Quantifying the Lock-in Effect in a Dynamic Industry

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Abstract

Several of the new product in high-tech industries have been introduced by entering firms, even though most of the technology used to produce these new products was developed by incumbent firms. This suggests that even though incumbent firms may have an advantage in developing new technology, the opportunity cost of switching from producing an old product to a new product is high enough to prevent the switch. Jovanovic and Nyarko (1996) suggest that one reason why leaders may tend to be slow to adopt new technologies: an opportunity cost of switching. This paper will extend the Jovanovic and Nyarko model to include multiple agents in a dynamic setting where agents can invest in learning. By structurally estimating this model using data from the hard drive industry, the lock-in effect of old technology can be quantified and its importance can be determined.

1 Introduction

Several of the new products in high-tech industries have been introduced by entering firms. In fact, most of these technologies used to produce the new product were developed by incumbent firms. In the hard drive industry, new diameters in the period 1977-1997 were first brought to the market by spin-outs, firms whose founders were formerly employed at one of the incumbent firms within the industry (see Franco and Filson (1999), and Christensen (1993)). This suggests that even though incumbent firms may have an advantage in developing new products and the technology used to produce these new products, the opportunity cost of switching from producing an old product to a new product is high enough to prevent the switch. As suggested in Irwin and Klenow (1994), the mechanism by which spillovers occur must first be identified and understood in order to make clear policy conclusions. In this case, there is evidence that employee mobility is important for sustainable growth.

Jovanovic and Nyarko (1996) suggest one reason why leaders may tend to be slow to adopt new technologies: an opportunity cost of switching. In their model, an agent improves his knowledge of a technology by using it to produce output. The improvements in the agent's knowledge correspond to efficiencies in production. Each technology has bounded productivity, so in order to continue production growth, the agent must continually switch to newer technologies. However, there is a cost to switching. An agent who switches to a new technology will not be as effective in operating it as in operating the old technology. Since the switch is costly because of a loss of expertise, an agent may choose to forestall switching technologies.

This paper will extend the Jovanovic and Nyarko model to include multiple agents in a dynamic competitive industry setting where agents can invest in learning. Though this is similar to Franco (1999) where the main focus was incremental change in technology, this model will include radical change as well. Christensen (1997) discusses the some of the differences in the effects of incremental changes and radical changes in the hard drive industry. He views the radical changes as producing significantly more important changes in the distribution of the firms within the industry. This paper will help to document these effects and quantify their magnitudes.

In the model, agents who operate firms will optimize over the choice of technology to produce and investment research. Each technology is used to produce a different product. Firms can hire researchers to improve their knowledge of the currently used technology and develop new technologies. Research is unfocused, so firms can not preclude researchers from developing new technologies and force them to focus on improving the current technology. Once learning has occurred, firms must decide whether or not to continue operating and if they do, whether or not to use the new technology or continue using the old technology. Researchers can with some probability imitate their employer's current technology or learn a new technology, depending on their employer's research outcomes. These agents will then decide whether or not to operate a firm using this technology or work as a researcher or an production worker in the following period. The knowledge of an agent who works as a production worker will remain unchanged. There are no adjustment costs from switching to a new technology.. The main reason that a firm would rather continue using an older technology is that its productivity is higher.

The evolution of the technologies and knowledge of the industry will evolve given the optimal choices by agents and can be completely characterized given initial conditions. Using data from the hard drive industry that includes product features, prices, quantities shipped, and firm genealogy, I will structurally estimate this model to test whether the issues posed in Jovanovic and Nyarko are quantitatively important as well as being qualitatively important. This will help to increase our understanding of why leaders may be unwilling to adopt new technologies and may have policy implications.

1.1 The Model

The model is set in a discrete time, infinite horizon environment. There is a continuum of *ex ante* homogeneous, infinitely lived agents in the industry. There are I products that can be produced by this industry. Each of these products can be produced by using a distinct technology associated with the product. Developing a new technology is the same as developing a new product and is viewed as a radical improvement. Supply is affected only by firms developing new technologies, which creates a new product, and increasing their own knowledge over a given technology, which lowers production costs. Improving in knowledge about a particular technology are considered to be incremental improvements. The demand for a product is given by $D(Q_n, Q_{-n})$, an inverse industry demand function, where Q_n is the quantity of product n produced at time t and Q_{-n} is vector of the quantities of all other products produced by this industry. This specification is flexible enough to allow products to be substitutes or compliments. D is downward sloping Q_n and continuous in both Q_n and Q_{-n}. There are no demand shocks, for ease of analysis.[1] The agents' discount factor is constant over time.

The timing of the model is as follows. At date t, agents know the distribution of the technology and know-how pairs across the industry. This is given by $\nu_t(I, \Theta)$ where the distribution of know-how over a particular technology n is ν_n. Technological know-how is indexed by θ which is an element of the set $\Theta = [\theta_L, \theta_H]$. Given this, agents decide whether to work as production workers, or researchers or operate a firm. Agents who work as production workers receive a wage, $W^{\mathbf{0}}$, and their technology and know-how pairs are unchanged from the previous period. Agents who work as researchers for firms within the industry receive a wage that depends, in equilibrium, on the firm's technology and know-how pair and how many researchers the firm employed. This is due to the fact that researchers can, with probability λ, learn their employer's current technology and know-how pair and, with some probability determined by how many researchers the firm hires, learn a new technology that was developed by the firm. In equilibrium, it is assumed that an agent will only work for firms that have either higher know-how about the same technology as the agent possessed or knowledge about a different technology, as yet unknown to the agent. Researchers can become entrepreneurs by leaving the firm without affecting the firm's viability: firms can produce output without researchers. Firms can only produce one product at a time. Agents who run firms must maximize profits given a cost function and innovation costs which are the cost of hiring researchers.

First, consider the case of an agent who chooses to work as a production worker. This agent receives a fixed wage given by $W^{\mathbf{0}}$. It is assumed that the outside option is fixed by the rest of the economy. The human capital of such an agent remains unchanged. In equilibrium, it can be shown, as in Franco and Filson (1999) that any agent who chose to work outside in the previous period will not operate a firm in the current period.

The other option is to work as a researcher. In equilibrium, a researcher's wage depends only on her employer's current technology and knowledge pair and her employer's learning expenditure. This is because her expected future value is a convex function of her employer's current technology and knowledge pair, which she may learn with probability λ, and the expected possibility of her employer learning a new technology which is dependent on how much learning effort is expended. Her wage also depends on the current distribution of knowledge within the

[1] This model can be incorporated into a general equilibrium model, as in Mitchell (1998), where the demand for the industry's good is unaffected by income and the wages paid outside the industry are constant.

industry. This helps to focus attention on the wage differentials between different firms instead of a matching problem that would arise. The results would not change significantly if researchers' output was dependent on their level of know-how and technology. A researcher who works for a firm with a higher θ will receive a higher payoff from having imitated its θ than a researcher who works for a firm with a lower θ and imitated her employer's θ. This difference is accounted for in the different wages. We can also compare wages across firms using different technologies.

The firm's choice variables are given by the vector (q, l), where q is the quantity produced and l is the innovative effort, given by the measure of researchers hired in each period. The firm's net revenue is given by

$$p(n, \nu)q - c(q, \theta, n) - lw(\theta, n, l, \nu)$$

The price of the good produced by the industry, in equilibrium, is determined by the distribution of knowledge in the industry since the industry is perfectly competitive and the good is homogeneous across all firms. The cost function satisfies standard conditions given by

$$c\left(0, n, \theta\right) = 0$$

$$\frac{dc(0,n,\theta)}{dq} = 0$$

$$\frac{dc(q,n,\theta)}{dq} > 0$$

$$\lim_{q\rightarrow\infty} c'\left(q, n, \theta\right) = \infty, \ \forall\theta \in \Theta$$

$$\frac{dc(q,n,\theta)}{d\theta} < 0$$

$$c\left(q, n, \theta\right) > c\left(q, n+1, \theta\right), \ \forall n$$

Note that the costs are decomposed into the cost associated with production of the good and that associated with innovation.

The transition function of the firm's knowledge and technology is given by a cumulative distribution function $\Psi(\theta', n'|\theta, n, l)$ that measures the probability of obtaining future know-how θ' about technology n' given current know-how θ about technology n and labor l. Note that it is not dependent on the cross distribution of agents, ν, since the firm's subsequent know-how is dependent on the firm's innovative effort, which is represented by how many researchers it hires or l, and its current knowledge, and not on the state of the industry. The properties of Ψ are

(i) Innovation is not guaranteed. $(\Psi(\theta, n|\theta, n, l) > 0)$
(ii) Innovation is costly. $(\Psi(\theta, n|\theta, n, 0) = 1)$

(iii) There is no forgetting. ($\Psi(\theta', n' | \theta, n, l) = 0$ if $\theta' < \theta$ or $n' < n$.)

(iv) Increasing effort and know-how improves prospects. (If $\widehat{\theta} \geq \theta$ and $\widehat{l} \geq l$, then $\Psi(\theta', n' | \widehat{\theta}, n, \widehat{l})$ first order stochastically dominates $\Psi(\theta', n' | \theta, n, l)$.)

(v) Learning is concave in researchers. (For any two learning expenditures, l_1 and l_2, and $a \in [0,1]$, $\Psi(\theta', n' | \theta, n, al_1 + (1-a)l_2)$ dominates $a\Psi(\theta', n' | \theta, n, l_1) + (1-\alpha)\Psi(\theta', n' | \theta, n, l_2)$ in the first order stochastic sense.)

(vi) New technologies are harder to acquire than improvements on older technologies. ($\int \Psi(\theta', m > n | \theta, n, l) < \int \Psi(\theta', n | \theta, n, l)$)

The first four assumptions are similar to those used in Jovanovic and MacDonald (1994), but the imitative possibilities are suppressed. This isolates the mechanism through which imitation occurs: imitation occurs only through researchers who work for firms in the industry. Assumption (v) helps to guarantee that firms with the same know-how about a given technology will choose to expend the same effort given the same distribution of know-how, instead of randomizing between different levels of effort.

So, imitation between existing firms is not allowed in this model. This is done to isolate the imitative effects: imitation occurs only through researchers who work within the industry. Firms can only learn by innovative effort through hiring researchers. Recall that researchers supply a homogeneous product to the firms. Any increase in the technology and know-how pair is based on the firm's innovative effort, its previous technology and know-how pair and the stochastic innovative shock.

Before the complete agent's problem is presented, the law of motion for the distribution of knowledge is presented and the timing of the model is made clear.

1.1.1 The Law of Motion

The law of motion depends on the actions of the agents in the economy. Recall that the knowledge of the agents who work outside the industry is unchanged. So, the distribution will be unaffected by their actions. In the case of agents who work as researchers within the industry, the distribution will be unaffected by $1 - \lambda - \int d\Psi(\theta', n' > n | l, \theta, n)$ of them, who fail to learn their employers' technology and knowledge pair, while λ of these agents will learn this pair and effect the next period's distribution and $\int d\Psi(\theta', n' > n | l, \theta, n)$ of these agents will learn a completely new technology n'. Finally, the plant owners will effect the distribution given their choice of innovative effort.

The law of motion is written formally using the following three subsets. Which agents are members of the subsets is determined by their actions. Let ν_P be the measure of agents who become firm owners, ν_R, the measure of agents who work as researchers within the industry and ν_W, the measure of agents who work outside the industry. We can further partition by technology n used. Let ν_{nP} be the measure of firms using technology n. Without loss of generality, each firm is assumed to hire only one type of researcher. So, all researchers at a particular firm will have the same level of technology and know-how. In order to keep account of how many agents are hired by which firms and both the firms' and the agents' type, the function z is used. $z(l,(n,\theta_r),(m,\theta_f))$ is the measure of firms with (m,θ_f) that hire l units of researchers with (n,θ_r) and has the following characteristics:

$$\int_{L\times(I,\Theta)} z\left(dl \times d\left(n,\theta_r\right)\times\left(m,\theta_f\right)\right) = \nu_{mP}\left(\theta_f\right)$$

$$\int_{L\times(I,\Theta)} l\ z\left(dl \times \left(n,\theta_r\right)\times d\left(m,\theta_f\right)\right) = \nu_{nR}\left(\theta_r\right)$$

$$\int_{L\times(I,\Theta)\times(I,\Theta)} z\left(dl \times d\left(n,\theta_r\right)\times d\left(m,\theta_f\right)\right) = \nu_{P}\left(\Theta\right)$$

$$\int_{L\times(I,\Theta)\times(I,\Theta)} l\ z\left(dl \times d\left(n,\theta_r\right)\times d\left(m,\theta_f\right)\right) = \nu_{R}\left(\Theta\right)$$

Note that $\nu(n,\theta)$ is the fraction of agents with the pair (n,θ). So, $\nu_{nP}(\theta_f)$ is the measure of plant owners with (n,θ_f) and $\nu_{nR}(\theta_r)$ is the measure of researchers with (n,θ_r). Recall that Θ is the set $[\theta_L,\theta_H]$ and I is the set of all possible technologies.

For any set $A\subset\Theta$,

$$\Phi(\nu_n)(A) = \nu_{nW}\left(A\right)$$

$$+(1-\lambda-\textstyle\int d\Psi\left(\theta',m'>m\left|l,\theta,m\geq n\right.\right))$$

$$\left(\int_{L\times(n,A)\times[(m\geq n,\Theta)]} l\ z\left(dl\times d\left(n,\theta_r\right)\times d\left(m,\theta_f\right)\right)\right)$$

$$+\lambda\int_{L\times(m\leq n,A)\times[(n,\Theta)]} lz\left(dl\times d\left(m,\theta_r\right)\times d\left(n,\theta_f\right)\right)$$

$$+\textstyle\int d\Psi\left(A,n\left|l,\theta,m\leq n\right.\right) l\nu_{mP}\left(\theta_f\right)$$

$$+\textstyle\int \Psi\left(A,n\left|l,\theta,n\right.\right) d\nu_{nP}\left(\Theta\right)$$

$$+\left\{\textstyle\int \Psi\left(A,n\left|l,\theta,m<n\right.\right) d\nu_{m<nP}\left(\Theta\right),\ \text{for}\ \forall\ V\left(A,n,\Phi\right)>V\left(\theta_f,m,\Phi\right)\right\}$$

The first branch represents the measure of agents who worked outside the industry and whose know-how was an element of the set A. Recall that the knowledge of these agents is unchanged. The second branch simply represents those agents who worked as researchers at firms and failed to learn their employer's technology and had technology n and knowledge that was an element of set A. The third branch is the measure of agents who worked as researchers for firms with technology n and knowledge in the set A who learned their employer's technology and knowledge pair. The fourth branch is the measure of agents who were researchers for firms with technology that was lower than n and developed a new technology n. The penultimate branch is those firms with technology n who knowledge about that technology was in the set A at the end of the period. This could be a result of either innovative effort or because their knowledge remained unchanged. The final branch is the measure of those incorporated agents whose technology was less than n and who innovated and developed technology n and knowledge that was within the set A.

1.2 The Agent's Complete Problem

The agent's value function, then, is given by a solution to the functional equation:

$$V(\theta, n, \nu) =$$
$$\max \left\{ \begin{array}{c} W^0 + V(\theta, n, \nu), \\ \max \left[\begin{array}{c} w(\theta_f, m, l) \\ +\beta \left(\begin{array}{c} \lambda V(\theta_f, m, \Phi(\nu)) \\ + \int V(\theta', m', \Phi(\nu)) \, d\Psi(\theta', m' > m | \theta_f, m, l) \\ + \left(1 - \lambda - \int d\Psi(\theta', m' > m \,| l, \theta_f, m)\right) V(\theta, n, \Phi(\nu)) \end{array} \right) \end{array} \right], \\ \max_{(q,l)} \left[\begin{array}{c} p(n, \nu) q - c(q, \theta, n) - lw(\theta, n, l) \\ +\beta \left(\begin{array}{c} \int V(\theta', n, \Phi(\nu)) \, d\Psi(\theta', n | \theta, n, l) \\ + \left(1 - \int d\Psi(\theta', n \,| l, \theta, n)\right) \\ \max \left(\begin{array}{c} V(\theta, n, \Phi(\nu)), \\ V(\theta', n', \Phi(\nu)) \, d\Psi(\theta', n' > n | \theta, n, l) \end{array} \right) \end{array} \right) \end{array} \right] \end{array} \right\} \quad (1)$$

where β is the discount factor and $V(\theta, \nu)$ is the value function. The first branch considers the lifetime income of taking a job outside the industry. Note that in this case the agent's knowledge doesn't change in the following period. The second is the return to choosing to become a researcher in the industry. In this case, the agent's future technology and knowledge pair becomes either the same as her employer with probability λ, or she learns a new technology if the firm develops one. Otherwise, her technology and knowledge pair remains unchanged. The last part defines the return for becoming an incorporated agent. Here the agent's future technology and knowledge pair, θ', is determined by the transition function Ψ.

1.3 Equilibrium

In Franco and Filson (1999), a model was developed and its implications were compared with data from the hard drive industry. It was shown that the model developed there was well-suited to fit the data and provided reasonable explanations for some of the unexplained facts about the hard drive industry. The above model builds on that one in several ways. As in Franco and Filson, agents must learn how to increase their productivity. Further, the productivity of the industry improves over time as agents learn. The main difference is that here agents must chose between different technologies and associated productivities. This difference is captured in the law of motion, which is used in the definition of equilibrium given below.

Definition 1 *An industry equilibrium is given by a sequence of prices,* $\{p_{nt}(\nu)\}_{t=0}^{\infty}$, *wages,* $\{w_t(\theta, n, l)\}_{t=0}^{\infty}$, *actions,* $\{q_t, l_t, \nu_{nWt}, \nu_{nRt}, \nu_{nPt}, z_t\}_{t=0}^{\infty}$, *and a distribution,* $\{\nu_t\}_{t=0}^{\infty}$ *such that for each n:*

1. $p(n, \nu) = D[\int q(n, \theta, \nu) d\nu_n, \int q(i \neq n, \theta, \nu) d\nu_{i \neq n}]$
2. The distribution ν_{nt} is consistent with optimization for all t
3. $z_n(n, \theta, l)$ is described by the maximizers defined by equation (1)
4. $\int l \, dz_n = \nu_{nR}$
5. $\int dz_n = \nu_{nP}$

In equilibrium, agents optimize. The price of the products produced by the industry is set equal to the inverse industry demand given the distribution of know-how. The next period's distribution of know-how and technology in the continuum is determined by which firms in the industry innovated in the current period in addition to which researchers imitated their employers knowledge and/or technology, given that these agents are acting optimally. Supply of labor for a particular firm is set equal to labor demanded by the wage and the supply of firms is equal to the demand for firms.

This equilibrium is a special case of the one presented in Jovanovic and Rosenthal (1988). Since there is no aggregate uncertainty and the sufficient conditions for such equilibrium to exist are satisfied, this equilibrium exists.

2 Wage Structure, Evolution of Knowledge and Prices

First, consider the wages paid to an agent who works as a researcher. This agent faces a trade-off between wages and future value of knowledge. This trade-off is discussed in the following proposition.

Proposition 2 *For any two firms i and j, using the same technology, n, with know-how θ_i and θ_j, respectively, which hire $l > 0$ of researchers with the same level of technology and know-how, (m, θ_r), such that either $m < n$ or if $m = n$, $\theta_i \geq \theta_r$ and $\theta_j \geq \theta_r$.*

$$w(\theta_r, m, \theta_i, n, l) + \beta \left(\lambda V(\theta_i, n, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n|\theta_i, n, l\right)\right)$$

$$= w(\theta_r, m, \theta_j, n, l) + \beta \left(\lambda V(\theta_j, n, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n|\theta_j, n, l\right)\right)$$

Proof. Recall all researchers produce a homogeneous product, innovative effort. Consider a researcher p with knowledge θ_p of m technology, working at an arbitrary firm i with technology and know-how (n, θ_i), where either $m < n$ or if $m = n$, $\theta_i \geq \theta_p$. The worker's return for working at firm i is given by

$$w\left(\theta_p, m, \theta_i, n, l\right) + \beta \begin{bmatrix} \lambda V(\theta_i, n, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n|\theta_i, n, l\right) \\ +(1 - \lambda - \int d\Psi\left(\theta', n' > n\left|l, \theta_i, n\right.\right))V(\theta_p, m, \Phi(\nu)) \end{bmatrix}$$

In order for worker p to be weakly indifferent between working for firm i, and any arbitrary firm j in the industry with technology and know-how (n, θ_j), the following must hold.

$$w\left(\theta_p, m, \theta_i, n, l\right) + \beta \begin{bmatrix} \lambda V(\theta_i, n, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n|\theta_i, n, l\right) \\ +(1 - \lambda - \int d\Psi\left(\theta', n' > n\left|l, \theta_i, n\right.\right))V(\theta_p, m, \Phi(\nu)) \end{bmatrix} \geq$$

$$w(\theta_p, m, \theta_j, n, l) + \beta \begin{bmatrix} \lambda V(\theta_j, n, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n|\theta_j, n, l\right) \\ +(1 - \lambda - \int d\Psi\left(\theta', n' > n\left|l, \theta_j, n\right.\right))V(\theta_p, m, \Phi(\nu)) \end{bmatrix} \forall j \neq i$$

This simplifies to

$$w\left(\theta_p, m, \theta_i, n, l\right) + \beta\left[\lambda V(\theta_i, n, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n|\theta_i, n, l\right)\right] \geq$$

$$w(\theta_p, m, \theta_j, n, l) + \beta\left[\lambda V(\theta_j, n, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n|\theta_j, n, l\right)\right]$$

Next, consider the case of a researcher q, working at an arbitrary firm j with (θ_j, n) where $\theta_j \geq \theta_q$ if $n = m$. Like researcher p, the following condition must be satisfied for him to be weakly indifferent between working at that firm j and an arbitrary firm i with (θ_i, n).

$$w\left(\theta_q, m, \theta_j, n, l\right) + \beta\begin{bmatrix}\lambda V(\theta_j, n, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n|\theta_i, n, l\right) \\ \\ +(1 - \lambda - \int d\Psi\left(\theta', n' > n\left|l, \theta_j, n\right.\right))V(\theta_q, m, \Phi(\nu))\end{bmatrix} \geq$$

$$w(\theta_q, m, \theta_i, n, l) + \beta\begin{bmatrix}\lambda V(\theta_i, n, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n|\theta_i, n, l\right) \\ \\ +(1 - \lambda - \int d\Psi\left(\theta', n' > n\left|l, \theta_i, n\right.\right))V(\theta_q, m, \Phi(\nu))\end{bmatrix} \forall i \neq j$$

Again, this simplifies to

$$w\left(\theta_q, m, \theta_j, n, l\right) + \beta\left[\lambda V(\theta_j, n, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n|\theta_j, n, l\right)\right] \geq$$

$$w(\theta_q, m, \theta_i, n, l) + \beta\left[\lambda V(\theta_i, n, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n|\theta_i, n, l\right)\right]$$

Recall that by assumption, both of these researchers have the same knowledge. By replacing θ_p and θ_q with θ_r, these two conditions imply Proposition 1, since both i and j are arbitrary.□ ■

This proposition shows that agents who work for a firm with a more know-how about a given technology will accept a lower wage. This is a result of the fact that imitation is site specific. Both the researchers and the firms know that only the researchers will be able to imitate either the current know-how and technology pair used by the employer or its new technology. Next, we can describe the wage differentials paid by firms using different technologies. Here, the agents who work as researchers determine the trade-off between the possibility of imitating a more productive technology or imitating a newly developed technology.

Proposition 3 ***Corollary 4*** *For any two firms i and j, with (θ_f, n_i) and (θ_f, n_j), respectively, where $n_i > n_j$ which hire $l > 0$ the same type of researchers with knowledge θ_r about technology n, such that either*

$n_j > n,\ or\ \theta_f > \theta_r,$

$$w\left(\theta_r, n, \theta_f, n_i, l\right) + \beta \begin{bmatrix} \lambda V(\theta_f, n_i, \Phi(\nu)) \\ + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n | \theta_f, n_i, l\right) \end{bmatrix}$$

$$= w\left(\theta_r, n, \theta_f, n_j, l\right) + \beta \begin{bmatrix} \lambda V(\theta_f, n_j, \Phi(\nu)) \\ + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n | \theta_f, n_j, l\right) \end{bmatrix}$$

Proof. The proof follows from the above proposition. First, we consider a researcher p with technology and know-how (θ_p, n), working at an arbitrary firm i with technology and know-how (θ_i, n_i), where either $n_i > n$, or $\theta_f > \theta_p$. The worker's return for working at firm i is given by

$$w\left(\theta_p, n, \theta_f, n_i, l\right) + \beta \begin{bmatrix} \lambda V(\theta_f, n_i, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n_i | \theta_f, n, l\right) \\ + (1 - \lambda - \int d\Psi\left(\theta', n' > n \left| l, \theta_f, n_i\right.\right)) V(\theta_p, n, \Phi(\nu)) \end{bmatrix}$$

In order for worker p to be weakly indifferent between working for firm i, and any arbitrary firm j in the industry with technology and know-how (n_j, θ_j), the following must hold.

$$w\left(\theta_p, n, \theta_f, n_i, l\right) + \beta\left[\lambda V(\theta_f, n_i, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n_i | \theta_f, n_i, l\right)\right] \geq$$

$$w(\theta_p, n, \theta_j, n_j, l) + \beta\left[\lambda V(\theta_j, n_j, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n_j | \theta_j, n_j, l\right)\right]$$

Next, consider the case of a researcher q, working at an arbitrary firm j with (θ_f, n_j) where either $\theta_f > \theta_q$, or $n_j > n$ and $n_i > n_j$. Like researcher p, the following condition must be satisfied for him to be weakly indifferent between working at that firm j and an arbitrary firm i with (θ_f, n_i).

$$w\left(\theta_q, n, \theta_f, n_j, l\right) + \beta \begin{bmatrix} \lambda V(\theta_f, n_j, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n_j | \theta_j, n, l\right) \\ + (1 - \lambda - \int d\Psi\left(\theta', n' > n \left| l, \theta_j, n_j\right.\right)) V(\theta_q, n, \Phi(\nu)) \end{bmatrix} \geq$$

$$w(\theta_q, n, \theta_f, n_i, l) + \beta \begin{bmatrix} \lambda V(\theta_f, n_i, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n_i | \theta_f, n_i, l\right) \\ + (1 - \lambda - \int d\Psi\left(\theta', n' > n_i \left| l, \theta_f, n_i\right.\right)) V(\theta_q, n, \Phi(\nu)) \end{bmatrix} \forall i \neq j$$

Again, this simplifies to

$$w\left(\theta_q, m, \theta_j, n, l\right) + \beta\left[\lambda V(\theta_j, n, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n | \theta_j, n, l\right)\right] \geq$$

$$w(\theta_q, m, \theta_i, n, l) + \beta\left[\lambda V(\theta_i, n, \Phi(\nu)) + \int V\left(\theta', n', \Phi\left(\nu\right)\right) d\Psi\left(\theta', n' > n | \theta_i, n, l\right)\right]$$

Recall that by assumption, both of these researchers have the same knowledge. By replacing θ_p and θ_q with θ_r, these two conditions imply Proposition 1, since both i and j are arbitrary.$\square$ $\blacksquare$

Here, the main difference is that the firms are using different technologies. Instead of the trade-off in wage paid by two firms with different know-how about the same technology, the agent faces a trade-off in wages by working as a researcher for a firm with a higher level of technology than another firm. The wages paid by a firm with a higher level of technology are lower than that paid by a firm with the lower technology. The structure of the wages paid by firms using one technology is highly structured. This is described in the following lemma.

Lemma 5 *The wage paid by any firm with technology n is non-decreasing in θ_f.*

Because the cost function is decreasing in θ, regardless of the level of technology used, the following is obvious.

Lemma 6 *The value function is non-decreasing in θ.*

Next, we can consider the evolution of the technologies used in the industry. Here, as technologies are developed, agents must choose to either use them in the future or continue using the older technology which is more productive. Firms who develop new technologies will face a trade-off between higher productivity with older technologies and lower productivity with newer technologies. Some will find that "sticking" with the older technologies is more profitable, but will, over time,. have to become either more productive with the older technology or develop an even newer technology.

Proposition 7 *Given ν_0, the equilibrium sequence, $\{\nu_t\}$, converges to a distribution, ν^*.*

Proof. There exists a monotone sequence of distribution functions underlying $\{\nu_t\}$ called F_t with the following property for some $(\theta_L, 1)$ and (θ_H, I)

$$F_t(\theta_L, 1) = 0 \text{ and } F_t(\theta_H, I) = 1, \text{ for } t = 1, 2, ..., \text{ and}$$

By Corollary 2 to Theorem 12.9, (Helly's Theorem) in Stokey, Lucas, Prescott (1989), there exists a distribution function F with

$$F(\theta_L, 1) = 0 \text{ and } F(\theta_H, I) = 1$$

and $\{F_t\}$ converges weakly to F.$\square$ $\blacksquare$

Proposition 2 introduces a distribution, ν^*, under which no learning occurs. Once ν^* is reached, no firms have any incentives to invest in innovation, since its costs outweighs the returns. This distribution, ν^*, depends on the initial distribution.

3 Data

New diameters were introduced in 1979, 1980, 1983, 1988 and 1991. The first was an 8" diameter which was introduced by International Memories, a spin-out of Memorex. International Memories was founded in 1977 and exited the hard drive industry in 1985. The second new diameter was a 5.25" which was introduced by Seagate, which was founded in 1979 and remained active in 1997. Seagate was spin-out of Shugart Associates. In 1983, Control Data introduced a 3.5" diameter. Control Data is the only firm to have introduced a new diameter in this period that was not a spin-out. The 2.5" diameter was introduced by PriarieTek, which was a spin-out of Miniscribe and was in the hard drive industry from 1986 to 1991. The last diameter introduced in this period was introduced by Integral Peripherals which was a spin-out of PriarieTek. It was founded in 1990 and remained active in 1997. Given this history, the periods of particular interest are 1978-1980, 1979-1981, 1987-1989, and 1990-1992, since the diameter introduced in 1983 was not introduced by a spin-out. However, it would be interesting to use that period to help determine why an incumbent firm was able to introduce a new diameter.

The main data source for the product features and firm genealogy is the *Disk/Trend Report* on Rigid Disk Drives (Porter (1977-1997)). The reports cover the period 1977-1997, and include detailed product characteristics of the drives produced by different firms each year, the dates that the drives were introduced, and the date the firm was founded. For new firms, information about the background of the founders is provided. For all firms, historical information and recent news is summarized. To determine spin-out-parent relationships, the histories from the *Disk/Trend Report* were supplemented with company press releases and articles provided by James Porter, the editor of the *Disk/Trend Report,* along with the *Directory of Corporate Affiliations,* the *International Directory of Company Histories,* and a study by Christensen (1993). The other data needed is information on product prices and quantities sold for the particular years of interest. The price and quantity data is not available for the earlier years, but is available more consisently for the last two periods. This is available from International Data Corporation.

By structurally estimating this model, we can estimate the standard errors of interest. In particular, we can consider if the two diameters of hard drives were complements or substitutes. This may have some bearing on the lock-in effect. It could be the case that if the goods are complements, the lock-in effect is stronger than if they are substitutes. One advantage of this model is that the competitive equilibrium is pareto optimal. This allows us to use the Planner's problem, which will minimize the computation time.

4 Summary

The research described here proposes to study and quantify the lock-in effect experienced by firms in high-tech industries, and in particular, the hard drive industry. There is strong evidence that there is a lock-in effect, since most of the new products have been introduced by entering firms even though these products were developed by incumbent firms. There is also strong evidence that a competitive firms model is appropriate, as a result of the study in Franco and Filson (1999).

This model is builds on several of the results of Jovanovic and Nyarko (1996) which suggest one reason why leaders may tend to be slow to adopt new technologies: an opportunity cost of switching. Even though, there are incremental improvements in productivity for any given technology, these may be outweighed by the benefits of new technologies, in the long run. However, agents who switch to a new technology may not be as effective in operating it as in operating the old technology. Since the switch is costly because of this loss of expertise, an agent may choose to forestall switching technologies.

Here, the main focus is on radical changes in technology. Christensen (1997) discusses the some of the differences created by radical changes in technology in the hard drive industry. He suggests that these changes are significantly more important in understanding the dynamics of the hard drive industry. This paper will help to document these effects and their magnitudes.

The evolution of the technologies and knowledge of the industry will evolve given the optimal choices by agents and can be completely characterized given initial conditions. I will consider whether leaders in this model will be unwilling to adopt new technologies in order to avoid paying switching costs. Using data from the hard drive industry, I can parameterize this model to test whether the issues posed in Jovanovic and Nyarko are quantitatively important as well as being qualitatively important.