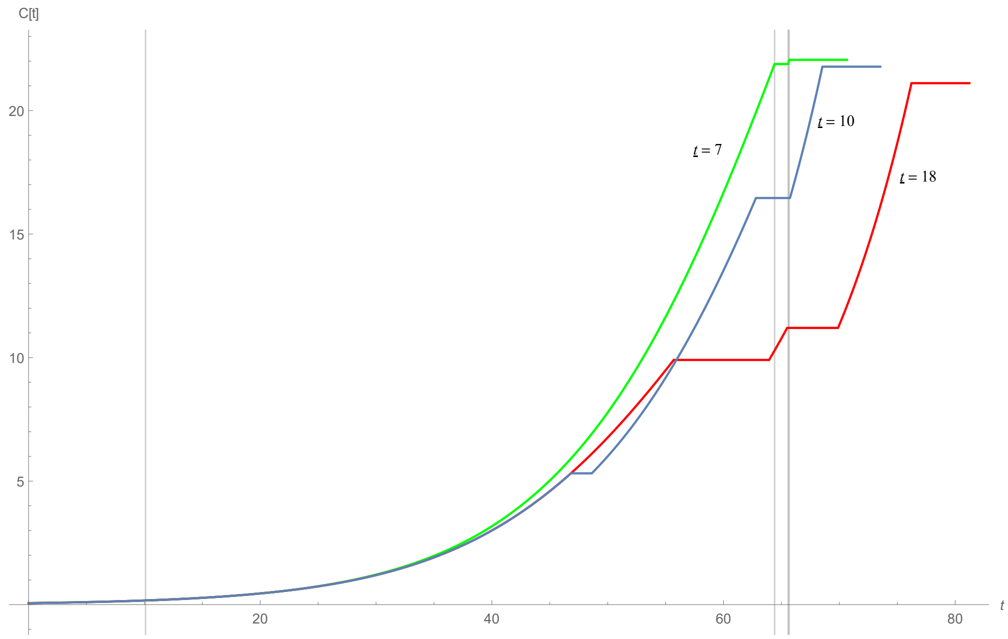

Figure 11: The effect of the emergence date $\underline{t}$ on the evolution of the consumption index $C(t)$

5 Reverse Preemption: Short-Run Welfare Implications

One of the common patterns of the previous section was that of reverse preemption: that market characteristics that made entry by leapfrogging firms more likely also tended to deter entry by forward-looking incumbents who feared being placed at a cost disadvantage by the new entrants. However, this suggests that changes in market conditions that potentially encourage future leapfrogging could have interesting short-run impacts as they might also deter current incumbent entry. As an application consider a (costless) research and development subsidy that either speeds up the emergence of a new cost-saving innovation or increases the size of the innovation (i.e., increases φ). To map the effect of this policy on welfare we plot the evolution over time of the consumption index $C(t)$ (see (2)). Note that $C(t)$ captures both the change in productivity over time as well as the change in the available product variety which is directly related to the number of firms in the industry.

First, consider an R&D subsidy that speeds up the emergence of a new cost-saving innovation (i.e., decreases $\underline{t}$). Figure 11 plots $C(t)$ for three different emergent dates ($\underline{t} = (7, 10, 18)$). As can be seen, earlier emergent dates lead to small welfare gains in the long-run as they lead to a small increase in the total number of firms (and, thus, product variety) (see above Figure 8). However, consider a policy change which leads the emergent date shifting from $\underline{t} = 18$ to $\underline{t} = 10$. As can be seen from Figure 11 while the later emergence date (see the curve for $\underline{t} = 18$) has lower long-run welfare, it also allows for more early incumbent entry and thus a period of higher short-run welfare for some values of t.

Next, consider an R&D subsidy that increases the size of the innovation (i.e., increases φ). Figure

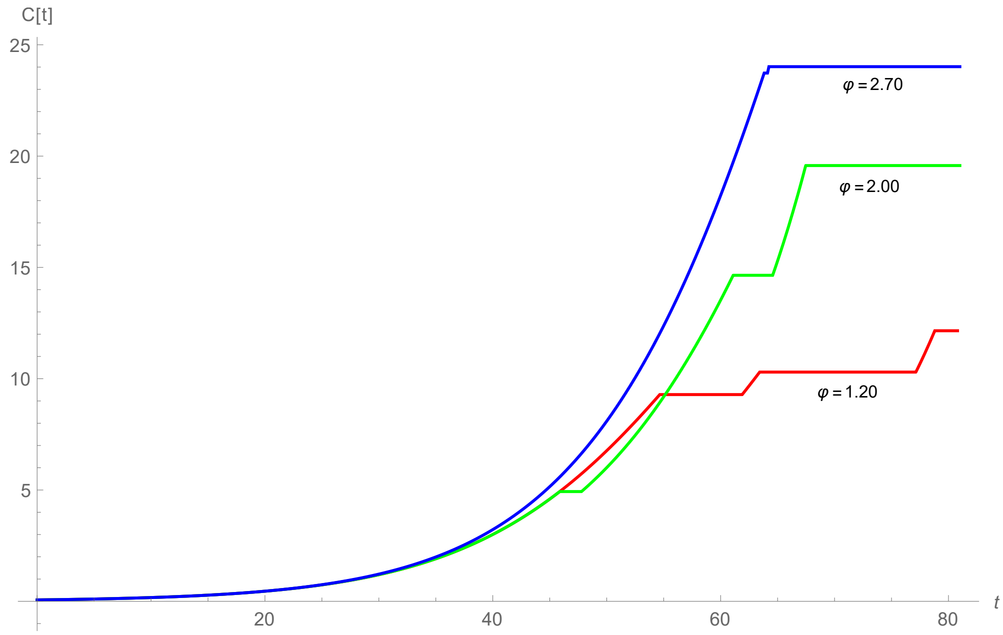

Figure 12: The effect of the productivity parameter φ on the evolution of the consumption index $C(t)$

12 plots $C(t)$ for three values of the size of the innovation ($\varphi = (1.2, 2, 2.7)$). Note that the "long run" gains from increasing φ are much higher than those shown in Figure 11 for $\underline{t}$. This is because an increase in φ leads to a direct increase in long-run industry productivity. However, despite these long-run gains, there still exists short-run welfare reversals. Once again, consider a policy change which leads to a much larger innovation (φ shifting from 1.2 to 2.0). As can be seen from Figure 12 the decreased cost-savings from a smaller innovation (see the curve for $\varphi = 1.2$) actually has a period of higher short-run welfare as it encourages early incumbent entry.

As can be seen, research subsidies which increase the arrival and size of new technologies can actually lead to lower welfare for a transitional period as they potentially deter current period entry by forward-looking firms. This is a rather general effect in the model: changes, which benefit leapfrogging (and thus typically lead to higher long-run welfare and productivity) often deter early incumbent entry. For example, apart from the change in the emergent date and the size of the innovation, this holds also with respect to α as can be seen from Figure 4, where leapfrogging leads to an earlier cutoff of the low-type entry process. Thus, our results might have implications for the more empirical literature that attempts to quantify the gains to different industrial policies such as R&D subsidies. For example, Acemoglu, Akcigit, Bloom, and Kerr (2013) argues that a subsidy to incumbent R&D could reduce welfare by deterring entry of new high-type firms. However, our results suggest that a generic research subsidy could also reduce welfare (at least in the short run) by deterring incumbent entry as well.

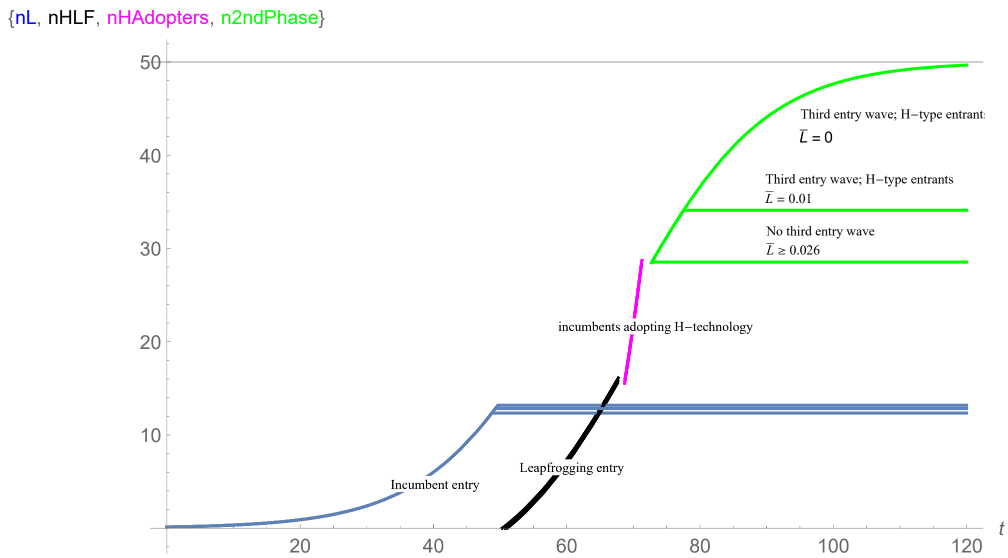

Figure 13: The effect of $\bar{L}$ on third generation entry

6 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. These findings explain recent empirical results and provide hypotheses for future empirical work on the relationship between fundamental variables such as the intensitiy of competition and the innovativeness of new technology and the market driven entry and adoption process of these technologies. Our results reveal a certain destructive power of an increase in innovativeness. Technology policies, which increase the incentives to adopt new technologies, are quite likely to have a negative short run welfare effect.

7 Appendix

7.1 Third-generation entry

In this section we briefly discuss the effect of $\bar{L}$ on entry and diffusion patterns. As mentioned in Section 4 if $\bar{L} = 0$ there will be a third wave of high-technology entry in the limit (as $L(t)$ and $H(t)$ converge to zero). Figure 13 shows the entry and diffusion patterns for the benchmark parameter set and for three values of $\bar{L}$: $\bar{L} = \{0, .01, .026\}$.

There are several things to note from this picture. First, the three lines labeled "Third Entry Wave" plot the timing of the third generation entry wave as well as it's effect on the total number of firms in the industry. Probably the most surprising result is the extent of the third generation entry in the case of $\bar{L} = 0$ where 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 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 third generation entry. A value of $\bar{L} = .01$ already reduces the number of third wave high tech entrants by more than two thirds and a value of .026 cuts off that entry wave completely (as a basis of comparison $F_0 = 100$ in the benchmark model. These results underline how little leeway is for a third 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 incumbent and leapfrogging entry and on the adoption pattern by incumbents. The three lines labeled "Incumbent Entry"' (and "Leapfrogging Entry") denotes the timing and number of firms entering as incumbents (and leapfroggers) while the lines labeled "Incumbent Adoption" plots the timing of adoption by incumbent firms for our three different values of $\bar{L}$. As can be seen, the three different lines are practically indistinguishable. This reinforces the fact that different values of $\bar{L}$ have little impact on the items of interest for this paper: incumbent and leapfrogging entry.

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