

Interdependency, Competition, and Industry Dynamics

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A systematic understanding of industry dynamics is critical to strategy research because individual firm performance dynamics both reflect and affect change at the industry level. Descriptive research on industry dynamics has identified a dominant pattern where prices fall, output rises, and the number of firms rises and then falls over time. Several models have been advanced to explain these patterns, with a particular focus on explaining why a shakeout in the number of firms occurs. In the most prominent models, shakeout is generated by rising realized heterogeneity among firms that either is assumed to be unrecognized but determined ex ante or is generated by stochastic innovation outcomes coupled with convex adjustment costs and scale advantages in innovation and learning. In this paper, we develop an alternative model where heterogeneity develops among firms over time (leading to a shakeout) because firms must make choices about highly interdependent productive activities where the ideal combinations cannot be easily deduced or imitated. By combining two established models (a Cournot model of competition with an NK model of interdependency in production activities), we are able to advance an alternative explanation for the observed patterns of industry behavior, including shakeout. We show that variation in the potential for interdependency in activities among industries is able to explain varying levels of shakeout as well as differing patterns of entry and exit among industries. Notably, the model generates several empirical predictions not apparent in past research and several that directly conflict with the results of prominent alternative models of industry dynamics. Specifically, we show that when the potential for interdependency within an industry is low, entry slows down and incumbent survival is all but assured, whereas in industries where the potential for interdependencies is high, shakeouts are severe and the rates of entry and exit remain high over longer time periods, with decreasing survival rates for incumbents.

Key words: industry evolution; complementarities; interdependencies

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1. Introduction

Critical to understanding contemporary differences in market share and profitability among firms within an industry is systematic knowledge of how those differences arose in the first place. Understanding the structural evolution of industries—the rate of change in output and prices, the rates of entry and exit (turnover), and the growth and decline of individual firms (mobility) and industry participation—is widely recognized as fundamental to identifying the origins of profitable market leaders who can sustain performance over time. Industry evolution provides important contingencies that affect the viability of various firm strategies. Without a keen grasp of the underlying mechanisms driving industry evolution and the resulting changes that occur at the industry level over time, we are less able to identify why certain firms in an industry are the winners and others losers (Agarwal and Gort 2002). In this paper, we advance an alternative explanation for observed patterns of industry evolution based on

interdependencies in productive activities (Milgrom and Roberts 1990, Levinthal 1997, Rivkin 2000) and identify novel predictions based on this underlying mechanism.

Over the years, researchers have endeavored to develop clear characterizations of industry evolution (see Gort and Klepper 1982, Agarwal and Gort 1996). Central to these investigations has been the observance of shakeout, i.e., a rise and then fall in the number of competitors over time. Following the inception of an industry, new entrants rush in, often driving up the rate of innovation and leading to a diverse set of ways to deliver value. Competition intensifies and industry exit increases. Over time the rate of entry decreases, eventually stabilizing at a low level. As a result, the number of firms within the industry grows exponentially at first, then peaks, and then declines, typically settling in with a few dominant firms. Although shakeout has dominated most discussion about industry dynamics, it is far from a universal pattern. Gort and Klepper (1982) report wide

variance in the prominence of shakeout across industries. In some industries, barely any shakeout at all occurs; in others, upwards of 80% of the firms in the industry exit.

A number of models have been advanced to explain the classic rise and fall associated with shakeout and the frequency and nature of observed deviations from this pattern. The most prominent formal models of industry evolution rely on *convex adjustment costs and scale advantages in innovation and learning* to generate the classic life-cycle with shakeout pattern (Ericson and Pakes 1995, Klepper 1996). For example, a firm with a small initial efficiency advantage or a chance innovative success may expand faster than its rivals. If adjustment costs are convex and there are scale advantages in exploiting further innovation, this firm's previous innovation success and expansion will justify larger subsequent investments in innovation and amplify its lead over time.

In contrast, we propose that *interdependency in productive activities* provides a robust, alternative explanation for the stylized facts about industry evolution and shakeout. By "interdependency in productive activities," we refer to the potential for the value of one activity to depend on whether a firm engages in another activity (Levinthal 1997). In the presence of interdependent and potentially complementary activities, firms face barriers to search and often struggle to discover valuable configurations of productive activities (Rivkin 2000). We advance that industries can vary in their potential for interdependencies and that these interdependencies are fundamental to productive activity. Interdependencies provide a powerful mechanism by which to introduce bounded rationality and search in the spirit of evolutionary economics (Nelson and Winter 1982b) and behavioral theories of the firm (Cyert and March 1963) to models of industry evolution.

In this paper, we construct and analyze a model of industry evolution in the presence of interdependency among firm activities. We first show that the model provides a set of sufficient mechanisms to explain varying levels of shakeout and differing patterns of entry and exit among industries. Specifically, we show that when the potential for interdependencies within an industry is low, entry slows down and incumbent survival is all but assured; in industries where the potential for interdependencies is high, however, shakeouts are severe and the rates of entry and exit remain high over longer time periods, with decreasing survival rates for incumbents.

Differences in interdependency not only provide an explanation for why incumbents are more or less successful in different industries, but they also can explain why incumbents contribute more to technological progress in some industries while in other

industries recent entrants make larger contributions. In this way, our model provides a potential resolution to the debate between the "old" and "new" Schumpeter about the growth contributions of incumbent firms versus new entrants. In industries where the potential for interdependency is low, incumbent firms are more likely to innovate and drive growth. In industries where the potential for interdependency is high, new entrants (entrepreneurs) are more likely to drive innovation and growth.

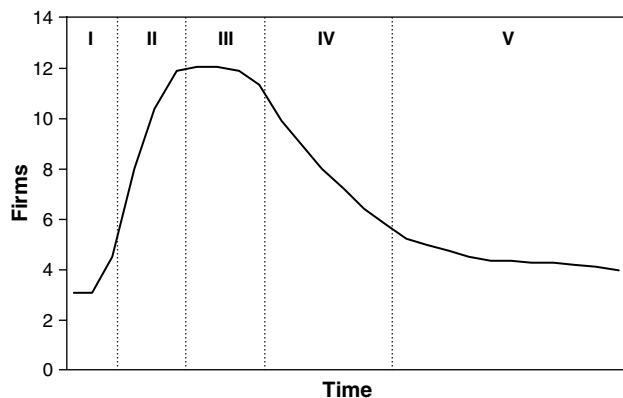
We argue that interdependency is at least as compelling as scale-based explanations (those relying on convex adjustment costs and scale advantages in appropriating returns to innovation) as a way of explaining industry dynamics. Interdependency complements these scale-based explanations by providing a separate mechanism to explain industry dynamics in general—and shakeout in particular—in markets where adjustment costs are low or linear or where innovation returns are independent of the previous scale. Interdependency, however, also conflicts with scale-based explanations, as they give rise to empirical predictions that in several cases are directly opposed to those of past models. Ultimately the two explanations differ in a fairly simple but fundamental way. In the presence of interdependency, past innovation conditions future innovation as it does in previous models, but not because they affect incentives to innovate, as in Klepper (1996) and Ericson and Pakes (1995). It is rather because they affect the content of what will be learned from innovative effort.

The key to this explanation is not differences in the amount of past innovative success, but differences in the content of past innovative successes, which lead to different technological trajectories (Dosi 1982). Our model focuses on the importance of what firms learn rather than solely on how much firms learn and how the nature of learning varies among industries.

2. The Evolution of Industry Structure

Shakeout has long been observed as industries evolve and has come to dominate managerial and scholarly discussion of industry dynamics (Klepper 2005). Shakeout takes a central place in Gort and Klepper's (1982) early and rich documentation and description of industry dynamics. Gort and Klepper studied the life cycles of 46 industries originating between 1887 and 1960 and representing a diverse mix of consumer, industrial, and military products. Their analysis for each industry began with the introduction of a substantial new innovation. They first looked at patterns of industry participation and observed that industries for new products pass through a brief period with few firms, followed by a rapid increase in the number of firms, which then falls rapidly to a relatively stable

Figure 1 Some Stylized Facts on Industry Dynamics



Notes. 1. Early on, industries are characterized by few competitors (Stage I). This period lasts from less than a year to 50 years with an average of 14.4 years.

2. Stage I is followed by a period of rapid entry and industry growth (Stage II). This period lasts from 2 to 25 years, with an average of 9.7 years.

3. Stage III is where entry and exit are roughly balanced. This period ranges from less than a year to 37 years with an average of 7.5 years.

4. In Stage IV, a shakeout occurs where the number of competitors falls by 19% to 77% from the peak number of firms with an average of 40%. This period lasts from 1 to 12 years with an average of 5.4 years.

5. In Stage V, the number of competitors remains fairly constant (rising or falling slowly).

6. Over the industry life-cycle, the rate of growth in output declines steadily with time.

7. Over the industry life-cycle, prices decline fairly steadily and at a decreasing rate over time.

8. Over the industry life-cycle, innovation rates rise then level out.

Source: Gort and Klepper 1982.

level (p. 639). During the evolution of the industry, Gort and Klepper also observed that output growth is initially high but declines steadily (p. 645); prices fall rapidly but at a decreasing rate (p. 647); and the rate of both major innovations and minor innovations rise, peak, and then remain stable over time, with major innovations peaking earlier (p. 648).

Gort and Klepper divided an industry's life-cycle into five stages defined by different rates of net entry (see Figure 1). The first stage is one with little net entry, where a few initial firms are alone in the industry, followed by a second stage defined by rapid entry, causing the number of firms to rise rapidly. Slowing entry and rising exit lead to a third stage, where industry participation remains fairly constant. Later, entry rates fall and exit rates increase, defining a fourth stage, where industry participation falls rapidly. Eventually exit rates slow and the industry enters a fifth stage defined by roughly stable industry participation. Gort and Klepper found that while industry participation rises, falls, then stabilizes, output increases quickly and prices fall rapidly with changes in both prices and output occurring at a decreasing rate over time.

While this full life-cycle pattern of industries has become widely recognized as a useful way of thinking

about industries, Gort and Klepper's data show that the pattern is far from universal or uniform. As discussed in Figure 1, the length of each stage varies considerably from industry to industry. In some cases, the stages are so short as to be excludable (e.g., the first stage lasting less than a year) or so long that the question arises whether the following stages are part of the same industry dynamic (e.g., the third stage, with stable participation, lasting nearly four decades).

The magnitude of the rise or fall in industry participation also varies quite a bit across industries. In 19 of the 46 industries that Gort and Klepper (1982) studied and 7 of the 16 industries studied by Agarwal and Gort (1996), there is no dramatic fall in the number of competing firms during the fourth stage defined by net exit (see Klepper 1997, pp. 165, 166). In addition to the presence or absence of a clear shakeout in industry participation in this fourth stage, we observe differences in finer patterns, such as how much industry progress is driven by incumbents or recent entrants and whether early entry conveys considerable or little survival advantage (Hannan 1998).

A number of theories have been advanced to explain these patterns. Jovanovic (1982) provided a model to explain why small firms grow more rapidly and are more likely to fail than larger firms. The model is based on a "theory of noisy selection," where firms are initially and randomly endowed with different levels of efficiency but only learn and update their beliefs about their type over time with noise in the signals. In this model, efficient firms recognize their efficiency over time and grow, and inefficient firms become aware of their inefficiency, leading them to contract and exit. To produce analytic results, the model assumes an infinite number of firms, so firms are all price takers that limit their output due to convex production costs rather than strategic concerns about the effect of their own output prices and the output of other firms.

Utterback and Abernathy (1975) provided an alternative explanation for the shakeout of firms, where firms take a more active role in determining their efficiency levels. Utterback and Abernathy based their explanation on a period of technological uncertainty that ends with the emergence of a dominant product design, after which firms that are unable to produce this design exit the market. Klepper (1996) pointed out that the appearance of a dominant design is far less predictable than the other regularities observed in industry life-cycles and proposed and explored a more complete analytical model to explain these patterns, along with an additional regularity involving a shift in emphasis from product to process innovation over time. Klepper's model is based on (a) advantages of scale in exploiting product and process innovations that lead larger firms to innovate more and

lead to a shift from product toward process innovation; (b) convex adjustment costs that limit the rate of firm expansion; (c) firms that make output choices to maximize current profits; (d) a pool of potential entrants; and (e) firms that make entry, exit, output, and R&D choices to maximize expected next-period profits.

Ericson and Pakes (1995) also provide a model of entry and exit among competing firms engaged in innovative efforts, though the model's primary purpose is to explain the "great variability in the fate of similar firms," with some firms growing while others contract. Their model allows firms to make entry and exit decisions based not only on current profits but also on expected future profits following later innovative efforts; entry and exit decisions are based on optimal stopping rules rather than current period profits. The model can produce a wide variety of behavior depending on parameterization, including a rise in the number of firms followed by a shake-out, high contemporaneous rates of both entry and exit, and a skewed distribution of firm lifetimes and firm performance. Similar to Klepper's model, convex adjustment costs allow for the expansionary period of high net entry while advantages of scale in innovation are key drivers of the eventual fall in the number of competitors.

All of these formal models (Jovanovic 1982, Ericson and Pakes 1995, Klepper 1996) assume that competitive decisions (entry, exit, and output quantity) are made with full information about current cost structures and demand conditions; yet also assume that firms have limited information about the ways to improve products or lower costs. When discussing the model of competitive decision making, we will reference both theoretical and empirical work to argue that the full-information model of competitive decisions is an imperfect, but still useful, approximation to competitive decision making in the limited information world in which managers operate. When discussing operational improvements, we will draw on prior research to argue that full information about the value of alternative activity sets is not a reasonable or useful model of managerial decision making in the operational sphere, at least not where there is a large potential for interdependency among activities.

In this paper, we advance an alternative approach to the operational improvement (learning) problem facing firms based on the degree to which firm activities are interdependent or complementary. Interdependency among firm activities is well documented at the product, process, and organizational levels (Demsetz 1973; Milgrom and Roberts 1990; Porter 1996; Ichniowski et al. 1997; Rivkin 2000; Siggelkow 2001, 2002; Kauffman 1989; Cassiman and Veugelers 2006). Activities are interdependent to the extent

that "the value of a particular feature of the organization [activity] depends on a variety of other features of the organization [activities] (Levinthal 1997, p. 936)." Interdependent activities are complementary when the marginal value of engaging in one activity is increased by engaging in another (Milgrom and Roberts 1990).

The potential for interdependency among a firm's activities may lead firms to adopt a host of specific practices in concert and may result in "distinctly separated clusters of firm characteristics" (Milgrom and Roberts 1990, p. 527). Early random differences in production decisions condition later choices, potentially leading to quite different bundles of activities (and profitability) for even initially similar firms (Levinthal 1997). These differences in activity bundles may persist as lagging firms struggle to imitate leading firms' bundles of highly interdependent activities (Rivkin 2000). To the extent that organizations are better at evaluating incremental than radical changes (Levitt 1975, Levinthal and March 1993, Nelson 2003) and limited in their ability to fully comprehend or re-create the practices of rivals without such understanding (Lippman and Rumelt 1982, Rivkin 2000), the presence of interdependencies will only reinforce within-industry heterogeneity.

As an illustration, consider a previously untried distribution process that is well suited to one firm but that creates costly complications or few benefits for a rival firm that uses a different set of manufacturing techniques. Because of its interactions with other practices, adopting the new distribution process may give the first firm a large performance advantage (Rivkin 2000) that persists because rivals (1) fail to observe adoption or performance changes (Dierickx and Cool 1989); (2) make errors when observing or changing interdependent differences among firms (Rivkin 2000); (3) cannot efficiently change some complementary difference or differences (Dierickx and Cool 1989, Oster 1982); or (4) favor incremental evaluation and adoption of changes that provide immediate improvements (March 1991, Levitt 1975, Christensen and Rosenbloom 1995).

The resulting limits to imitation and search are central to a number of streams of literature in strategy and economics. Fundamental to the resource-based view of strategy is the notion that heterogeneity in individual firm resources and capabilities may lead to performance differences among firms and that these advantages are not "competed away" because of the inability of competitors to perfectly imitate one another. Difficulty in imitation and search is also fundamental to Nelson and Winter's (1982a, b) evolutionary economics and behavioral theories of the firm (Simon 1961, Cyert and March 1963).

Some work has begun to map the existence of these interdependencies in competitive settings to industry observables (see Lenox et al. 2006). While this research has examined the effects on cross-sectional distributions of firm and industry profits, the implications of interdependencies in a competitive setting for longitudinal patterns of industry dynamics remain to be explored. Using the model presented in the following section, we link potential interdependencies in productive activities with industry dynamics. In doing this, we demonstrate that interdependencies provide a viable alternative approach to re-creating central stylized facts about industry evolution and that variation among industries in the potential for interdependencies can generate known variants of those patterns. We then use the model to generate novel insights about the performance of incumbents and the contributions of incumbents and entrants to technological progress.

3. The Model¹

For our analysis, we adopt the model of Lenox et al. (2006). Lenox, Rockart, and Lewin constructed the model to address questions about the cross-sectional distribution of profits within and among industries. Specifically, they used the model to evaluate whether varying interdependencies among activities might explain different distributions of firm profits within and across industries at a given point in time. To do this, Lenox et al. evaluated the cross-sectional profit distributions only after the model had stabilized, finding the highest expected profits in industries with moderate levels of interdependency, where some but not all firms were able to discover highly effective combinations of activities.

The model developed, however, is evolutionary and most importantly incorporates explicit treatment of competition, which gives structure to firms' entry, exit, and production quantity decisions. The evolutionary nature of the model, and its explicit treatment of firm production decisions, allows it to be used not only for exploring questions of cross-sectional industry outcomes, but also of dynamic behavior of entry, exit, and changes in firm size in industries over time. We present and apply the model in this paper for that purpose.

The model has similarities but key differences from previous models of industry evolution. It makes similar assumptions about potential entrants, exit, and output choices to those in Klepper (1996), but assumes that innovative outcomes are conditioned not on the scale of current production but on the firm's current method of conducting productive activities. Unlike

Klepper (1996) and Ericson and Pakes (1995), the Lenox et al. (2006) do not incorporate advantage from past scale in appropriating innovation, nor does their model include convex expansion costs. Although such advantages and costs exist in some industries, excluding them focuses on how incomplete knowledge of interdependence in activities and time consuming imitation (as opposed to the complete and relatively rapid imitation assumed by Klepper) affects industry dynamics and firm performance over time.

The overall model is composed of (1) a model of competition among firms that maps the distribution of firm cost to industry outcomes and (2) a model of interdependency among a firm's resources and practices that determines firm performance in terms of cost. For the model of competition, we primarily consider an undifferentiated market, where industry price depends on demand conditions and total industry output. Consumers are assumed to choose firms that maximize their own utility, and firms act to maximize their profits. As a robustness test, we also consider a model of competition, where competitors are differentiated in quality and thus each firm's sales depend on demand conditions as well as on the quality and price offered by that firm and every other competitor (see the online appendix provided in the e-companion).² For the model of interdependency, we adopt a general representation of interdependencies among activities that allows for interactions consistent with Kauffman's (1989) NK model, which has been introduced into the strategic management field by Levinthal (1997) and Rivkin (2000). We consider each model in turn.

3.1. Competitive Submodel

Undifferentiated firms are typically modeled as price competitors (Bertrand) or quantity competitors (Cournot). Models of price competition invariably lead to industries in which no firm makes a profit or only a single monopolist survives. Because these two possible outcomes represent only a narrow range of the known patterns of industry structure, we adopt and adapt the classic quantity competition model of Cournot. The Cournot model can lead to monopoly as a special case when one firm has much lower costs than other firms—in which case that firm will choose to produce at levels that drives all others out of the industry—but also allows for a wide range of oligopoly structures to develop.

Specifically, in Cournot competition, each firm i attempts to achieve the highest possible profits (π_i)

¹ Portions of this section are excerpted from Lenox et al. (2006).

² An electronic companion to this paper is available as part of the online version that can be found at <http://mansci.journal.informs.org/>.

given their production costs $c_i(q_i)$ by setting an output quantity (q_i):

$$\pi_i = p(Q)q_i - c_i(q_i), \quad (1)$$

where the market price (p) falls linearly with overall industry output (Q):

$$p(Q) = \alpha - \beta Q \quad (2)$$

and costs increase linearly with output:

$$c_i(q_i) = c_i q_i + c_f. \quad (3)$$

If we solve for the profit-maximizing output quantity:

$$\max_q \pi_i = (\alpha - \beta \sum q_i)q_i - c_i q_i - c_f, \quad (4)$$

we find that a rational oligopolist will set quantity such that

$$q_i^* = (\alpha + \sum c_i) / \beta(n + 1) - c_i / \beta, \quad (5)$$

where n is the number of competitors and $\sum c_i$ is the sum of marginal costs across all firms. Intuitively, the highest output and greatest profits will go to the firms with the lowest variable costs.

In this undifferentiated competition model, the advantages of being a low-cost producer vary both with the magnitude of one's cost advantage and with the number of firms in the market. Ultimately, entry and exit and firm scale are functions of both an individual firm's marginal costs and the distribution of these marginal costs among competing firms within the industry. This highlights the importance of an explicit treatment of the competitive environment when exploring the effects of an industry's potential for interdependency on industry dynamics. The relationship between a firm's profits and its efficiency depends on the number of competitors and the distribution of efficiency among those competitors, both of which also change with the industry's potential for interdependency in activities.

The Cournot model assumes highly rational behavior by managers. Clearly, there is the potential for incorporating richer behavioral elements into such models of competitive decision making (Zajac and Bazerman 1991). Our model requires only knowledge of a firm's own costs and the average costs of rivals (Equation (5)), examples abound where firms struggle to solve for best response curves to determine output given such information. Experimental findings, however, indicate that Cournot output levels are a reasonably accurate representation of output choices by individuals in competitive situations, very similar to the ones modeled in this research, where a number of participants compete with heterogeneous costs and no direct information about each other's

costs (Rassenti et al. 2000). In these experimental markets, there are random differences between subject output choices, and there is an upward bias in average output decisions relative to Cournot, as have been found in empirical studies (Bresnahan and Reiss 1991), though we expect that including an upward bias or noise would complicate analysis without substantially changing model behavior.

3.2. NK Submodel of Interdependencies

Rather than focus on input costs such as labor and capital or one-dimensional accumulations of efficiency based on past investments and cumulative output, the competitive model assumes that costs are driven by the details of what firms do. Specifically, cost is assumed to be driven by how firms conduct each activity in a large set of activities. The full model captures firms actively engaged in experimenting with existing configurations of activities and altering how they perform activities in an attempt to lower marginal cost (Lippman and Rumelt 1982). Appropriate decisions about how firms should perform each activity are complicated by interactions among those activities, which, depending on how the other activities are conducted, can result in complementarities or conflicts that increase or reduce efficiency, respectively.

Our analysis assumes that the extent of interactions among activities is a characteristic that varies among industries but not within industries over time. In other words, we define the *potential for interdependency in activities* (PIA) as a latent property that remains constant within an industry over time. By this definition, many of the interactions will go unrecognized until firms try novel approaches to one or more activities (perhaps made possible by engineering breakthroughs or scientific discoveries), at which point it might appear that the interdependencies have changed. By defining interdependencies in this manner, we include in firm behavior changes in activities resulting from "breakthrough" ideas and scientific discoveries (e.g., new materials, contracting forms, or process technologies).

We adopt the widely applied NK model of interdependency to capture differences in PIA among industries (Kauffman 1989). This is a critical point for our analysis, because our goal is to make predictions about how industry dynamics differ based on the potential for interdependency. The NK model as applied in management research can be viewed as a complex production function depending not only on aggregate supplies of capital and labor but also on a firm's specific mix of activities, practices, and resources.³ The N in the NK model refers to the

³For the sake of simplicity, we refer to activities, practices, and resources simply as activities and the possible combinations of the activities, practices, and resources as activity sets.

number of potentially interdependent activities that a firm may adopt or employ, and the K refers to the number of activities that interact with each of the N activities.

Higher values of K lead to more expected combinations of activities that could complement or conflict with one another to produce a distinctly lower cost than would be expected by a combination of independent changes. Thus, K serves as a good proxy for an industry's PIA. For example, whether to use just-in-time logistics, piece-rate payments, sampling techniques to control quality, work teams, and stock options as incentives would naturally fall among the N decisions that a manufacturing firm needs to make. Researchers have found evidence that steel-producing firms that adopt incentive pay, teams, flexible job assignments, employment security, and training enjoy higher productivity than would be expected from the sum of the individual gains to be generated from each of these activities (Ichniowski et al. 1997).

One of the desirable aspects of the NK specification is that it captures interdependency in a more general sense than is captured in analytical specifications (Ghemawat and Levinthal 2000). Milgrom and Roberts (1990) provide an analytical treatment of interdependency where doing more of each activity enhances the value of doing more of every other activity. This fully complementary assumption allows for closed-form comparative static results using the concepts of lattice theory and supermodularity. The NK specification, however, "avoids imposing a specific structure on the linkages among choices" and "allows the richness of such linkages to vary across situations"; thus, we can explore the effects of both complements and conflicts among activities (Ghemawat and Levinthal 2000, p. 17). Conflicts are represented in the NK model whenever the value of an individual practice increases in the absence of another practice.

The NK submodel provides the foundation for an agent-based model where each firm in the industry is an agent assigned a vector of N binary activity decisions, s_i , that represent the way it does each activity. For example, a firm that adopts just-in-time supply logistics, forgoes piece rate payments, uses quality sampling, encourages integrated work teams, and refuses to offer stock options may have an activity set as follows: $s_i = [10110]$. For each activity decision, we randomly generate 2^{K+1} cost values that characterize the potential interactions within that industry. For example, if each activity decision interacts with three other decisions, there are 16 (2^{3+1}) potential values for each activity, and those values are determined by random draws from a $U(0, 1)$ distribution. Each activity in each firm is then assigned the value that corresponds to the way that activity is carried out and to

how the $(K - 1)$ related practices with which it interacts are conducted. The firm's overall marginal cost is determined by the average of the assigned values for all its activities.

The implications of interdependency in activity sets captured by the NK model are perhaps most easily understood using the imagery of a three-dimensional physical landscape (Kauffman 1989). Imagine mapping all possible activity sets along a two-dimensional plane and defining a surface or "landscape" above that plane where the height of that surface represents the efficiency corresponding to each activity set. The firm's objective in such a world is to find the peak of the highest "hill" in that n -dimensional landscape.⁴ When there are no interdependencies among activities, the landscape is gently sloping with a single peak. Any firm will find this peak simply by altering activities one at a time and making individual alterations that improve performance at each step. This is not true, however, when interdependencies are present. The greater the number of activities each activity relies on, the more rugged the landscape becomes—local optima proliferate—and no rapid algorithmic solution can find the highest peak among the increasingly many similar peaks under these conditions (Rivkin 2000, Weinberger 1991).

If the firm has full information about how every activity would interact with every other of the N activities, an optimal activity set could quickly be determined by exhaustive computational search. In practice, firms must discover the way many activities interact. Consistent with past research, we consider this a more difficult task than determining appropriate output levels based on revealed costs. Thus, we give greater attention to search considerations when modeling learning and improvement than when modeling competitive behavior. Firms must engage in costly and time-consuming data gathering and trial-and-error discovery to determine the nature of the interdependency among activities and how these interdependencies affect the cost coefficients. Therefore, firms are unable to quickly and efficiently calculate a globally optimal decision and are forced to rely on experience and experiments to evaluate how changes in activities will affect and be affected by other activities.

We specify a repeated evolutionary game to capture firms learning the nature of the landscape. Firms evaluate and implement changes in activities by determining how those activities would complement or conflict with their current activities and by observing choices other firms made. We assume that all firms

⁴ We will refer to the highest peak as being the most efficient point to sustain the imagery, though in fact firms are seeking the lowest marginal cost in the undifferentiated competitive model.

within an industry are endowed with an initial set of activities and observe their own cost relative to competitors. At each iteration, firms search for activity sets that will improve their cost. Improvements in cost are likely but not guaranteed to lead to higher profits, as improvements by competitors may offset gains made by a firm.

We examine two primary categories of search—innovation and imitation—employed in previous research (Nelson and Winter 1982a, b; Massini et al. 2005). In any given period, firms generally search only a small fraction of the enormous number of possible changes to their activity sets and concentrate their search on “local” alternatives that involve relatively incremental modifications. Because there are an infinite number of variants possible for capturing limited and local innovative search, we adopt the basic innovative search model employed by Levinthal (1997). Firms consider a single change in an activity at a time and adopt any change that represents an improvement.⁵ Imitation occurs in a similar manner to innovation, in that firms only evaluate a subset of all possible changes at any given time. When imitating, however, firms adopt changes that will make them more like the best firm, even if doing so raises costs from conflicts with other activities.⁶

As a practical matter, imitation and innovation take place simultaneously (Westney 1987, Szulanski 2000). The model includes a parameter (γ) that represents the likelihood that a firm searches for possibilities for imitation versus internal innovation. A firm with γ equal to zero will rely purely on internal innovation, but as γ rises toward a value of unity the firm becomes increasingly and eventually totally reliant on imitation. Prior to each time period each firm considers altering each individual activity with probability θ .⁷ In each period, firms adjust their activity

⁵ Variants on this innovative search strategy have been employed by other researchers. Rivkin (2000) broadens the search and focuses changes by assuming that firms evaluate all alternative activity sets with up to M changes from the current activity set and select the very best one. Levinthal (1997) also considers the possibility of innovative “long-jumps,” where a firm considers a single randomly drawn alternative where as many as all elements of the activity set may change. Rivkin and Siggelkow (2003) and others also consider the effects of organizational structures that divide search and evaluation into subsets of firms’ activities.

⁶ Imitation, like innovation, has been modeled in varying ways. For example, Rivkin (2000) allows firms to imitate on many dimensions at once but with error.

⁷ In each period, a firm has the potential to consider altering each of its resource decisions. Given the probability (θ) of considering one resource decision, the probability of considering all resource decisions is θ^N . Thus for $\theta = 0.10$ and $N = 10$, the likelihood of considering altering at least one decision is 65% ($1 - (1 - \theta)^N$) and all decisions is 0.0000001%. We emphasize that *considering altering* a resource decision does not necessarily mean a firm *will alter* a decision.

sets; then we determine the marginal cost, total cost, quantities produced, prices, and profits for each firm before firms consider changing activities again.

The computational steps proceed as follows. Firms are endowed with a randomly generated set of activities. Each firm decides whether to update its activities before the next period based on a logic of imitation (chosen with probability γ) or a logic of local search that will be applied to all activity decisions for that period. Then, with probability θ , that firm considers changing its first activity using the chosen logic. If that firm considers changing the activity and is following an imitation logic, the firm will mimic the activity choice of the most successful firm in the previous period industry. If that firm considers changing the activity and is following a local search logic, the firm changes its activity choice if and only if it will improve its profitability in the industry, given the current state of the world.⁸ The same logic is reapplied to each activity considered, taking into account any changes made in the activity set so far. Each firm continues through all activities in this manner. Because the choices are probabilistic and independent, the firm may consider changing no activities, a few activities, or potentially all activities.

We assume that firms enter and exit the industry depending on the attractiveness of the industry and their ability to compete effectively in the industry. Firms exit the industry when they are unable to produce profitably ($q_i^* \leq 0$). At any time t , we assume that there exists a pool of potential entrants. Potential entrants attempt entry in a given time period stochastically:

$$P(\text{entry}) = \min(\lambda \bar{\pi}^\tau, 1), \quad (6)$$

where $\bar{\pi}$ is average industry profits and λ ($\lambda \geq 0$) and τ ($\tau \in 0, 1$) are parameters. The parameter τ allows us to investigate the effect of profits in encouraging entry. $\tau = 0$ means that profits do not affect entry, while higher values indicate that higher profits induce greater entry.

Attempting entry and engaging in production are two different decisions. A firm that attempts entry calculates expected profits based on knowledge of its own marginal cost and the marginal cost of all other competing firms. Incumbent firms and firms attempting entry will enter the market (i.e., produce) if they anticipate positive profits in the following period.⁹

⁸ All else being equal, improvements in cost or quality will lead to increases in profits. Thus, the results are identical if firms choose activities that improve cost or quality rather than profits.

⁹ We experimented with profit hurdle rates greater than zero and found that they have no effect on the results presented in this paper. Higher hurdle rates decrease the likelihood of entry and increase the likelihood of exit but do not affect the general patterns presented here.

4. Analysis and Results

To analyze the model, we rely on computational methods. During the course of our computational experiments, firms simultaneously compete on cost and search for more productive combinations of activities. We generate the variation and selection of activity sets for each firm in the population according to its updating heuristic. We calculate the marginal cost, total cost, quantities produced, prices, and profits for each firm according to our competitive model.¹⁰ Firms enter and exit the industry according to the specification described above. For each simulated industry, this process of search and production is repeated for 100 time periods.

Overall, we simulated 50,000 test industries. Across test cases, we varied the updating heuristics firms use (γ) and the potential for interdependency of the industry (K). For each test case, we assigned the rate of search (θ), the number of activities under consideration (N), demand parameters (α , β , and ρ),¹¹ and entry parameters (λ , τ).¹² We generate an industry production function (i.e., a cost landscape) by randomly drawing marginal cost equation coefficients from a uniform distribution ranging from zero to one.¹³ Finally, we randomly initialized firms' activity

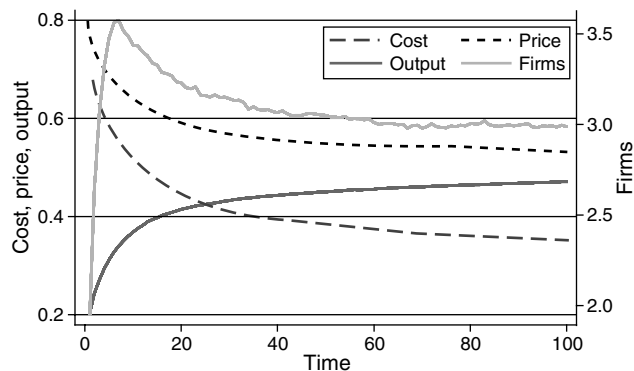
¹⁰ One of the interesting features of NK environments is that the greater the potential for interdependency in activities, the better the best possible low-cost (or high-quality) configurations of activities (Kauffman 1989). In other words, the best position achievable (the global optima) improves as the number of interactions (K) among activities rises. To increase comparability across industries, we decided to eliminate this feature of the NK specification by expressing individual firm marginal cost as one less the percent global attained plus a constant, so that higher values indicate lower cost. A constant is included to ensure that the best achievable marginal cost is greater than zero. Varying this constant has no bearing on our results.

¹¹ We assume $\alpha = 1$ and $\beta = 1$. Assuming $\alpha = 1$ is simply a scaling of the overall demand curve and does not, therefore, limit generalizability of the results. If one substitutes the individual production quantity function (Equation (5)) into the profit function (Equation (4)), it is clear that the slope of the demand curve β directly raises or lowers the output and gross margin for firms but does not change the relative output or relative gross margins among firms. By scaling gross margins up or down, however, more elastic demand will increase the disparity in profits among firms when there are positive fixed costs.

¹² For the results presented, we assume a pool of 20 potential entrants. Assuming a likelihood of attempted entry of 50%, the probability that all 20 firms would attempt to enter simultaneously is 0.000001. We experimented with larger and smaller pools and found that they did not substantively affect the results reported.

¹³ It is important that the comparison we are noting is among industries with different levels of potential for interdependency. Casual conversation sometimes suggests that innovative firms or technologies "create" new complementarities. We treat such innovations as occurring within the model whenever three or more activities interact ($K > 2$) and a firm changes one of these activities so that it is now more valuable to do two other activities in a given way than it was before.

Figure 2 Cost, Price, Output, and Firms over Time



Note. To increase comparability, we graphed the results from simulations with firms making decisions about 20 critical business practices ($N = 20$), where the practices range from completely independent ($K = 1$) to completely interdependent ($K = N$). For the analyses presented, we set parameters $\alpha = 1$, $\beta = 1$, $\lambda = 1$, and $\tau = 0.5$. Sensitivity analysis found that the general patterns presented persist at various parameter values.

sets (s_i) such that at entry each activity decision was equally likely to assume a value of zero or one.

Figure 2 presents averages over the 50,000 simulated industries of industry average marginal cost, industry output, industry price, and the number of firms in the industry over time. The results of our computational experiments conform to the classic stylization of industry dynamics observed by Gort and Klepper (1982): Costs fall at a decreasing rate, output rises at a decreasing rate, prices fall at a decreasing rate, and the industry undergoes a substantial shakeout as the number of firms producing first rises and then falls.

Our first three observations about industry dynamics (falling costs, rising output, and falling prices) follow quite logically from entry, learning, competition, and downward-sloping demand curves. Industry average marginal cost declines over time as more efficient firms enter and as incumbent firms learn more efficient combinations of activities. As gains are made, the discovery of more efficient combinations either by entrants or incumbents becomes more difficult and less likely, decreasing the rate of improvement in marginal costs. Transforming Equation (5), we see that as firms compete, falling average costs (\bar{c}_i) and increased participation (n) lead to greater industry output:

$$\sum_i q_i^* = n(\alpha - \bar{c}_i) / \beta(n + 1). \quad (7)$$

Finally, increased output with a downward-sloping demand curve leads to falling prices (see Equation (2)).

This dynamic pattern of diminishing rates of change in costs, output, and prices is quite robust across industries, both empirically and in our computational

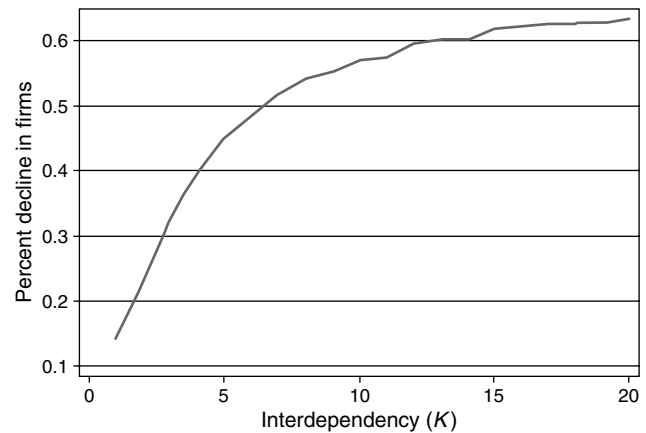
results. What is variable across industries is the degree of shakeout. Gort and Klepper (1982) report that the degree of shakeout can vary from no shakeout (0% reduction) to widespread failure and exit (77% reduction). In our model, we observe shakeouts that vary in severity from 0% to 87.5% (s.d. = 21.5%), with a mean shakeout of 51%. What may explain this variance?

In general, shakeouts occur when there is a drop in the number of firms that can compete profitably. In Cournot competition, the number of firms that are competitive (i.e., profitable) rises as firms become more efficient on average and falls when the variation in efficiency among firms rises. A simple intuition for these two effects on the number of competitive firms is that, in the first case, low costs mean a larger total market and, in the second case, greater variation in efficiency means fewer firms are likely to be competitive with the market leaders. This is easy to see from Equation (5): The probability of any one of the potential competitors having positive output and thus staying in the market (1) rises as the average cost structure falls and (2) falls as the firms own cost structure lags behind the average. Because efficiency rises consistently over time at all levels of interdependence (i.e., average marginal costs are falling), shakeout must be explained by the latter effect. To explain shakeout in our model, we must look to factors that lead to a rise in the variance in efficiency among firms.

We explore three potential sources of variation in efficiency and hence shakeout in our model: the rate of search (θ); the extent of knowledge spillovers, or imitation, by firms (γ); and the degree of interdependence in productive activities (K). Shakeout varies with the rate of search and the extent of imitation in unsurprising ways: Higher rates of search lead to less severe shakeouts. Rapid search by incumbents means that fewer firms enter the industry and more rapid imitation reduces the variance in efficiency among incumbents, thus reducing the peak industry participation and increasing the minimum industry participation. Much more interesting is the effect of interdependency on the degree of shakeout. In Figure 3, we present the average percentage decline in the number of firms from the peak to the end of our simulation runs across various levels of industry PIA, represented by our parameter K . We find that the degree of shakeout increases with PIA, but at a decreasing rate. What explains this relationship?

In the earliest stages of an industry, the dynamics are similar at all levels of PIA. Pioneering firms are relatively inefficient and have had little opportunity to learn and improve their operations. New entrants tend to be competitive and rush into the market. Incumbents with poor prospects for improvement are

Figure 3 Shakeout at Varying Levels of Interdependency (K)



Note. To increase comparability, we graphed the results from simulations with firms making decisions about 20 critical business practices ($N = 20$), where the practices range from completely independent ($K = 1$) to completely interdependent ($K = N$). For the analyses presented, we set parameters $\alpha = 1$, $\beta = 1$, $\lambda = 1$, and $\tau = 0.5$. Sensitivity analysis found that the general patterns presented persist at various parameter values.

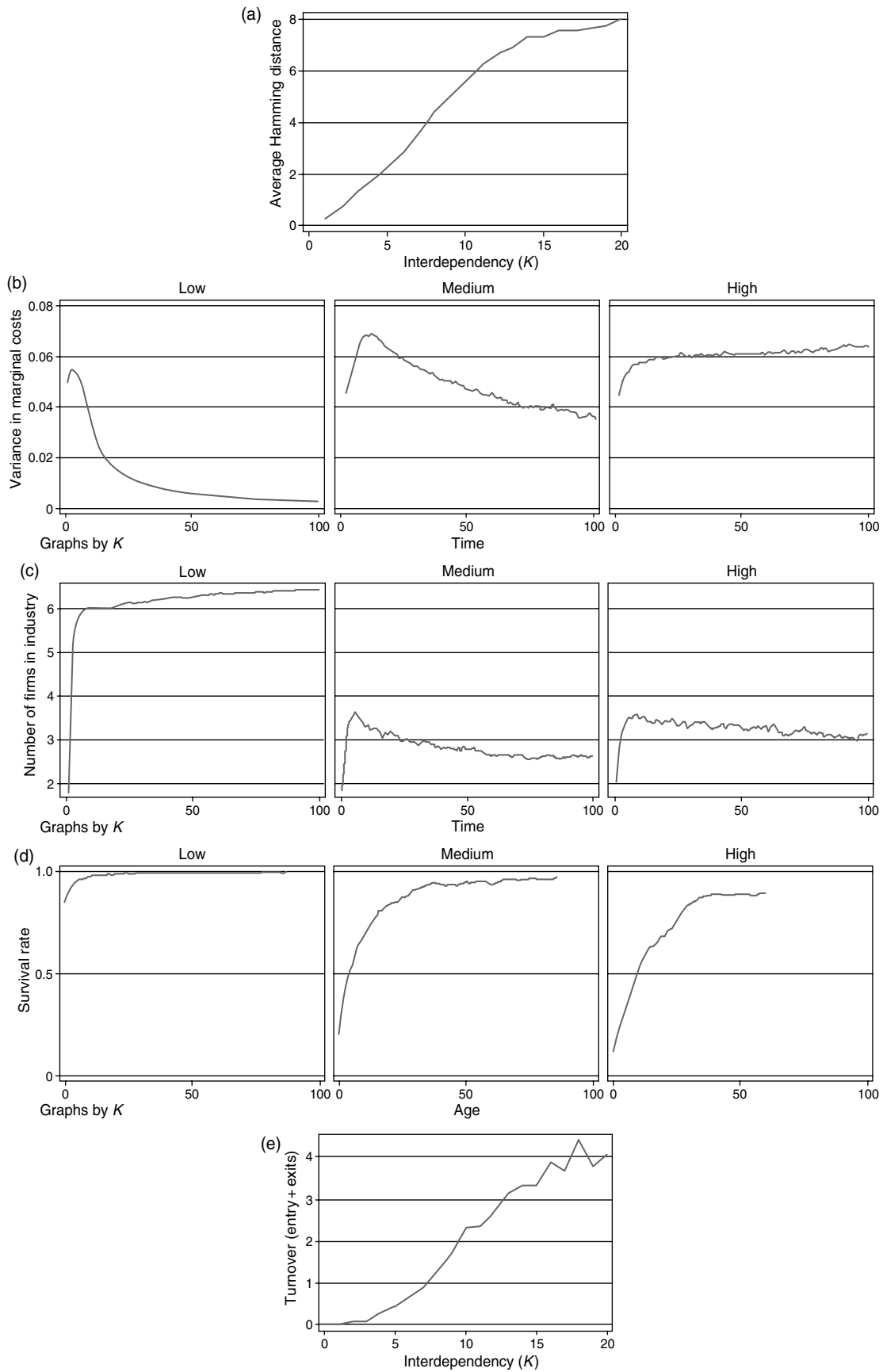
still competitive with their peers with more promising prospects. As firms experiment with other configurations of activities, new productive sets of activities are discovered driving down marginal costs, and the industry expands. During this period, we see a great deal of entry and little exit, resulting in a rapidly rising number of firms.

At very low PIA, as time progresses, variance decreases rapidly as firms generally discover the same (often the optimal) combination of activities. This is due to the relative simplicity of the decision problem facing managers in low PIA industries. Evoking the landscape imagery, all firms are climbing up a single large hill. We demonstrate this visually in Figure 4(a), which shows the relationship between PIA (K) and the mean Hamming distance between competitors' activity sets.¹⁴ At low levels of PIA ($K = 1$), the mean Hamming distance is near zero. In other words, firms are adopting almost identical configurations of activities. As a result, variance in firm cost structures falls over time (see Figure 4(b)), leading to a smooth rise in the number of firms with little or no shakeout (see Figure 4(c)).

At moderate levels of PIA, we see greater heterogeneity in firm activity sets (see Figure 4(a)). As the parameter K is increased, the number of local optima increases; that is, the landscape becomes more rugged. In essence, the manager's decision problem becomes more complex and fewer firms discover

¹⁴ The Hamming distance is a measure of similarity between two strings. The Hamming distance between two strings of equal length is the number of positions for which the corresponding values are different. In our model with binary values, the Hamming distance is equivalent to the Euclidean distance.

Figure 4 (a)–(e) Underlying Drivers of Shakeout



the optimal configuration of activities. We see a rise in the variance in efficiency as firms explore different regions of the decision space and become effectively “trapped” on local optima (see Figure 4(b)). In essence, differences in the learning rates of firms that experiment with different configurations of activities increases variance. As a result, performance tends to diverge over time. Those on “low hills” slow or stop progressing, while those on higher hills continue to learn and build an advantage over their peers and potential entrants. As at low levels of PIA, the learning advantages of incumbents reduce the number of competitive entrants. However, unlike low levels of PIA, incumbents are climbing different hills, and the difference between those on high and low hills leads to increasing rates of exit. As entry rates fall and exit rates rise, the higher-PIA industries shift from a period of rapid growth in participation to a period of shakeout until production is dominated by the most efficient players. As a result, we observe a sharp rise in the number of firms as the industry grows, followed by a decrease in the number of industry players (see Figure 4(c)). As laggard firms exit the industry, we see a subsequent decrease in the variance in marginal costs, as only efficient players with similar configurations of activities remain (see Figure 4(b)).

At very high PIA, firms rarely adopt similar combinations of activities. On average, 40% of firms’ activity choices (8 of 20) differ within an industry at $K = 20$ (see Figure 4(a)). Interdependency creates a highly nonlinear decision environment characterized by numerous local optima. As with moderate PIA, variance in efficiency rises as firms explore different regions of the decision space (see Figure 4(b)), and we observe a sharp rise in the number of firms as the industry grows, followed by a shakeout as efficient firms drive out inefficient firms (see Figure 4(c)).¹⁵ Interestingly, however, we do *not* observe a subsequent reduction in variance after shakeout at high levels of PIA (see Figure 4(b)).

¹⁵ While the fractional shakeouts we observe at higher interdependency are larger (Figure 3), shakeouts appear to be largest at moderate levels of K when the data are aggregated across runs (Figure 4). The eyeball calculation we can do from the aggregated data in Figure 4 is deceptive, because we lose information in the aggregation. At moderate levels of interdependency, the average absolute reduction in the number of firms is greater than at high levels of interdependency (Figure 4). However, at moderate and lower levels of interdependency, the average absolute reduction in the number of firms is more positively correlated with the maximum number of firms. The high positive correlation between the reduction in the number of firms and the maximum number of firms reduces the average fractional shakeout at lower levels of interdependency, as presented in Figure 3. Eyeball calculations on the averages for maximum and minimum from the aggregated data in Figure 4 cannot incorporate this correlation and thus overstate the average shakeout in industries.

At higher levels of PIA, local optima are more numerous but fairly similar in height (Weinberger 1991). Thus, while the variance in activity sets is high, variance in efficiency (i.e., marginal costs) is less severe. In other words, firms are trying different combinations of activities with relatively similar modest outcomes. While firms that survive the shakeout at moderate levels of PIA are likely to be on a trajectory toward the same combination of activities (i.e., on the same hill), firms surviving the shakeout at high levels of PIA are in a world with far more local optima and thus are unlikely to be on the same trajectory. This means that continued learning by the survivors reinforces exit in eliminating variance at moderate levels of PIA (as firms activity sets become increasingly similar), while survivor learning at higher levels of PIA does little to further eliminate differences.

Not only are incumbents more likely to be on different hills at higher levels of PIA, but these hills are less unique and less uniquely high. This last observation provides potential insight into the smaller survival benefits associated with age at higher levels of PIA. Under all parameterizations of the model, the longer a firm has been in the industry the more likely it is to remain in the industry for another period of competition. This is a natural outcome of improvement through innovation and imitation, as captured in the model. As the preceding discussion suggests, however, the advantages of age are less as the level of PIA rises (see Figure 4(d)). The few and high hills at lower levels of PIA mean that incumbents are likely to have found the highest peaks and to have accumulated substantial learning advantage over potential entrants. Thus they face little risk of a potential entrant discovering a higher position on a hill. As a result, entry and exit are relatively low post shakeout, and once established in the industry, firms tend to survive for long periods. The many and low hills at high levels of PIA mean that incumbents have scant learning advantages over potential entrants, who often happen on quite different hills that may be higher than those incumbents have already climbed. The result is that entry and exit stay high at high levels of interdependency and incumbents have lower survival rates. In other words, high-PIA industries experience greater turnover (entry + exit) (see Figure 4(e)).

5. Discussion

Across a number of literatures, a broad and robust set of empirical regularities have been observed with regard to industry evolution. This model is able to recreate the patterns observed in improvements in efficiency (continued but with less-substantial improvement as time passes), industry output (increasing at a decreasing rate), prices (steady decline at

a decreasing rate), and industry participation (rapid entry is followed by mass exit, leading to a shakeout and a stable number of competitors). Notably, the model explains these patterns absent the central mechanisms of past models, which relied on convex adjustment costs and scale economies in learning, and instead gives center stage to the managerial challenges involved in improving the internal workings of firms.

The model generates several empirical predictions not apparent in previous models of industry dynamics. We predict that shakeouts will be more severe in industries with highly interdependent sets of activities. Industries with the least shakeout will be ones where firms have the fewest interdependent decisions they can choose to vary, such as vertically disaggregated industries where firms use common suppliers, and highly regulated industries. Industries with moderate interdependency will see the variance in performance among firms fall after the shakeout, while variance in performance will remain high in industries with higher interdependencies. Undifferentiated industries with the most severe shakeouts will have the greatest variety in the ways firms conduct business. This means that while there may be a dominant design in the final product from the consumer's perspective, there will still be substantial variety in the organizational and technological processes that competing firms employ.

Our model also provides several empirical implications that directly conflict with the predictions of prior models. Shakeouts may occur without the combination of scale advantages in exploiting innovation and convex scale adjustment costs that serve, in prior models, to create variation and shakeout by skewing innovation effort toward firms that are already successful and thus large. Prior models predict more severe shakeout when industry leaders are better protected by scale advantages, and thus entry is uncommon. In contrast, our model predicts that the most severe shakeouts will occur in industries with the highest ongoing rates of entry and exit (i.e., turnover). Similarly, we predict that industries with the least shakeout will see most improvements made by incumbents, and industries with the most shakeout will see the greatest improvements made by new entrants. This is in direct opposition to what we would expect if scale advantages and convex adjustment costs drive shakeout; in that case, we would expect larger incumbents to have an even greater share of the innovations in industries that have the most substantial shakeout. We leave resolution of these conflicting predictions to empirical study.

Our model provides explanations for a number of theoretical and empirical conundrums. We provide an explanation for why we may observe high

variance in growth rates even in highly concentrated industries (see Caves 1998): interdependency creates different potentials for improvement among firms, leading to contraction among leading firms as higher potential laggards and new entrants eventually improve and overtake leaders. In addition, the fundamental attribute of our model—that the difficulty of search increases with interdependency—provides some interesting insight into the historic debate about the locus of innovation. In his early work, Joseph Schumpeter proposed that new entrants (entrepreneurs) were responsible for productivity gains. In later work, he argued that only large incumbent firms would have the resources and scale to support investment in R&D and consequently were more likely to drive innovation (Nelson and Winter 1982b). Our model provides a novel way of resolving Schumpeter's conflicting observations of innovation, led in some cases by entrants and in other cases by incumbents.

In low-PIA environments, incumbent firms contribute the vast majority of the overall industry efficiency improvement found during the period of simulation.¹⁶ This result occurs because of the ease of imitation and global success of local improvement, which leads to a low rate of entry, a high survival rate of incumbents, and the high likelihood that incumbent firms will attain the most efficient possible set of activities. As PIA rises, the difficulties of finding the best possible configuration of activities from any given starting point or through imitation leads to increased entry and exit and the high likelihood that later entrants will find superior sets of activities to those already discovered by incumbents. With the parameters chosen for the model, the drop-off in the importance of incumbent innovation is quite dramatic. Incumbents contribute more than 90% of the efficiency gains for low PIA, approximately 70% of the gains for moderate PIA, and less than 25% of the efficiency gains for high PIA.

In general, our results emphasize the importance of experimentation relative to incremental learning in industries with high interdependency in activities. New entrants lack the opportunity for incremental learning that results from past production, but they have a greater likelihood of considering a novel configuration of activities than incumbents. While we've assumed a strong form of experimentation for entrants (they choose randomly), entrants will have an advantage as long as the pool of potential entrants

¹⁶ We calculate the contribution of incumbents to efficiency by calculating the change in share-weighted average efficiency of firms that survived from the start of the industry and dividing this by the change in the share-weighted efficiency of firms at the start and end of the industry.

is more likely to consider a broader set of configurations than incumbents. One might conclude that incumbents should widely experiment with configurations to replicate entrants' proclivity for novelty. However, to the extent that there are costs to experimentation and limits to the amount of experimentation a firm can undertake in any given time period, a large population of potential entrants is at an advantage simply in the number of experiments they will run. This does not necessarily mean it is better to be a potential entrant, only that potential entrants are a greater threat in high-interdependency environments.

5.1. Robustness

We conducted our computational experiments over a wide range of parameter specifications. The results presented represent averages across these experiments. The general shakeout pattern observed results from the probabilistic entry of firms into expanding markets and differential rates of improvement in firms during this expansion. For very small markets (i.e., ones where our demand parameters, α and β , are set very low), it is feasible that the industry may not be large enough to support more than one or two firms, preventing overentry and shakeout. For very low entry rates (i.e., ones where our entry parameters, λ and τ , are set near zero), it is possible that pioneering firms will have sufficient time to improve before significant entry occurs and thus prevent further entry and shakeout. We view these as special cases that illustrate how our model can handle a wide variety of industry environments.

We advance that the general insights of our model are not necessarily tied to the narrow specifications we adopt. The NK specification is a simple, intuitive model of interdependencies. Arguably, any production environment in which the decision problem grows increasingly complex (in a narrow technical sense) should generate the requisite variety in firm activities. In the same vein, the key attributes of the Cournot specification are the notions that firms can survive even if they are not identical to the industry leaders, firms are more profitable when they have lower costs, and that substantially higher-cost firms are likely to be forced out of the market by substantially lower-cost firms. Other models of competition with these properties should be able to generate similar results, as long as they retain this attribute.

To test this last assertion, we modeled an alternative competitive environment, vertical differentiation (see the online appendix for model). We adopted a random utility model in which an individual consumer's utility is determined by the combination of price and product quality and a product-specific random component. Aggregating across consumers and firms generates a multinomial logistic demand equation

(McFadden 1974). Rather than compete on the cost of production, as determined by firms' activity sets (as in our Cournot specification), firms compete in terms of quality, where different combinations of activities lead to different quality levels. Computational experiments with our vertical differentiation model generated results similar to those generated using the Cournot specification (see the online appendix for results).

5.2. Limitations

For the sake of parsimony, we make a number of simplifying assumptions that may not match with competitive reality. As we have highlighted throughout the paper, we assume that there are no adjustment costs or scale advantages in innovating and learning. We do this to isolate the mechanisms of interest to us (interdependencies) versus previous treatments by Klepper (1996) and Ericson and Pakes (1995). We do not want to suggest that such costs and scale advantages do not exist. We simply want to point out that interdependency is sufficient to generate many of the stylized facts about industry evolution without these mechanisms and that interdependencies provide additional novel insights not found in previous models.

For our analysis, we assume that managers are rather myopic. When deciding to enter or exit the industry, managers look at their current profitability relative to other firms within the industry. If firms have different expectations about their improvement rates vis-à-vis their rivals, they may be willing to expect losses in the short run and higher profits in the future. Adding greater managerial foresight, however, is likely to exacerbate many of our findings. In low-interdependency environments, new entrants will recognize that they are unlikely to catch incumbents and will be even less likely to invest in innovation or even to enter the industry. In high-interdependency environments, new entrants realize higher improvement rates than incumbents and thus will be willing to tolerate losses in the short run, increasing entrepreneurial entry and turnover.

As a result of these assumptions concerning managerial myopia and no adjustment costs and scale advantages, we choose not to explicitly model the inputs to search (e.g., R&D) as an endogenous choice of the firm. In our model, all firms are assigned a constant search strategy (γ). One could imagine allowing firms to adjust γ given their position relative to rivals. Furthermore, one could assign different costs to different search strategies; for example, the costs of innovation could be more or less than the costs of imitation. We choose not to model this process because such an addition should have an effect on our results only if we included adjustment costs or scale advantages to innovating (which we purposefully do not

wish to include in the model). In future work, we plan to include such additions, as they do allow us to explore a host of interesting questions about favorable search strategies in interdependent environments.

The desire to provide a simple model imposes some limitations on the phenomena that we can explain. There are a host of known stylized (and likely some yet undocumented) regularities that this model does not address, such as patterns of change in ownership (Caves 1998), diversification, and changes in the balance of research and development efforts on products and processes (Klepper 1996). Small extensions to the model may allow the model to explain some of these patterns, and, if interpreted boldly, the rapid bunched alteration of activities that gives way to more sequential alteration of activities could be seen as explaining observations of rapid fundamental innovations giving way to more incremental innovations. However, more substantial extensions to the model are likely necessary to explain higher-level and additional patterns, such as changes in ownership. We leave these to future work.

5.3. Empirical Strategies

Analyzing the model reveals how industry dynamics vary, given the underlying interdependency in the firm's production function. For industries with the highest degree of interdependency we expect a greater increase and later a drop in the number of competitors, that is, a more severe shakeout, and greater turnover after shakeout. Perhaps most intriguing is the result that, in high-interdependency industries, variance in efficiency continues to increase even after shakeout. To the extent that we can develop reasonable proxy measures for interdependency, each of these dimensions on which industry dynamics vary becomes a potential target for empirical research. Developing good ways to measure the potential for interdependency in activities is one of the big challenges facing this broader line of research. We are exploring the use of questionnaire responses to identify the level of interdependency in an industry. Preliminary analysis suggests that such measures lead to intuitive results: Industries such as food products, logging, and wood products (e.g., kitchen cabinets) have a low potential for interdependency, but industries such as semiconductors, medical devices, and navigation systems have a high potential for interdependency. We leave a complete analysis to future studies.

Even without direct measures of interdependency, however, analysis of the model reveals interesting patterns of industry dynamics. We expect that marginal cost declines will be considerably lower in some industries (i.e., those with greater interdependency among activities), and these industries will not only

see slower price declines and smaller increases in output as we would naturally expect when costs fall more slowly in a competitive setting, but they will also see more severe shakeout and higher turnover with greater rates of both exit and entry than other industries. This is in many ways a surprising result; the least technologically progressive industries force the greatest reduction in participation and attract the greatest apparent attention of new entrants, despite average to poor performance. In doing so, they create the greatest risk for incumbents of being replaced.

6. Conclusion

A fundamental understanding of industry evolution is critical to strategy research. The mechanisms that impart advantage for some firms over others should be evident in their effects on industry dynamics, and their efficacy will likely be altered with the course of industry evolution. In this paper, we develop a model of industry evolution based on the presence of interdependencies among firms' potential productive activities. We demonstrate that the model can explain many of the stylized facts that have accumulated about industry evolution. More important, our model provides novel insights into why patterns may vary across industries.

By providing a rival explanation for industry evolution based on interdependencies and complementarities rather than on convex adjustment costs or scale advantages in innovation and learning, we have endeavored to create a closer link between key ideas stimulating work in business strategy and research on industry structure and dynamics. Strategy researchers have long relied on limitations to search and imitation to explain sustained heterogeneity among firms (Lippman and Rumelt 1982, Barney 1986, Carroll 1993, Levinthal 1995). Recent research has provided a leap forward in formalism by using the NK model (Levinthal 1997, Rivkin 2000) to represent basic concepts such as interconnectedness and causal ambiguity (Dierickx and Cool 1989) that have long intrigued researchers in the strategy field. These concepts are a natural element of a field that originated with questions of how managers understand connections and make tradeoffs among narrower functional considerations.

The study of the effects of interdependency on industry evolution provides a very useful mechanism for strengthening the connections between both past and future strategy research at the firm and industry levels. The robust set of empirical regularities that have been observed with regard to industry evolution are a much greater boon to strategy researchers if the models to explain those behaviors can connect them to concepts at the center of strategy research. The

marriage in this paper of a formal model of competition to an explicit representation of constrained search due to interdependency connects firm-level theorizing in strategy with industry-level theorizing and specifically with empirical work on industry dynamics.

7. Electronic Companion

An electronic companion to this paper is available as part of the online version that can be found at <http://mansci.journal.informs.org/>.

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