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Technology uncertainty, sunk costs, and industry shakeout

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I propose a novel explanation for new industry shakeouts: because of capacity sunk costs and the fear of backing the wrong technology, firms initially invest up to a small capacity, leading to a large number of initial entrants. As the dust settles and a dominant technology emerges, surviving firms expand to their long-term optimal capacity, which results in a reduction in the number of competitors notwithstanding the increase in total market output.

JEL classification: L11, L23, L25, M13.

1. Introduction

A common feature of the evolution of new industries is the occurrence of a shakeout: a significant decrease in the number of active firms that takes place during a phase of market expansion. Industry shakeouts have been documented for a variety of industries, from automobiles to computers (Gort and Klepper, 1982; Klepper and Graddy, 1990; Filson, 2002). While the theoretical explanation for industry shakeouts varies, most models have one element in common: at some point in the industry lifecycle, the best technology's marginal cost schedule decreases, that is, technology evolution calls for larger firm sizes. If the increase in firm size is greater than the rate of market expansion, then a shakeout must take place (Gort and Klepper, 1982; Hopenhayn, 1993; Jovanovic and MacDonald, 1994; Klepper, 1996; Klepper and Miller, 1996).[1]

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[1]A different stream of literature interprets shakeouts as overshooting in the entry process when there is limited coordination among potential entrants. Building on the work of Dixit and Shapiro (1986) and Cabral (1993), Klepper and Miller (1996) test the explanatory power of this approach, finding the empirical support to be mixed. On this approach, see also Vettas (2000).

I propose a complementary explanation for the drastic reduction in the number of active firms. My theory relies on the interaction of two well-documented stylized facts about industry evolution: technology uncertainty and investment sunk costs. Before introducing my theory in greater detail, I describe these stylized facts a little further.

The first stylized fact is that the early evolution of an industry is a time of great uncertainty that may be gradually or rapidly resolved. Initially, firms invest in creating different product variants; and as consumers experiment with the various offerings, a winner eventually emerges—a dominant design—at which point firms start focusing on how better to produce it (Utterback and Abernathy, 1975; Abernathy and Utterback, 1978; see also Mueller and Tilton, 1969, Tushman and Anderson, 1986). However, the resolution of uncertainty need not be limited to consumer preferences: often, multiple competing technologies battle for dominance until a *de facto* standard emerges (Dosi, 1982; Anderson and Tushman, 1990; Schilling, 1998).

The second stylized fact is that many of the firms' product and process investments are to some extent sunk (Lambson, 1991; Dixit and Pindyck, 1994; Cabral, 1995); that is, these investments lose value considerably if the firm decides to leave the industry (if, for example, it happens to back the wrong horse).

In this article, I put these two ideas together and show that they lead to a very natural theory of industry shakeout. The idea is that firms initially invest up to small capacity levels; and once uncertainty has been resolved, some of the firms leave the industry whereas the remaining ones expand their capacity to the optimal long-run level. Although market output is smaller in the initial phase of industry expansion, each firm's output is *much* smaller, which in turn implies that the number of firms is greater. This is the essence of an industry shakeout: whereas market output increases, the number of active firms decreases.

In other words, firms in my model play a "wait-and-see" strategy: since capacity costs are sunk, while there is uncertainty regarding the technological path the industry will take, firms prefer to invest at small capacity levels even though a large capacity is more efficient. Once technology uncertainty is resolved, firms switch to the efficient (large) capacity, which in turn triggers an industry shakeout.

Lest this seem a trivial point, I note (and below show formally) that this reasoning depends critically on investment cost sunkness: if investments were not sunk, then the resolution of technology uncertainty would simply lead firms to switch production technology from the "orphaned" ones to the winning technology design; no change in firm size would take place, and thus no change in the number of firms would take place either.

1.1 Related literature and contribution

My article is by no means the first attempt at explaining industry shakeouts. Gort and Klepper (1982) made a seminal contribution both by presenting systematic evidence from dozens of new industries as well as by developing a conceptual model capable of explaining industry shakeouts. To the best of my knowledge, Hopenhayn (1993) proposed the first mathematical, equilibrium models of industry shakeout; he also performed a series of numerical simulations. Additional models and empirical applications were developed by Jovanovic and MacDonald (1994), Klepper (1996), and Klepper and Miller (1996).[2]

In these models, output per firm increases over time because marginal cost decreases (possibly at the expense of higher fixed costs). In other words, an increase in economies of scale leads to an increase in firm size. If this shift in production technology is sufficiently significant with respect to the increase in total demand, then the number of firms decreases even as industry size increases. By contrast, in my model all production technologies are available at all times, including the more efficient ones.[3] However, because of the sunk nature of capacity cost and the uncertainty regarding technology paths, firms prefer to play a "wait-and-see" strategy, investing at low capacity levels until technology uncertainty is resolved. The resolution of technology uncertainty triggers the switch to mass production technologies, which in turn leads to an industry shakeout.

I see the effect of sunk costs as complementary to the effect of technology change described in the previous literature. An industry shakeout requires that either cost functions change (leading to lower marginal cost) or capacity costs are sunk. Or both. In fact, the reality of most industries probably reflects both theories. The relative contribution of each theory is then a matter of empirical research.[4]

The remainder of the article is structured as follows. In Section 2, I provide a brief account of the early stages of the US automobile industry, a helpful illustration of the industry shakeout phenomenon. In Section 3, I lay down my basic model of industry evolution. In Section 4, I present the main result, stating when and why an industry shakeout takes place, in particular the role of capacity sunk costs in producing such shakeout. Section 5 concludes the article.

[2]See also Dosi *et al.* (1997) and the papers in the same special issue for a broader perspective on industry dynamics, including the dynamics of new industries.

[3]I do assume that one of the technologies is "orphaned" and becomes economically impractical. In a way, this corresponds to a cost increase. However, this could simply correspond to an increase in fixed cost. In other words, my model and result, differently from the previous literature, is consistent with the assumption that marginal cost remains constant. I do not mean to imply a marginal cost constant over time is a realistic assumption; rather, I make this assumption so as to highlight that a shakeout may result from a combination of sunk costs and technology uncertainty.

[4]The literature on patent races—for example, Lee and Wilde (1980)—shares some of the features of my model, in particular the feature that Nature randomly chooses winners and losers (one in the case of a patent race, several in my case). However, the analogy between the two models does not extend beyond this aspect. In particular, a distinctive feature in my model is the option between different production capacity levels in the presence of sunk costs.

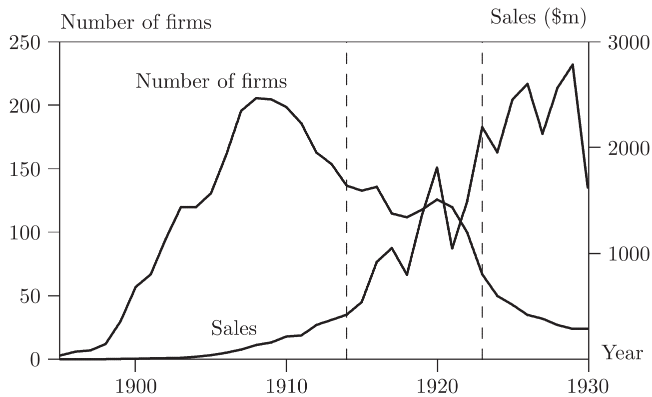

Figure 1 Evolution of the US automobile industry, 1895–1930. The dashed lines mark, chronologically, the laying out of the Ford Model T assembly line; and the introduction of the all-steel, closed-body automobile by Dodge.

2. The early US auto industry

The automobile industry provides an interesting illustration of the industry shakeout phenomenon. Figure 1 overlays the time path of sales in the US auto industry (right scale) with the time path of the number of automobile manufacturers (left scale).[5] The data clearly show an industry shakeout: the number of active firms peaked at 206 in 1908, dropping to 126 in 1920 (a "local peak"), then further dropping to 24 in 1930. By 1942, when the war effort put a hold on US auto production, there were eight active firms.

Equally interesting, Figure 1 shows that, notwithstanding some fluctuations, total output increased throughout the period in question. In other words, the decrease in the number of producers was not accompanied by a decrease in total output. Or, to put it differently, the increase in firm output more than compensated for the decline in the number of firms.[6]

From a technology point of view, the first two decades of the 20th century were a period of very rapid development.[7] By 1900, three different engine technologies vied for dominance: steam, electric, and internal combustion (mostly with gasoline as

[5]See Cabral and Wang (2009) for notes on the data.

[6]The very last drop in total output (1930) marks the beginning of a more sustained downward movement corresponding to the great depression.

[7]"It is estimated that over 100,000 patents created the modern automobile," writes Mary Bellis in about.com (accessed October 2010).

fuel).[8] Electric engines still had an edge by 1900, but soon after that lost the "race" to steam and gasoline; and although for a while the steam engine performed better than the gasoline engine (e.g., in terms of maximum speed), from 1900 to 1920 gasoline cars gradually took over the market, to the point that by 1920 the steam car "was an anachronism."[9]

There was also considerable evolution in automobile production technology. A critical point was the installation of assembly lines in the Ford plants manufacturing the Model T. The Model T had been introduced in 1908 with considerable success. However, the 1914 shift in production capacity led to a considerable increase in sales: by 1927, 15 million Model Ts had been manufactured. It is worth noting that assembly lines and mass production were not brought to the auto industry by Ford but rather by Olds (the Curved Dash Oldsmobile), as early as 1901.

Many other product and process innovations took place during this period. Of particular note is the shift from wood to steel in the production of car bodies. Although steel had been used for a long time, the first all-steel, closed body automobile was introduced by Dodge in 1923. Utterback (1994) points to this event as the emergence of a new dominant design ("by 1925, fully half of US auto production was all-steel, closed, body cars") that led to the second shakeout observed during the 1920s.

In sum, the automobile industry possesses all of the features described in the previous section: a new industry with considerable technology uncertainty (both with respect to the product and the production process); and a shift from low-scale to large-scale production as uncertainty was resolved. This in turn led to an industry shakeout (or possibly two industry shakeouts) of considerable magnitude, notwithstanding the relatively constant increase in industry demand.

I next present a model that is consistent with these observations. The basic model is laid out in Section 3, whereas Section 4 shows that sunk costs in technology investment play a crucial role in the occurrence of shakeouts.

3. A model of industry evolution

Consider a competitive industry in discrete time ($t = 1, 2, \ldots$). In each period, there is a demand $D(p)$ for the industry's homogeneous product. By assuming product homogeneity, I am ignoring all technology uncertainty related to product design, focusing instead on technology uncertainty. However, as I will argue later, the thrust of my argument is valid in both cases. In addition to product homogeneity, I also

[8]The first self-powered road vehicle, attributed to N. Cugnot in 1769, was powered by a steam engine. Although there is some historical debate, the world's first practical automobile powered by an internal-combustion engine is commonly attributed to K. Benz in 1885.

[9]See http://en.wikipedia.org/wiki/Steam_car (accessed October 2010).

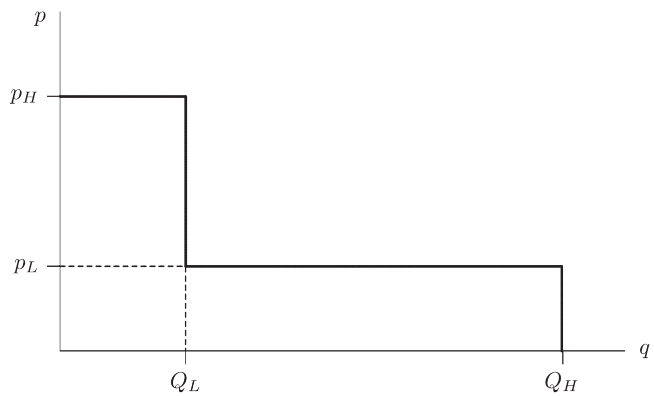

Figure 2 Demand function.

assume that firms are of atomic size with respect to market demand, and thus price takers.[10]

I assume market demand, illustrated in Figure 2, has the following properties: if $p \leq p_L$, then demand is given by Q_H; if $p_L < p \leq p_H$, then demand is given by $Q_L < Q_H$; and if $p > p_H$ then demand is zero. This stylized representation of demand encapsulates the idea that there are two distinct market segments: enthusiasts, who are willing to pay up to a high amount (p_H); and the mass market, where consumers are only willing to pay up to p_L. In the rest of the article, I will assume that p_H is sufficiently high that equilibrium price always falls below it.

Regarding supply, each firm must choose one of four possible combinations of technology path and production capacity, as shown in the following table.

	Production capacity	
	Low scale	High scale
Technology path *A*	*A*, *L*	*A*, *H*
Technology path *B*	*B*, *L*	*B*, *H*

Specifically, each firm much choose between following technology path *A* or technology path *B*. Using the automobile industry as an example, one may think of *A* as

[10]Technical note: below I assume that portions of the demand curve are vertical. This may conflict with my assumption that firms are price takers: even an infinitesimal change in one of the firm's output level should imply a discontinuous change in equilibrium price. However, by assuming a downward sloping demand curve that is arbitrarily close to vertical we can effectively obtain the same results consistently with the assumption of price-taking behavior.

corresponding to the steam engine and B to the gasoline engine. At the outset, both paths look equally promising: capacity costs are the same and so is the likelihood that the technology will succeed. At $t=2$, however, one of the technology paths hits a dead end and is "orphaned." What I have in mind is the situation whereby, as the alternative technology is shown to be superior, complementary resources move toward this technology so that the "orphaned" technology becomes economically impracticable. Economic impracticability notwithstanding, I assume orphaned technology capacity is worth ϕ per unit, as some of the production capacity can be adapted to the alternative technology. Specifically, I will assume that $\phi=0$ and later show that if I perturb the model by making $\phi>0$ but small then the result remains valid. Given these assumptions, it follows that firms that opted for an orphaned technology must either exit or switch technologies.

In addition to choosing a technology path, firms must also choose a production capacity. I assume there are two alternative production capacity choices, L and H. I will also refer to these as the niche and the mass-market production capacities, respectively. Continuing with the automobile industry analogy, we may think of production capacity H as the assembly line-type organization pioneered by Oldsmobile and perfected by Ford, whereas production capacity L corresponds to the lower-scale organization so typical of early entrants. Numerically, I assume that for a setup cost of c_i a firm is able to produce at zero additional cost up to a capacity k_i, where $i=L$, H and $c_L<c_H$ and $k_L<k_H$. In other words, production capacity H (the mass-market one) requires a higher setup cost, c_H, but enables the firm to produce up to a higher capacity, k_H. Notice that, by assumption, the marginal cost is the same under both production capacities. I make this assumption so as to differentiate my results from previous results: in my model, a shakeout is not due to a reduction in marginal cost as highlighted in the previous literature.

An important distinction between production capacities L and H is that setting up k_H (mass production) requires the firm to pay c_H as a *sunk cost*, whereas operating at the k_L level allows the firm to pay the rental cost $(1-\delta)c_L$ in each period. The thrust of my argument is that, if technology investment is not a sunk cost, then firms opt for a mass-market technology from the get-go (regardless of the technology path they opt for); whereas under sunk costs firms prefer a niche technology until technology uncertainty is resolved.

I make a rather extreme assumption: one level of production capacity involves no sunk costs, whereas the other level of production capacity is entirely sunk. The important property, however, is that the degree of sunkness is greater for the larger-capacity option. I will return to this issue later.

A few more pieces of notation are required before proceeding. First, I assume firms must pay an entry cost e over and above the setup cost c_i specific to each production capacity level. The entry cost e is independent of the technology path or capacity level chosen by the firms.[11] Moreover, I assume that e is distributed according to $F(e)$. For simplicity, I assume F is uniform, and with no additional loss of generality I normalize units so that $F(e) = e$. Finally, I denote by δ the discount factor.

I make a number of assumptions regarding parameter values.

Assumption 1 $\frac{Q_H}{k_H} < \frac{Q_L}{k_L}$

Assumption 2 $\frac{\left(\frac{Q_H}{k_H} + c_H\right)(1-\delta)}{k_H} < p_L < \frac{\frac{Q_L}{k_L} + (1-\delta)\, c_L}{k_L}$

Assumption 3 $Q_L\left(\frac{k_H}{k_L} - 1\right) - \delta\, c_L\, k_H < c_H\, k_L - c_L\, k_H < Q_H\left(1 - \frac{k_L}{k_H}\right)$

Assumption 1 is crucial for obtaining a shakeout: it must be the case than capacity levels increase by more than market demand. If the two alternative capacity levels are not sufficiently different, then a shakeout does not take place. Assumption 2 states that the mass market choke price is sufficiently high so that $Q = Q_H$ when there are no sunk costs; and sufficiently low that $Q = Q_L$ when there are sunk costs (and technology uncertainty has not been resolved). Finally, Assumption 3 states that the cost advantage of mass production is sufficiently great that it is the chosen technology without sunk costs but not high enough for it to be optimal when there are sunk costs (and technology uncertainty has not been resolved).

Violating the above assumptions leads to corner solutions, where the disparity between sunk costs and no sunk costs does not take place; and where a shakeout does not take place either. This is not surprising. In fact, Gort and Klepper (1982) show that not all new industries exhibit a shakeout pattern. It should be stressed, however, that the above assumptions define an open set of parameter values. For example, suppose that $\delta = 0.9$, $p_L = 0.1$, $k_L = 10$, $c_L = 4$, $k_H = 50$, $c_H = 20$, $Q_L = 10$ and $Q_H = 30$. Then all inequalities are satisfied strictly.[12]

The equilibrium notion I will consider is that of symmetric Nash equilibrium. Since there are two alternative technology paths, in equilibrium, half of the entrants will choose each of the technology paths.

I now have all of the necessary ingredients to move on to the main result, namely that, in equilibrium, a shakeout will take place; and moreover, that a shakeout would not take place were the initial investments not sunk.

[11] I also assume that each firm can only open one plant.

[12] Recall that I assume that firms are atomic, that is, of infinitesimal size, thus avoiding the issue of integer constraints. In this particular example, the number of firms in the first period, $Q_L/k_L = 1$, should be interpreted as the measure of firms, not the (natural) number of firms.

4. Industry shakeout

As Jovanovic and MacDonald (1994) state, a theory that explains the evolution of industries like the US automobile tire industry (the particular industry they focus on), must address the following time-series features: "an increase in average and total output, and a nonmonotone time path for firm numbers." My main result states that such an equilibrium exists, and moreover, the above features only take place if capacity costs are sunk.

> **Theorem 1 (sunk costs and industry shakeout)**: *Under A*1–*A*3, *there exists a unique equilibrium. If investment costs are not sunk, then* $n_1 = n_2 = n_t$; *if investment costs are sunk, then* $n_1 > n_2 = n_t$ *even though* $Q_1 < Q_2 = Q_t$ ($t \geq 2$).

The proof is presented in the Appendix A. Figure 3 illustrates the evolution of the number of competitors. If there are no sunk costs, then firms invest to their optimal long-run level from the get-go. The resolution of uncertainty regarding technology only has the effect of inducing some firms to switch from one technology to another; but the optimal output level per firm always remains the same: k_H. If the k_H capacity investment costs are sunk, however, then firms initially prefer to produce with the low-capacity, period-rental option (firm capacity k_L). As a result, the total number of firms is greater. When technology uncertainty is resolved, some of the firms who backed the wrong technology exit the industry, leading to a shakeout.

Figure 4 complements Figure 3 in describing the equilibrium with and without sunk costs. When capacity costs are not sunk, firms mass-produce from the get-go. This leads to equilibrium price p_0 and total output Q_H in every period. If k_H capacity costs are sunk, however, then firms initially choose the niche capacity level k_L.

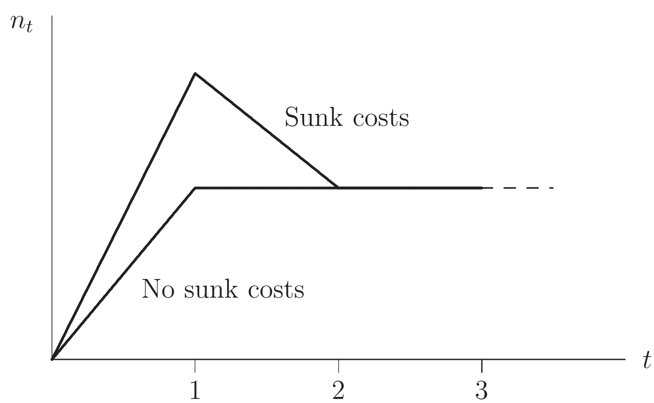

Figure 3 Number of active firms with and without sunk costs.

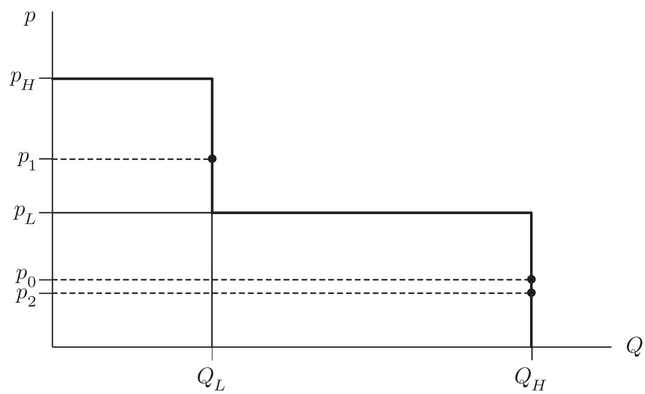

Figure 4 Equilibrium price and output.

Total market demand is Q_L and equilibrium price p_1. In the second period, some of the firms exit, whereas the others invest capacity k_H. Total output expands to Q_H and equilibrium price drops to p_2.

Notice that p_2 is lower than p_0. Although total output and number of active firms is the same, the reason for the price difference is that, at $t=2$, entry costs have already been paid and so p_2 corresponds to the indifference condition for a zero entry cost firm, whereas p_0 corresponds to the indifference condition for a firm with entry cost $e>0$.

Note that at $t=1$ the number of firms is greater under sunk costs than under no sunk costs. Even though total output under sunk costs is lower ($Q_L < Q_H$), each firm's capacity is so much lower under the sunk costs case that the number of firms is lower. From $t=2$ on, all firms choose k_H capacity levels. Since total output is the same under sunk costs and under no sunk costs, it follows that the number of firms is also the same. However, in a more general case—in particular, with a downward-sloping demand curve—$p_2 < p_0$ implies a greater number of firms under sunk costs even after the first period. In other words, even though market conditions with and without sunk costs are the same after $t=2$, the number of active firms may be permanently different between the two cases. Why? Because the initial entry cost is sunk, which implies that there is some degree of path dependence: a good fraction of the many initial entrants under the sunk cost case remain active in future periods.

5. Final remarks

I propose what I think is a very natural theory of industry shakeout: because of capacity sunk costs and the fear of backing the wrong technology, each firm initially invests up to a small capacity, leading to a large number of initial competitors.

As the dust settles down and a dominant technology emerges, surviving firms expand to their long-term optimal capacity, which in turn results in a shakeout.

I purposely set up a very stylized model where marginal costs are constant. In this way, the effects I consider are different from those present in previous theories of industry shakeout. In reality, it is likely that both declining marginal cost and capacity cost sunkness contribute to the existence and the extent of industry shakeouts. I see my theory as a complement to our current understanding of the evolution of new industries and industry shakeouts.

I should also note that, while my model is rather stark and stylized, the results are not knife-edged. The inequalities corresponding to Assumptions 1–3 form an open set of parameter values. This means that I can perturb the model slightly and still obtain the same type of results. For example, the assumption that capacity investment in a technology is "orphaned" has no residual value may be relaxed. Likewise, the assumption that the L production capacity involves no sunk costs whereas all setup costs of the H production capacity are sunk can be made less extreme. However, such changes would be at the cost of a considerably more complicated model and with no apparent gain in clarity.

Gort and Klepper (1982) present evidence of new industries exhibiting a shakeout, as well as new industries exhibiting no shakeout. The main contribution of this article is to show that a shakeout is more likely in industries with: (i) alternative technology paths of uncertain viability and (ii) alternative production technologies, from small-scale "job shop" production technologies with great flexibility to large-scale, very specific production technologies.

Acknowledgements

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References

Abernathy, W. J. and J. M. Utterback (1978), 'Patterns of industrial innovation,' *Technology Review*, **80**, 41–47.

Anderson, P. and M. L. Tushman (1990), 'Technological discontinuities and dominant designs: a cyclical model of technological change,' *Administrative Science Quarterly*, **35**, 604–633.

Cabral, L. (1993), 'Experience advantages and entry dynamics,' *Journal of Economic Theory*, **59**, 403–416.

Cabral, L. (1995), 'Sunk costs, firm size and firm growth,' *Journal of Industrial Economics*, **43**, 161–172.

Cabral, L. and Z. Wang (2009), 'Spin-offs: theory and evidence from the early U.S. automobile industry,' Research Paper, New York University and Kansas City Fed.

Dixit, A. and R. Pindyck (1994), *Investment Under Uncertainty*. Princeton University Press: Princeton, NJ.

Dixit, A. and C. Shapiro (1986), 'Entry dynamics with mixed strategies,' in L. Thomas (ed.), *The Economics of Strategic Planning*. Lexington Books: Lexington, MA, pp. 63–79.

Dosi, G. (1982), 'Technological paradigms and technological trajectories,' *Research Policy*, **11**, 147–162.

Dosi, G., F. Malerba, O. Marsili and L. Orsenigo (1997), 'Industrial structures and dynamics: evidence, interpretations and puzzles,' *Industrial and Corporate Change*, **6**, 3–24.

Eggers, J. P. (2007), 'Falling flat: failed technologies and investment under uncertainty,' Working Paper, NYU Stern. Forthcoming in *Administrative Science Quarterly*.

Filson, D. (2002), 'Product and process innovations in the life cycle of an industry,' *Journal of Economic Behavior and Organization*, **49**, 97–112.

Gort, M. and S. Klepper (1982), 'Time paths in the diffusion of product innovations,' *Economic Journal*, **92**, 630–653.

Hopenhayn, H. (1993), 'The shakeout,' Economics Working Paper No. 33, Universitat Pompeu Fabra.

Jovanovic, B. and G. M. MacDonald (1994), 'The life cycle of a competitive industry,' *Journal of Political Economy*, **102**, 322–347.

Klepper, S. (1996), 'Entry, exit, growth, and innovation over the product life cycle,' *American Economic Review*, **86**, 562–583.

Klepper, S. and E. Graddy (1990), 'The evolution of new industries and the determinants of market structure,' *RAND Journal of Economics*, **21**, 27–44.

Klepper, S. and J. Miller (1996), 'Entry, exit, and shakeouts in the United States in new manufactured products,' *International Journal of Industrial Organization*, **13**, 413–614.

Lambson, V. E. (1991), 'Industry evolution with sunk costs and uncertain market conditions,' *International Journal of Industrial Organization*, **9**, 171–196.

Lee, T. and L. L. Wilde (1980), 'Market structure and innovation: a reformulation,' *Quarterly Journal of Economics*, **94**, 429–436.

Mueller, D. C. and J. Tilton (1969), 'Research and development costs as a barrier to entry,' *Canadian Journal of Economics*, **2**, 570–579.

Schilling, M. A. (1998), 'Technological lockout: an integrative model of the economic and strategic factors driving technological success and failure,' *Academy of Management Review*, **23**, 267–284.

Tushman, M. and P. Anderson (1986), 'Technological discontinuities and organizational environment,' *Administrative Science Quarterly*, **31**, 439–456.

Utterback, J. M. (1994), *Mastering the Dynamics of Innovation*. Harvard Business School: Boston, MA.

Utterback, J. M. and W. J. Abernathy (1975), 'A dynamic model of product and process innovation,' *Omega*, **3**, 639–656.

Vettas, N. (2000), 'On entry, exit, and coordination with mixed strategies,' *European Economic Review*, **44**, 1557–1576.

Appendix A

Proof of Theorem 1: Consider first the case with no uncertainty. In what follows I will show that it is an equilibrium for Q_H/k_H firms to enter. The indifferent entrant has entry cost e^N such that

$$e = \frac{p_0\, k_H}{1-\delta} - c_H$$

where p_0 is the equilibrium price (in every period) when there are no sunk costs (or no uncertainty). Since $F(e) = e$, the balance between supply, $F(e^N)\, k_H$, and demand, Q_H, implies that

$$\frac{p_0\, k_H}{1-\delta} - c_H = \frac{Q_H}{k_H}$$

from which we obtain

$$p_0 = \frac{\left(\frac{Q_H}{k_H} + c_H\right)(1-\delta)}{k_H} \qquad (A1)$$

The first inequality in Assumption 2 implies that $p_0 < p_L$, consistently with our assumption that $Q = Q_H$.

In order for the mass-production technology to be an optimal strategy, it must be that

$$\frac{p_0\, k_H}{1-\delta} - c_H > \frac{p_0\, k_L}{1-\delta} - c_L$$

Substituting (A1) for p_0, and simplifying, we obtain the second inequality in Assumption 3.

Consider now the case with sunk costs. The indifferent entrant has entry cost e^S such that

$$p_1\, k_L - (1-\delta)\, c_L = e^S$$

Since $F(e)=e$, the balance between supply, $F(e^S)\ k_L$, and demand, Q_L, implies that

$$p_1\, k_L - (1-\delta)\, c_L = \frac{Q_L}{k_L}$$

or

$$p_1 = \frac{\frac{Q_L}{k_L} + (1-\delta)\, c_L}{k_L} \tag{A2}$$

The second inequality in Assumption 2 implies that $p_1 > p_L$.

In order for the niche-production technology to be an optimal strategy, it must be that

$$p_1\, k_L - (1-\delta)\, c_L > p_1\, k_H - c_H + \tfrac{1}{2}\, \frac{\delta}{1-\delta}\, p_2\, k_H$$

Substituting (A2) for p_1, and simplifying, we obtain the first inequality in Assumption 3.

Under sunk costs, the equilibrium number of firms is given by $n_1 = Q_L/k_L$ in the first period and $n_2 = Q_H/k_H$ from $t=2$ on. Assumption 1 implies that $n_2 < n_1$: an industry shakeout. Under no sunk cost, however, the number of firm is always given by $n = Q_H/k_H$. ■