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The Organizational Evolution of Global Technological Competition*

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Abstract

Various industries are marked by rapid technological change and increasingly global competition. We explain how such developments provide a context for “Red Queen” competition, where organizational learning and competition accelerate each other over time. Arguing that competition stimulates organizational development, we predict that organizations experiencing a history of competition are less likely to fail. This implies that a strategy of technological differentiation generates short-run survival advantages, but backfires over time as isolated organizations suffer from increasing rates of failure. Also, we argue that the Red Queen magnifies differences in competitiveness among organizations due to underlying differences in their propensities to learn, so that technologically leading organizations are especially strong competitors. This strength, paradoxically, makes technological leadership a hazardous strategy because technological leaders must compete against stronger rivals. We find support for these conjectures in a study of the worldwide hard disk drive market, estimating organizational ecology models that allow for increasing global competition over time and that help to explain national differences in organizational survival rates.

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The Organizational Evolution of Global Technological Competition

Considerable attention goes to industries characterized by rapid technological change and global competition. From the perspective of individual organizations, such industries are difficult to penetrate and perhaps even more difficult to survive. In markets such as semiconductors, telecommunications, and computer hardware and software, we have seen many – sometimes the majority – of organizations failing, while the rate of technological change and the globalization of competition seem to intensify. That such fantastic progress has generated treacherous conditions for commercial organizations raises the dilemma first elaborated by Schumpeter (1934): In the extreme, it is hardly worthwhile for organizations to compete through innovation today only to be upended by a new innovator tomorrow. How can individual organizations find it worthwhile to enter into the innovative contests that so clearly benefit society as a whole, but just as clearly threaten the viability of those who participate?

Current thinking includes two possible strategies for dealing with the Schumpeterian dilemma. Schumpeter's resolution, still much in vogue, was the promise of great rewards for a strategy of technological leadership. His thinking was that organizations would innovate in order to enjoy so-called entrepreneurial rents, the returns that come with being positioned peerlessly ahead of the competition (Schumpeter, 1934). A second solution is the strategy of technological isolation, or differentiation – a possibility where markets contain differences based on dimensions such as geography or technology. Organizations sometimes find protection from competition by becoming adept at serving these isolated market positions. Most current research and theory on organizations in fast-changing markets focuses on the causes and consequences of these two forms of positional advantage. Consensus has it that to survive amidst rapid technological change and intensifying global competition, organizations must maintain a positional advantage either through technological leadership or differentiation. The remainders – those who run the race but fall behind – are thought destined for failure.

At first glance, the attractiveness of technological leadership or differentiation appears self-evident. Any debate, it seems, would be about how – not whether – to attain a positional advantage when faced with rapid technological change and increasing globalization. We think, however, that these strategies each carry with them unintended consequences that may, in some cases, make them particularly hazardous. To illuminate these unintended consequences requires that we understand the context of rapid technological change as an ecology of organizations. We portray organizations competing in an ecology of learning, in which change by one organization triggers change in others in a self-exciting co-evolutionary process dubbed the "Red Queen" by evolutionary theorists (Van Valen, 1973) – with reference to Lewis Carroll's Through the Looking Glass in which Alice comments to the Red Queen that, though she is running, she appears to be standing still. Indeed, although technological change may take place at a fantastic pace in absolute terms, what matters to organizations in competition are their relative positions – which may remain stable or even fall amidst the rapid changes taking place industry-wide. By thinking in terms of this coevolution, we identify some unintended ways that the strategies of technological leadership and technological differentiation may backfire, and we construct a model of global competition to explain national differences in organizational survival rates.

Dynamic Competition Among Organizations

Competition among organizations is powerful especially when triggered by innovation. Schumpeter (1950: 84) made this point in his classic description of innovation-based competition that “commands a decisive cost or quality advantage and which strikes not at the margins of the profits and the outputs of the existing firms but at their foundations and their very lives.” In this spirit, studies of such dynamic competition typically adopt a “racing” metaphor when describing the process. The image of organizations racing is explicit in many studies of technological leadership (Schoonhoven et.al., 1989; Lawless and Anderson, 1996; Lerner, 1997). More generally, the race metaphor is implicit in the various research traditions that are concerned with technological development in organizations and industry (Abernathy and Utterback, 1978; Dosi, 1982; Iansiti and Khanna, 1995). Organizations are known to follow different strategies when confronted with dynamic competition, as described in simulation models of competition between innovators and imitators (Nelson and Winter, 1982; Mezias and Lant, 1994). Others have investigated differences among organizations in their ability to successfully adopt new innovations in an effort to keep pace with industrial evolution (Tushman and Anderson, 1986; Mitchell, 1989; Henderson and Clark, 1990; Wade, 1996). Across these various distinctions, however, researchers by and large accept the underlying assumption that when firms compete on the basis of innovation, rewards go to the relatively swift at the expense of those left behind.

For organizations involved in dynamic competition, the racing metaphor implies that survival chances hinge on the ability to adapt (Haveman, 1992). Many researchers have asserted that organizations become increasingly adapted to their environment by learning over time (Stinchcombe, 1965) or with cumulative output (e.g. Ingram and Baum, 1997). Various research traditions allow organizational learning to be more or less adaptive (Aldrich, 1999). Nelson and Winter's (1982) model depicts organizations developing routines of varying adaptiveness, with the most adaptive organizations rewarded by increases in size. Consistent with this argument, Barron et.al. (1994) find that failure rates actually increase with age for those organizations that remain small. The possibility of maladaptive learning is elaborated by March and his students in models that allow for old lessons to become inappropriate (Levinthal and March, 1981; Levitt and March, 1988), and for high-variance "exploration" strategies to carry considerably greater risk of failure (March, 1991; Levinthal, 1997; Sorenson, 2000; Fleming and Sorenson, 2001). For all their differences, however, these various research traditions share a common understanding that in the face of dynamic competition, organizations are confronted with the need to adapt or fail.

These two central features of fast-changing industries – technological competition and an imperative to learn – are combined causally in the process of Red Queen evolution. Assuming that competition triggers learning, and that learning makes organizations stronger competitors, the result is a self-exciting process of organizational development and intensifying competition (Barnett and Hansen, 1996). Next, we discuss how the Red Queen describes industries characterized by rapid technological change, and then we apply these ideas to the worldwide market for hard disk drives.

The Red Queen

Our view of organizational learning builds on the model developed by March and his colleagues (March, 1988, 1994). Several of the basic assumptions in that model merit review. First, we assume that people in organizations "satisfice" when confronted with the need to make decisions (March and Simon, 1958). A so-called problemistic search for alternatives is triggered when performance falls below some aspiration level, and is continued until performance is considered satisfactory (Cyert and March, 1963). This search proceeds sequentially, presumably, stopping at the first satisfactory solution (rather than continuing until the best possible solution is found). Finally, search is assumed to remain "local," restricted to solutions that are only incrementally different from current practice, only moving to more distant possible solutions when no satisfactory local solutions are found. By these assumptions, then, we portray organizations as adapting incrementally in an effort to maintain at least a minimum, satisfactory level of performance.

Now consider a population of competing organizations, each behaving according to the satisficing model. In this context, the organization-learning process does not end once a given organization improves its performance by adopting some new practice. Instead, the innovating organization, by improving its own performance, now has increased the intensity of competition felt by the other organizations in the population. At some point, this increased competitive intensity will reduce performance in other organizations enough to trigger search in these organizations. As each of these organizations finds solutions that restore its performance, in turn, competition again increases for the rest of the population – again triggering the search for improvements.

So learning and competition are linked causally, each accelerating the other in the ongoing process of Red Queen evolution.

Red Queen evolution has several noteworthy properties. High rates of absolute change may conceal a relatively stable configuration of players – thus the reference to Lewis Carroll's Red Queen (quoted in Van Valen, 1973) and her statement that "in this place it takes all the running you can do, to keep in the same place." To identify competitive positions, then, we will need to identify the *relative* positions of organizations, and to note when change occurs in these relative positions. For instance, in the disk drive market organizations often moved backwards in relative position even as they improved their technologies greatly in absolute terms, because rivals were improving their technologies at an even faster rate. In fact, some of the fastest *relative* movements among disk drive manufacturers occurred in cases when a firm did not change much in absolute terms while everyone else continued to change. Like a stopped car on a freeway, the fastest-mover in relative terms may be the one who is standing still (see Stuart and Podolny, 1996).

Relative position is important to defining aspiration levels. To the extent that aspiration levels are socially constructed, references to relative standing help members of organizations to define when performance is a "problem" to begin with (March, 1994). In the context of the Red Queen, the ongoing progress of the larger organizational population suggests that aspiration levels will also increase over time (Miner and Haunschild, 1995). Furthermore, to the extent that organizations "benchmark" from high-end outliers in the population, aspiration levels are even more likely to increase over time – further accelerating the pace of change.

Another noteworthy property of Red Queen evolution is that large-scale change develops over time through a series of many, self-accelerating but incremental steps. Ordinarily large-scale change is portrayed as taking place in discrete "reorientations" that redefine the basis of competition at a moment in time (Tushman and Anderson, 1986). Red Queen evolution, by contrast, explains the experience of industries where large numbers of individually marginal changes cumulate over time into dramatic technological progress (see Levinthal, 1998). Such a process characterizes the hard disk drive industry, where many innovations have accumulated over time – and at an increasing rate – into a record of dramatic technological improvement (McKendrick et.al., 2000).

Finally, one particularly attractive feature of the Red Queen is that it allows for changes to happen throughout the many, disparate parts of a complex organization. In contrast, models of evolutionary processes among contending rivals sometimes are depicted in anthropomorphic terms, in which organizations are portrayed as strategists making choices in contention with each other. Yet organizations caught up in the fray of rapid technological change may be reacting on many fronts at once, or in a number of distinct, disconnected reactions – each resulting from a process of satisficing in some part of the organization but without any one actor strategizing in the larger evolutionary game (Burgelman, 2001). In this way, our thinking allows many, individually small responses to have cumulatively large strategic impact – but without requiring less plausible assumptions of overall strategic intent.

Implications for Differentiation

Red Queen evolution has several testable implications for organizations competing in rapidly changing industries. One immediate implication is that organizational learning is driven by exposure to competition. Under conditions of Red Queen competition, organizations that have endured competition are more likely to have learned. To the extent that learning enhances organizational survival, we predict: *the more that an organizations has endured competition, the greater its chances of survival.* Note, however, that this result could come about without individual organizations learning, but rather through a process of differential selection where "fit" organizations survive competition while "unfit" organizations are culled from the population. The more competition an organization has endured, by this thinking, the more likely it is to be one of the fit organizations and so the more likely it is to have a low failure rate. We grant that some Red Queen evolution will be driven by selection rather than by the processes of organizational learning that we describe. However, we doubt the extreme position that no learning takes place whatsoever, and that all differences are due to differential selection. Reality, we expect, will include some organizations learning from competition as well as some culling through differential selection. In any case, whether through learning or selection, we expect that organizations will have greater survival chances if they have endured more competition.

Our prediction implies that neither development nor obsolescence is "built in" to the process of organizations aging. Rather, whether and how organizations develop over time hinges on whether they are exposed to competition. Organizations that have endured competition are likely to be better adapted, and may even appear to have moved down a "learning curve." By contrast, organizations that have remained isolated from competition will not have been spurred by Red Queen evolution, and consequently are more likely to exhibit liabilities of senescence and obsolescence as their ages increase (Barron et al., 1994). In neither case, however, will these outcomes be the inevitable outcome of aging (cf. Christensen and Rosenbloom, 1995). Rather, we think that change in survival chances over time depends on whether organizations have been exposed to competition.

Our prediction reveals a possible unintended consequence associated with the strategy of technological differentiation. A large literature in organizational ecology documents that competition is *localized* on various dimensions, with organizations more likely to compete with one another the more that they "overlap" in the same ecological niche (McPherson, 1983; Hannan and Freeman, 1989; Baum and Mezias, 1992; Baum and Singh, 1994; Podolny et.al., 1996). In particular, organizations face less competition, and so are more viable, the more that they are differentiated on various dimensions – including technology (Podolny et.al., 1996) and geography (Carroll and Hannan, 2000: 233), the dimensions most relevant to the disk drive market. Our prediction suggests that organizations pay a hidden cost for such differentiation. Isolation from competition has obvious current-time benefits, but also has the less-obvious downside that it deprives an organization of the engine of development. The more that change is driven by Red Queen evolution, the more that there will be a trade off between positional advantage that isolates an organization from competition, and the advantages that come from the development of new capabilities. In this way, positional- and capabilities-based advantage may be inversely related, with those in safe places enjoying their positions but suffering over time as they fall behind those who remain in the race.

Implications for Technology Leadership

To see the implications of the Red Queen for the strategy of technology leadership, consider that organizations are likely to differ in their ability to learn, and that Red Queen evolution is likely to magnify the importance of these differences. As Cohen and Levinthal (1990) argued, organizations are likely to differ in their ability to assimilate and act on information. In short, some organizations learn better than others. Playing one iteration of the Red Queen, we would expect to see relatively adaptive organizations improve more than relatively inert ones – although these differences might be very minor. Played over and over in the ongoing process of Red Queen evolution, however, these differences will magnify with each successive response, sorting among organizations in the race so that relatively adaptive firms far outpace those in the back of the pack. Eventually, this sorting process is likely to generate large differences across the fitness distribution of organizations.

If we assume that organizations generate stronger competition the more that they adapt through the Red Queen evolution, then this fitness distribution will reflect differences in the competitive intensity generated by organizations. At the top of the distribution will be the most formidable competitors – those that have fared best at responding to repeated competitive challenges (see Lerner, 1997, for evidence of this in the hard disk drive market). At the other extreme will be those organizations that are losing the race and that generate relatively weak competition. If the competitive game were to be decided by this ranking, those at the slow end of the race would be crushed when placed next to the formidable competitors in positions of technological leadership. It is this comparison that analysts have in mind when they advocate technological leadership in industries marked by rapid technological change.

The implications are quite different, however, if ranking in the race corresponds to segmentation of the market into technological niches. In many industries, more advanced and less advanced technologies each appeals to different customers, requires different inputs, and often competes on a different basis (Podolny and Stuart, 1995). Certainly this has been the case in the disk drive market, where low-capacity products and high-capacity products are suitable for entirely different markets (McKendrick et.al., 2000). Under such conditions of market segmentation, sorting into high and low positions in the technological race decides whom one must compete against – akin to "choosing the right pond" (Frank, 1987; Park and Podolny, 2000). Those who run behind in low-end positions may be weaker competitors and in that sense may have "lost" the technological race, but in that market segment they confront only the weakest competitors – the other organizations at the low end of the distribution. Meanwhile, the "winners" of the technological race have to compete against the most formidable competitors in the industry. Ironically, this means that *the fastest players in the race may end up failing precisely because they are in a leadership position* – the position where the strongest competitors reside. With market segmentation, then, Red Queen competition is likely to sort organizations into low and high-end niches, with technology leaders facing the strongest competition.

Implications for Global Competition

Sometimes with rapid technological change comes worldwide competition among firms in an industry, as has been the case for the disk drive manufacturers that we study. What are the implications of the Red Queen for patterns of global competition? To address this question, first note that when firms from different countries compete, cross-national differences among organizations become apparent – differences that remain unnoticed when firms remain confined within the boundaries of domestic markets (Anand and Kogut, 1997). National context – including for example people and their expertise, culture, technologies, social structures, industrial networks, and political and market institutions – arguably creates similarities in the strengths and weaknesses shared by organizations from the same country (Porter, 1990; Kogut, 1992; Nelson, 1993). Some have speculated that such cross-national differences might account for much of the observed worldwide variations we see in the viability of firms (Chandler, 1994).

We are curious whether national differences among firms' survival chances might, in fact, reflect national differences in Red Queen evolution. Although there are obviously many factors that may account for differences in the viability of firms from country to country, we are intrigued by the possibility that some national markets may have experienced more Red Queen competition than others – as implied by Porter's (1990) framework describing the national origins of firms. Extending our idea that exposure to competition accelerates learning and so increases a firm's survivability, we are curious whether *firms based in countries marked by a history of competition may be more likely to survive than firms from less competitive domestic markets*. If so, then observed national differences in organizational survival rates will depend on the degree to which organizations have been exposed to domestic competition.

A related question concerns national differences in the competition generated by firms. Does it matter whether an organization's rivals are foreign or domestic (Zaheer and Mosakowski, 1997)? At one extreme, if a firm's domestic rivals generate very strong competition while potential rivals from other countries generate none, then market competition can be seen as strictly domestic. (This idea is implicit in most organizational ecology models of competition applied to different geographic areas. See Carroll and Hannan, 2000.) At the other extreme, if the strength of competition generated by both domestic and foreign-based rivals is equally strong, then competition can be regarded as global. At any point in time, observed patterns of competition in an industry could be described as more or less global depending on how much it resembles one of these two extreme cases. Thinking in terms of the Red Queen, we are curious whether global competition develops over time as firms coevolve. Early on, when the Red Queen is young and so organizations are less developed as rivals, they might generate only limited, domestic competition. *As time passes and organizations develop, however, the competition generated by organizations should become more global in its impact*. If we are correct, then Red Queen development is behind the often-discussed globalization of competition. Furthermore, such globalization implies the blurring of differences between domestic and foreign rivals, with the two becoming increasingly indistinguishable over time – a prediction in sharp contrast to the idea that national differences persist as organizations compete globally (e.g. Porter, 1990).

A Model of Global Technological Competition

We investigate our ideas by estimating ecological models of competition on data describing all manufacturers of hard disk drives – an appropriate context given its history of rapid technological change. Ecological models are well suited to testing our ideas because they allow for the explicit estimation of competition among organizations. The so-called density dependent model allows each organization's viability to vary as a function of the number, or density, of other organizations in the population (Carroll and Hannan, 2000). Failure rates are thought to be non-monotonically related to density, falling with initial increases in density as legitimacy increases but ultimately increasing as competitive effects grow with crowding in the population (Hannan and Freeman, 1989; Hannan and Carroll, 1992). Furthermore, persistently higher failure rates are found for organizations facing greater density at the time of their birth – the so-called density delay effect attributed to problems caused by building an organization under adverse conditions (Carroll and Hannan, 1989). Our model will include these various density effects. For our purposes, the effects of disaggregated and weighted densities will also be estimated, because these allow for competitive intensity to vary across technological niches and over time (Barnett, 1997). In particular, we need to allow for competition to depend on both technological and geographic differentiation.

Beginning with geographic differences, our model treats the extent of global competition as an empirical question. Specifically, we estimate the model:

$$r_j(t) = r_j(t)^* \exp[\alpha_d N_d + \alpha_f N_f],$$

where r_j is the failure rate organization j which is allowed to vary as a function of its market tenure t, $r_j(t)^*$ is the baseline failure rate for organization j estimated as a function of observables, N is the number of rival organizations confronted by j (not including j) from its domestic market (subscript d) and from foreign regions (subscript f), and the coefficients α allow us to detect ecological competition – where increases in the number of rivals drives up j's failure rate. If competition is stronger from domestic rivals than from foreign rivals, then we will find $\alpha_d > \alpha_f$. If competition is "global," such that competition is just as strong from a foreign-based rival as from a domestic one, then we would expect to find $\alpha_d > 0$ and $\alpha_f > 0$, but will be unable to reject the null of equality between these competition coefficients.

We also adapt the model to test for changes in the globalization of competition over time. We run this test in two ways. First, we test to see whether foreign competition increases in intensity as a function of the competitive experience of foreign rivals, as one might expect based on Red Queen reasoning (see Barnett and Hansen, 1996). The second specification allows the intensity foreign competition to change with calendar time, so that all rivals become more globally potent over time. This specification is an adaptation of the approach developed by Hannan, 1997. These two specifications are estimated alone and together to see which, if any, pattern of globalization appears in our data.

Our arguments about technological differentiation suggest that we should operationalize density using technology overlap measures as well as simple counts (see Carroll and Hannan, 2000). These overlap measures equal density counts if all organizations compete in all technological areas. For any of j's rivals that overlap j's technological domain only partially, however, they contribute to j's overlap score only in proportion to their degree of overlap. We specify the possible technological domain of each organization j to include *relatively* low-, medium-, and high-capacity positions in each of the various “form-factors” (diameters) of hard disk drives that existed in a given year. (The emphasis in Red Queen evolution is on relative position, so we defined these relative levels to account for changes over time in absolute capacity as we explain in the Appendix.) For instance, an organization j offering both 3.5-inch and 5.25-inch products in a given year could have been in any of 6 technology segments: low-, medium-, and high-capacity within the 3.5-inch form factor and low-, medium-, and high-capacity within the 5.25-inch form factor. If organization j were in all 6 of these segments, then a rival that overlaps this organization in only 1 of these 6 segments would contribute 1/6 to j’s technology-overlap density score. By contrast, a rival that offered products in all 6 of these areas would contribute 1 to j’s technology-overlap score. At the extremes, if an organization produced in the same form factors and capacity levels as all other manufacturers, then for it the technology-overlap density would equal simply the number of other organizations. If an organization did not overlap with any other manufacturers, however, then its technology-overlap density would equal 0 reflecting its complete technological differentiation. For each firm in each year we disaggregated the raw count of its rivals into technology-overlap and non-overlap densities. If competition in the industry was technologically segmented, as we suspect, then failure rates will be driven especially by overlap density as opposed to non-overlap density.

We further refined this specification to allow for separate competitive effects among firms within the (relatively) high-end niche and among those within the (relatively) low-end niche. (In many instances, the numbers of firms at the high-end in our data were too small to obtain meaningful estimates of density effects for that category. Consequently, the medium- and high-capacity levels were combined to create a single high-end density measure in contrast to the low-end density measure.) This specification allows us to test whether, in fact, there are distinct high-end and low-end niches in disk drives, and whether stronger competition made the high-end niche more hazardous as we suspect.

Following our discussion of the Red Queen, we specified $r_j(t)^*$ to test for the survival implications of each organization j's exposure to competition. For each organization in each year t, we measured the sum of its domestic technology-overlap density score in each previous year from its birth through year t-1. If exposure to competition enhanced survival chances, as we argue, then this variable should reduce exit rates. We also estimated a more complex specification of prior exposure to competition – one that put more weight on more recent years – in order to investigate whether old, possibly outdated experience drives up failure rates while only more recent experience is survival enhancing (Barnett and Hansen, 1996).

Each organization's technology mix is measured using variables that sum the number of form factors (of different relative capacity levels) in which the firm had product offerings. For example, a firm with low-capacity product offerings in three different form factors would have a measure of 3 for "number of low-capacity form-factors produced." If this firm also produced medium-capacity products in four form factors and high-capacity products in one form factor, then it would also have a measure of 5 for "number of medium- and high-capacity form factors produced." These variables mirror the technology-overlap densities, and allow us to investigate whether and how being relatively ahead or behind in the technology race affected survival rates.

Various control variables also are included in our specification of $r_j(t)^*$.   Calendar year is included to control for secular trends not otherwise captured in our specification.

Indicator variables are included for the region of the global economy where each organization was headquartered, with North America serving as the left-out category. Indicator variables are also included measuring whether or not a given organization in a given year was producing in a given form factor. Because organizations could be in any or all form factors at once, there is no left out category among these indicators. Organizational size is specified using two variables. One measure is a simple indicator variable set equal to 1 for large organizations and set equal to 0 otherwise. (For years prior to 1976, this designation was made by examining historical documents to identify major players in the industry in each year. For observations after 1976, we relied on the data source Disk/Trend.) We also have a measure of size in terms of the dollar value of hard disk drive sales, but this measure was available only for large organizations and only after 1976. Both variables are included in all models. Finally, we include two different measures of strategic differences among these organizations. An indicator variable is included for firms engaged in any "captive" production (vertically-integrated production of drives for their own use in making computers), and is allowed to vary from year to year for each firm. Following Carroll et. al. (1996), we also include an indicator variable to distinguish between *de novo* firms – those that entered the industry as a start up – and *de alio* entrants who moved or expanded into the industry from some other industry.

We modeled the failure rate using a piecewise-exponential specification for each organization's market tenure. This is an extremely flexible specification that allows failure rates to change freely from period to period. We selected periods to be as fine grained as possible while not being so short as to prevent the estimation of statistically meaningful effects. Note that many studies measure t in terms of organizational age, but instead we measure t in terms of market tenure. For *de novo* firms that are born as hard disk drive manufacturers, age and tenure are the same. Firms with operations in other markets, however, may have been born before they entered the hard disk drive market. In these cases market tenure differs from organizational age and tenure rather than age is used in our analysis.

We estimated the instantaneous rates of failure among these firms using the software package TDA (Blossfeld and Rohwer, 1995). This is a widely available, standard package that allows the estimation of our piecewise exponential model, and that takes into consideration the fact that some organizations do not exit by the end of the sample period. Estimates were obtained with the data segmented into organization years, as described in the Appendix, so that time-varying independent variables could be updated from year to year.

The Market for Hard Disk Drives

Hard disk drives (HDDs) are magnetic storage and retrieval devices used with computers and are increasingly found in a number of other applications. The main components include disks, recording heads, a motor, an actuator mechanism, and electronics. Data are stored on a platter made either of glass or, more commonly, a rigid aluminum alloy that is coated with magnetic material, and the motor rotates the platter. Data are read from and written to the platter by a tiny read/write head flying just above the platter without making contact. The HDD has an actuator arm similar to a phonograph that moves the head to the proper place above the platter. Once in position, the head retrieves the information, transfers it to the computer's central processing unit (CPU), and the information appears on the screen of the monitor.

The defining characteristic of competition in the industry has been the race among firms to deliver higher storage capacities on ever-smaller devices. Since IBM manufactured the first movable-head disk drive in 1956, the industry has undergone tremendous technological change, much of it led by IBM. Although technological advances in semiconductors have generally been credited for most of the price and performance improvements in computers, fewer people are aware that progress in disk drive capacity kept pace. The amount of data that can be stored on a square inch of a disk grew almost 30% per year between 1957 and 1990, and since 1991 has increased about 60% a year. This has translated into enormous increases in storage capacity at low prices. IBM's first disk drive offered 5 megabytes of storage; the largest disk drive shipped in 1997 offered an astonishing 47 gigabytes of capacity. The *average* disk drive capacity as recently as 1991 was 145 megabytes; in 1997, it was 2.65 gigabytes. The price per megabyte of storage fell at an annual rate of 40% between 1980 and 1996 (CRN, 1997). Average price per megabyte in 1991 was $5.23, plunging to 10 cents in 1997; and during the same period disk drive manufacturers doubled the capacity of a disk drive every 18 months while keeping unit prices constant.

Following IBM, some 30 firms entered the industry between 1960 and 1970, a period of considerable technological experimentation. Between 1957 and 1963, disk drives were fixed, refrigerator-sized units, often weighing more than a ton. While IBM's original disk drive employed a 24-inch form factor, other companies introduced drives using disks as large as 39 inches. IBM's early disk drives used 25-50 disks stacked on a vertical spindle; Bryant Computer Products, an early competitor, arrayed 24 of its enormous 39-inch disks along a horizontal shaft. Only after 1963, when IBM introduced a 14-inch disk drive using removable "disk packs," did the industry begin to converge on that form factor. The disk pack drive offered an elegantly simple solution to the problems faced by mainframe computer customers, who continually demanded more -- and more reliable -- storage capacity. Fixed disk drives faced technological and operational constraints. Removable disk packs allowed users to enjoy virtually unlimited storage, though most of it was "off-line." And IBM continued to improve the technology, especially the arm positioning technique and lower flying height of the head, both of which increased recording densities. Even so, 24-inch and larger fixed disk drives coexisted with the disk pack for a short while and continued to be shipped into the early 1970s.

The industry has included some captive manufacturers who produce drives for their own computer products, non-captive manufacturers who produce for sale on the market, and firms who engage in both captive and non-captive production. Most manufacturers have been non-captive, benefiting from so-called "plug compatibility" – where peripherals and components could be produced to standard specifications and then assembled into various computer models. These manufacturers often introduced disk drives that were identical copies of IBM's removable disk pack drives, but with faster access times and much lower prices (Frost, 1970; Dorfman, 1987; Christensen, 1993, 1997). Plug compatibility was not limited to IBM systems – though it was far and away the largest customer – but extended to systems made by other computer manufacturers as well. Memorex, Potter Instrument Co., Marshall Data Systems, CalComp's Century Data

Systems Division, and Information Storage Systems emerged as the most prominent plug-compatible disk drive makers. Other operations such as Iomec, Electronic Memories' Caelus subsidiary, and Computer Memory Devices offered 14-inch cartridge drives for the emerging minicomputer industry, as did IBM. Figure 1 shows how the numbers of all hard disk drive manufacturers changed over time. Table 1 describes our data, constructed as described in the Appendix.

Insert figure 1 and table 1 about here

A parallel trend was evident in Japan and Europe, although on a smaller scale. In Japan, the principal computer companies made their own disk drives: NEC, Fujitsu, Hitachi, and Toshiba all entered in the mid-to-late 1960s. Although Hitachi began to market its IBM-compatible disk drives in the U.S. in 1968, for the most part the size of the market for Japanese computers limited the market for their disk drives. A smaller domestic market also meant fewer independent Japanese disk drive companies entered in the 1970s as alternative sources of supply, namely Mitsubishi and Hokushin Electric Works. In Europe Siemens and Philips made disk drives for their own computer systems, while Data Recording Instruments (Europe's first firm to ship hard disk drives), Compagnie des Computeurs, and later BASF produced for the market. Compagnie Internationale de l'Informatique, or CII, (which later was merged into CII-Honeywell Bull and then Bull Peripherals) and Sperac (the peripherals maker established under France's Plan Calcul computer policy and ultimately absorbed by CII) engaged in both captive and non-captive production. In Eastern Europe COMECON mandated a geographical division of labor for the computer industry, with DZU of Bulgaria designated as the principal disk drive supplier for all computers in the region. Despite the directive, Control Data established a joint venture in Romania, ROM Control Data, that made peripherals including disk drives. Figure 2 shows the numbers of manufacturers by home region over time.

Insert figure 2 about here

During the 1970s, captive production remained the largest channel for disk drives, reflecting IBM dominance, though the relative importance of the market for HDDs grew among computer manufacturers (sometimes called original equipment manufacturers – OEMs – in this context). Led by Control Data, Diablo Systems, CalComp and Memorex, the non-captive market reached $631 million in 1979, but was still well below the $2.8 billion associated with captive production (Disk/Trend, 1980). In 1979, American firms had 81.1 percent of the global HDD market, Japan 14.3 percent, and Europe the remainder. Between them, IBM and Control Data comprised just short of 40 percent of the market.

A turning point in the history of the industry occurred in November, 1973, when IBM shipped the 3340 disk drive, which became known as the "Winchester" and set the standard for disk drive architecture (Christensen, 1997). In a sense, the Winchester returned the industry to its beginnings: The original IBM, Bryant and Data Products drives were all fixed drives. Though the removable disk packs offered the advantages of convenience and unlimited storage, they were subject to contamination. For example, a single smoke particle – which is larger than the distance between the flying head and the disk – can damage the disk. At the same time, higher densities could only be achieved by lowering flying height and by preventing particles from interfering with the head-media interface. The Winchester technology bundled the heads and disks together in one sealed box. These and other controls enabled the recording head to fly lower and the drive to achieve greater storage capacities. Although the older technologies continued to find markets well into the 1980s, technological progress in the industry since the introduction of the Winchester drive has involved improving upon and miniaturizing the basic Winchester architecture. Form factors decreased from 14-inches to 8-inch diameters in the 1970s, 5.25-inch and 3.5-inch in the early-to-mid 1980s, and 2.5-inch drives for notebook computers in the late 1980s to early 1990s.

The debut of the IBM PC in 1981 accelerated these developments. The PC defined the dominant design in the industry for many years (Langlois, 1992; Anderson, 1995). In addition to setting the standard for what a desktop computer should look like, it featured an open architecture that attracted the entry not only of some of IBM's established mainframe and minicomputer rivals but start-ups that set out to manufacture IBM clones. Compaq and Dell became two of the most important American entrants, but many of the new clone makers emerged outside the U.S., especially Taiwan, Korea and Japan. The same open architecture that attracted the new clone manufacturers also stimulated entry into peripheral equipment. While mainframe and minicomputer manufacturers made many of their own peripherals and components, personal computer companies outsourced their production almost entirely.

Similar dynamics developed in the HDD industry as disk drives were adapted to fit into a PC. There was an explosion in new entries after 1980, when the first drive designed for a desktop computer was introduced. (Figure 3 plots entries and exits in the HDD market over time.) Attempting to build on their success in other peripherals, several Korean and Taiwanese firms entered, as did a dozen Brazilian manufacturers protected by that country's "informatics" policies. More than 100 firms entered after 1980, but the ensuing shake out pared the number of participants appreciably. By 1998, the end of our study period, fewer firms made disk drives than at any time since 1968. The HDD graveyard is crowded with prominent American, European and Japanese companies. Genereal Electric, Burroughs/Unisys, Conner Peripherals, Hewlett-Packard, Mitsubishi, Matsushita, Olivetti, BASF, Sony, Philips and Siemens are among the formidable firms forced to exit the industry. By the end of 1998, hard disk drives had become a $28.8 billion industry, with only a handful of American firms holding 80% of the global market, Japanese 14%, and Korean firms accounting for most of the remaining 6%.

Insert figure 3 about here

<u>Results</u>

We report estimates of baseline models in Table 2. Model 1 includes the effects of market tenure, calendar year, region effects (with North America as the left-out category), form-factor indicators, and the number of form factor product offerings at different relative capacity levels for each organization. Model 2 also includes our measures of organizational size, and Model 3 includes all of these variables as well as indicator variables for organizations engaged in any captive production and those that were founded *de novo* (as opposed to *de alio*). When the size measures are included in Model 2, their strong negative effect dramatically reduces the effects of the number of product offerings. These product measures had been strong and negative in Model 1, apparently spuriously reflecting a size effect. Also, with size controlled in Model 2, market-tenure dependence becomes clearly positive; older organizations are more likely to exit but this effect is not seen until the advantages of size are controlled, the pattern identified by Barron et.al. (1994). (The market tenure effects are interpreted by comparing each of the piecewise effects from tenure period to tenure period.)

Insert table 2 about here

Tables 3a and 3b report estimates of models that include various specifications of density, including technology-overlap densities. Model 4 has all the variables that are in Model 3 as well as density, density squared, and density at founding. These aggregate density terms do almost nothing to improve the model statistically, nor does the simpler specification of Model 5 that includes only aggregate density (without the squared term or density at founding). Model 6 disaggregates the worldwide density term into two separate terms, one for the number of organizations from each firm's home region, and the other counting the number of organizations from regions other than a firm's home region. This specification reveals two strong, opposing patterns. Organizations in a firm's home region generated statistically significant competition, while organizations from other regions actually generated mutualism – reducing a firm's failure rate. This pattern is consistent with models that reveal geographically localized competition together with life-enhancing legitimacy effects coming from increases in numbers of organizations over broader geographic areas (Hannan and Carroll, 2000).

Insert tables 3a and 3b about here

Models 7 through 11 look at more refined specifications of the domestic competition found in Model 6. Model 7 separates the domestic density term of Model 6 into two parts, one measuring the degree of technology overlap each organization has with its domestic rivals and the other term measuring the degree of non-overlap. The estimates in this model show competition coming largely from technologically overlapping rivals. This competitive effect is twice as strong as the competition effect estimated in Model 6, which did not take technology overlap into account, and is nearly three times as strong as the competition generated by non-overlapping domestic rivals.

Models 6 and 7 show a puzzling pattern of effects for a firm's product position. (See the effects of the "number of low-capacity form factors" versus the "number of medium and high-capacity form factors.") It appears, once domestic competition is isolated, that firms are more likely to survive if they fall behind in the technology race, with the survival-enhancing effects of low-capacity production twice that of medium- and high-capacity production. The specification in Model 8 completely eliminates this difference, however. Model 8 allows the strength of competition to differ, depending upon whether a rival is technologically advanced or retarded. As we expected, technologically advanced rivals generated stronger competition – competition that was nearly twice as strong as that generated by technologically slow rivals. Controlling for this difference then eliminates the apparent survival-enhancing effect of being technologically behind. Low-capacity firms had the advantage of competing against weaker competitors. By contrast, firms in positions of technological leadership were plagued by extremely powerful competition from the formidable rivals they faced in that niche.

Model 9 includes the effect of a firm's prior (domestic) competitive experience on its own exit rate. This variable lowers the chances of exit, as expected. Conditional on survival, firms that have faced more competition in the past are less likely to fail. Interestingly, once the effect of competitive experience is controlled, the pattern of positive tenure dependence in failure rates becomes considerably stronger (see Model 9 in Table 3b). Apparently, the liability of aging is particularly acute for technologically and geographically differentiated firms; these organizations hold a positional "advantage," and so do not develop over time by gaining competitive experience. Figure 4 illustrates this pattern (using the estimates from the most complete specification, Model 15). Organizations that have never faced competition – those that are technologically or geographically differentiated – see their exit rates escalate dramatically as they remain in the market. This increase is nearly halved, however, if a firm endures the average level of competitive experience observed (per tenure level) in the data. And firms that accumulate the maximum observed competitive experience (per tenure level) see their exit rates increase by only about 1/3 of the increase seen by technologically differentiated "monopolists." These differences highlight the trade-off associated with positional advantage. Technologically and geographically differentiated firms face less competition today, but they forgo the benefits of exposure to competition that would have helped them tomorrow.

In models not shown, we also estimated more complicated specifications of experience dependence that allow more recent experience to have differing effects than experience in the more distant past. Including a recency-weighted experience term, however, did not contribute statistically to the model's fit and the term itself was not significant. At least according to this specification, then, we do not find evidence of a "competence trap" associated with distant-past exposure to competition (cf. Barnett and Hansen, 1996).

Insert figure 4 about here

But do the benefits of isolation outweigh the downside of missing out on the Red Queen? Figure 5 illustrates the trade off between suffering from rivalry and benefiting from competitive experience over time (again using estimates from our most complete specification, Model 15). The failure-enhancing effects of competition are strong (see the y-intercepts in Figure 5). An organization facing one rival in the advanced-technology niche sees its failure rate increase by about 14.6%. That amounts to about a 20-fold increase in the exit rate for firms facing the maximum-observed 22 rivals in the advanced-technology niche. A firm competing in the low-technology niche sees an increase of about 8.5% due to competition from one rival there – weaker competition than that felt among advanced-technology rivals but still sufficient to increase failure rates by about six-fold at the maximum observed 22 rivals seen in that niche. As time passes, however, these competitive effects are offset by the benefits of competitive experience. Assuming the number of rivals remains the same, after about 10 years a firm in the low-technology niche enjoys more benefits from experience than it suffers from current-time competition. In the more hazardous advanced-technology niche, this threshold is crossed 6 years later. In either case (and conditional upon survival), competition eventually enhances a firm's survival chances.

Insert figure 5 about here

Models 10 and 11 investigate whether competition intensified over time among domestic rivals. Model 10 includes (domestic) technology-overlap density with each rival's contribution to the measure weighted by its prior (domestic) competitive experience. If domestic rivals become stronger competitors as their competitive experience increases, this term should have a positive and significant effect on failure rates – indicating that more experienced domestic rivals generated stronger competition. Model 11 instead includes an interaction of (domestic) technology-overlap density and calendar time. This term allows domestic rivals to generate stronger competition as the industry ages – regardless of their own ages or amount of competitive experience. As it turns out, neither of these terms is statistically significant. At least as far as these specifications can detect, domestic competition remained strong but constant over time in the disk-drive market.

A different story emerges for foreign competition, however. Tables 4a and 4b investigate competition from foreign rivals in greater detail. Model 12 is similar to

Model 9, except that the density of rivals from other regions of the world is specified as a technology-overlap density, and a (domestic) experience-weighted technology-overlap density is also included for foreign rivals. These two terms together show an interesting pattern of effects. The failure-reducing effect of foreign rivals remains for the technology-overlap density, but competition is stronger from more experienced rivals. Model 13 then includes an interaction between (foreign) technology-overlap density and calendar time. This model shows that the increase in the strength of foreign competition clearly occurs with the passage of calendar time, and that including this effect virtually eliminates the experience-weighted density effect that had been strong and significant in Model 12. It seems clear that competition becomes increasingly global as calendar time passes. Model 14 then omits the experience-weighted foreign density term and the effect of the calendar year interaction is robust. The most parsimonious specification, Model 15, also eliminates the consistently non-significant effect of non-overlap density, and again the competitive effect of the calendar year-foreign density interaction is robust.

Insert tables 4a and 4b about here

Figure 6 illustrates the way that competition became more global over time according to the estimates of Model 15. The plot reflects the negative effect of technology overlap with foreign rivals, together with the positive effect of technology overlap interacted with calendar time. In the early days, the existence of foreign rivals made a firm more likely to survive – lowering failure rates by about 20% per rival, for instance, back in 1963. This survival-enhancing effect is consistent with the argument that geographically separated organizations contribute to legitimating one another even as they are too distant to generate noticeable competition. Over time, however, the pattern changes, with foreign rivals generating increasing competition. By the end of the 1980s organizations are actually driving up the failure rates of rivals in other countries. And, by the end of the study period, the competitive effect of foreign rivals has grown to be almost indistinguishable from that generated by domestic rivals. (To see this, compare the far right endpoint of the plot in Figure 6, which illustrates recent foreign competition, to the y-intercepts in Figure 5, which illustrate the strength of domestic competition.) These results suggest that by the end of the 1990s, competition in the hard disk drive market had become global.

Insert figure 6 about here

Looking across all models one can see an interesting pattern in the regional indicator variables. The overall picture suggests that estimates of regional differences in exit rates are very sensitive to model specification – in particular to whether models properly specify organizational size and domestic versus foreign competition. With size advantages controlled in Models 2 and 3, North America-based firms appear to be more likely to exit than firms based in most other regions – although this difference is sometimes not statistically significant. Then an interesting change occurs in Model 6. Once density effects are specified separately for home and foreign rivals, the various region effects switch direction. These indicator variables had been negative compared to North America, meaning that North America-based organizations had higher exit rates.

With region-specific competition controlled, however, these effects turn positive and significant in some cases. This pattern suggests that North American firms actually had lower failure rates after controlling for the strong competition that they face in their home market. The pattern again reverses, however, after including the benefits of prior exposure to competition (from Model 9 on) and especially after controlling for the increase in foreign competition over time in Models 12 through 15. These models show North American firms to be more likely to fail than firms based in most other regions (although the difference is statistically significant only for the comparison to Eastern European firms). All in all, it appears that country-by-country differences in exit rates hinge largely on differences in the competitiveness of markets and the sizes of organizations.

Finally, we note that firms with captive production were more likely to exit the industry than those that produce only for sale to the open market. Put differently, computer manufacturers that were vertically integrated into HDD manufacturing have been more likely to exit the HDD market than firms that produce HDDs only for sale to other firms.

Discussion and Conclusion

We began by noting a broad consensus among scholars that, to survive, organizations involved in fast-changing industries need either to stay ahead or to differentiate. With Red Queen competition in mind, however, organizations pursuing either of these positional strategies may suffer from adverse consequences, as our analysis demonstrates. Organizations that differentiated gained the obvious benefit of lower failure rates due to less competition. Such firms, however, were isolated from the forces of Red Queen evolution and so did not reap the survival-enhancing benefits that come from experiencing competition. Our estimates show that this disadvantage comes to outweigh the benefits of isolation as time passes. In this way, positional advantage is traded off against development for organizations that isolate themselves from competition, much to their disadvantage in the long run.

Similarly, the positional strategy of technological leadership also turns out to have life-threatening implications. If competition is segmented into high-end and low-end niches (which turned out to be the case for the hard disk drive industry), then technological leaders suffer from being exposed to the strongest competition. In fact, our estimates initially showed that technological laggards were less likely to fail. This paradoxical finding turned out to be due to the fact that weaker competitors populate the low-technology niche in disk drives. Once this competitive difference was explicitly modeled, the apparent low-technology survival advantage was eliminated. These findings are consistent with our thinking that the Red Queen magnifies differences in competitiveness among organizations, so that organizations at the technological frontier are much stronger competitors than those that lag behind.

Of course, alternative explanations may also be able to account for these patterns. The most likely alternative explanation would be that differential selection, rather than organizational learning, is at work. It is likely that competition culls among organizations, leaving those that had a survival advantage to begin with. Such a process could account for our finding that organizations are more likely to survive the more that they have faced competition in the past. Although we cannot empirically disconfirm this possibility in a study of organizational failure, we are reluctant to accept that selection alone is responsible for out findings. Organizational learning and selection both occur, and consequently we think it is likely that both learning and selection play a role in Red Queen development.

Our findings also have implications for the study of global competition. Many scholars, but most notably Michael Porter (1990), emphasize the continuing importance of home-country effects even as firms engage in global competition. Our findings suggest, however, that at least in the hard disk drive market competition became increasingly global over time and, consequently, country-specific advantages have faded in importance as time has passed. In agreement with Porter, however, we do find (as one would expect in light of the Red Queen) that exposure to competitive markets at home was beneficial to organizations, at least in terms of their life chances. Similarly, although many have noted country-specific differences in failure rates among disk drive manufacturers (e.g. Chesbrough, 1999), we note that these differences are not at all robust in when specified in models that allow for Red Queen development and global competition.

We think our findings demonstrate the usefulness of taking an ecological approach to the study of technological competition. Typically studies of technological development limit their empirical analysis to the effects of each firm’s technological strategy on its own viability. Meanwhile, the ecology of organizations is modeled (if at all) in terms of aggregate density rather than more detailed specifications that allow for technological differences to shape competition (e.g. Christensen, Suarez, and Utterback, 1998). Our findings indicate that when technology shapes competition, as was the case in the hard disk drive industry, the strongest effects on survival come not from firm-specific technological differences but rather come from ecological competition among firms – competition that, in turn, depends largely on the technologies of firms. We urge researchers to investigate more technologically informed models of ecological competition.

Another implication of our work here concerns the study of organizational change as a relative phenomenon. Early on, Hannan and Freeman (1984) noted the importance of relative position when understanding the consequences of organizational change. By and large, however, studies of organizational change have focused on absolute changes. Such a lens would do little to illuminate patterns in Red Queen markets like hard disk drives. In such contexts, each organizations position must be understood relative to its rivals', and patterns of change are only "slow" or "fast" when understood by comparison to the other organizations in the population. We suggest that further research should look into other contexts where by thinking in terms of Red Queen competition we can illuminate patterns of success and failure.

To conclude, we think it is interesting to think, more broadly, about the development of organizational capabilities in light of Red Queen evolution. To the extent that organizational capabilities develop through Red Queen competition, then our findings suggest an inverse relationship between strategic capabilities and strategic position. Strategic managers typically try to avoid competition, and to some degree the field of "strategic management" exists in order to explain how to attain so-called positional advantages that isolate an organization from rivalry. If isolation from rivalry removes a firm from the Red Queen, however, then we pay a price in the long run for such positional advantage. We argue that more attention should be paid to the possibility that by enduring positional advantages may, in fact, backfire over time by depriving organizations of the engine that generates capabilities.

Appendix: Data

Data on the disk drive industry were gathered from market research reports, publicly available financial information, industry participants, and an extensive search of the business press. From these disparate sources, the life history of each disk drive company was compiled. These histories cover entry and exit dates, sales, presence in a given form factor, product technical specifications, acquisition history, and nationality for each company that made a hard disk drive since the first known manufacture of a disk in 1956 through 1998. The resulting database includes 169 organizations that manufactured hard disk drives at any time or place over the period. Nearly all organizations (155) exited the industry by the end of 1998. The data cover 1511 organization-years, as described in Table 1.

The primary source of data for this study is the Disk/Trend Report, published annually since 1977 by Disk/Trend, Inc., a market research company. These reports track every known company that made hard disk drives, list detailed product specifications and shipment dates, and publish revenue and unit shipment information by form factor and capacity range. The reports do not, however, list the date of first entry for many companies that produced disk drives before 1976. In several instances, companies operating in 1976 shipped their first disk drives in the 1960s, but these products were no longer in production when the first Disk/Trend Report was published and so "first shipment" dates could not be determined. We contacted surviving companies for information, spoke with retired engineers involved in the development of a company's first disk drive for both surviving and former disk drive producers and often received copies of written technical and market information in their possession, reviewed company documents in the files of Disk/Trend, Inc., and researched company histories in books, financial reports, and the business press. Reports by two market research firms in particular were basic sources of information on product specifications and shipment dates of firms operating during the 1960s and early 1970s (HTW, 1970; MDS, 1972). These searches resulted in earlier entry dates than would otherwise be inferred from information in Disk/Trend for 20 of 32 firms making disk drives as of January 1, 1976. An additional 15 companies made disk drives but exited the industry before Disk/Trend was first published. Of these 35 firms (20 plus 15), precise dates of first shipment for 14 companies were unavailable; instead entry dates were set at 3 months after first product announcement.

Life events were coded so that name changes and reorganizations were not counted as entries and exits. A number of disk drive companies changed their names or were acquired during the period of study. Name changes sometimes occurred when a parent firm announced a new strategy. In these cases, the disk drive operations may have been combined with some other corporate activity. These were not coded as market exits. For instance, England's Data Recording Instruments put its disk drive operations into a newly formed peripherals operation named Data Recording Equipment in 1978, and its name was changed again in 1982 to Newbury Data after it was combined with other operations. Over time these incarnations were treated as the same entity, so its reorganizations were not counted as entries or exits. Nor did we code as exits any acquisitions of disk drive firms by non-disk drive companies if the disk drive operations were left largely intact. For example, Perkin Elmer acquired Wangco, a disk drive maker. Wangco then continued to make disk drives as a Perkin Elmer subsidiary. The acquisition was thus not coded as an exit (or a new entry). By contrast, if a company was liquidated and the liquidated assets formed the basis of a new company, then the two events were coded as an exit and an entry.

To map the technology race in this industry, we coded for each firm whether it shipped a product in a particular form factor and capacity range in any given year. The bulk of shipments were non-captive market transactions, and our analysis of the technology positions of each firm is restricted to these shipments. (We do include firms in the survival analysis, however, even if they only engaged in captive production.) We relied on Disk/Trend technology classifications for all 1976-1998 observations. Disk/Trend created product group categories by drive type (cartridge disk drives, disk pack drives, fixed disk drives) and by capacity range (30-60 megabytes, 100-300 megabytes, etc.). Because of the dramatic improvements in disk drive capacity over the years, these categories evolved over time. For instance, in 1976 Disk/Trend created nine product groups, including a group consisting of firms shipping disk drives of less than 12 megabytes and one consisting of firms shipping disk drives greater than 200 megabytes. In 1996, nine product groups were also used, but this time the smallest capacity range for a product group was less than 500 megabytes and the largest was for more than 20 gigabytes. We coded whether a given product group (capacity range) represented a *relatively* "low," "medium," or "high" capacity disk drive for that form factor in that year. Thus, the technological position of a firm in a given form factor was made relative to that of other firms in the same form factor (other firms shipping 5.25-inch drives, for example) and not across form factors, and a disk drive that was a high capacity product in one year could become a medium or low capacity product in the next year or two.

Although the Disk/Trend Report is an incredibly rich and exhaustive source of information on products, revenues and shipment volumes, its use requires some care. When a disk drive company acquires another, Disk/Trend lists the combined products under the name of the acquiring firm. However, Disk/Trend notes the shipment dates of products that were originally developed by the *acquired* firm as the dates of first shipment, not dates of first shipment by the acquiring firm. Knowing this, we took care not to code a company as shipping a particular disk drive earlier than it actually had. Moreover, many products were announced that never shipped, and sometimes the same product was reportedly shipped on two different dates depending on the year of the Disk/Trend Report. A couple of companies, such as Memorex Telex, were listed as disk drive companies when in fact they only resold drives made by other manufacturers. In a few cases it was not clear that a company actually ever shipped a product. For example, Disk/Trend Report would describe a new company and list its products, all of which were scheduled to be shipped sometime after the publication date of Disk/Trend Report. That company would not appear in the next year's report, however, and it was unclear whether the firm in fact shipped the products only to exit before Disk/Trend was published the following year, or else never shipped. Each of the more than 10,000 products listed in the Disk/Trend Reports (including the same product appearing in more than one year) were checked for such anomalies. When problems were encountered, Disk/Trend, Inc. was contacted and always kindly helped us to clarify.

We also had to classify products and capacity ranges for 1956-1975, prior to the publication of Disk/Trend. This required the creation of product groups that mirrored the technological state of the industry. We started by extending the 1976 product group classifications back in time until it seemed to collide with the reality of the products being offered. This resulted in a gradual reduction in the number of product groups in the 14-inch form factor, and the creation of product groups for larger form factors. First, as was the practice in Disk/Trend, we grouped together similarly sized form factors. Thus, 39-inch, 34-inch, and 31-inch products were grouped together as one form factor; 28-inch, 26-inch, and 24-inch products were similarly grouped; and 16-inch, 14-inch and 12-inch products were classified as a single form factor. (For reporting purposes, Disk/Trend, for example, grouped 10.5-inch drives with the 14-inch form factor, 9-inch drives with 8-inch, 3.9-inch drives with 3.5-inch, 3-inch drives with 2.5-inch, and 1.3-inch drives with 1.8-inch.) Only a few new capacity ranges were created for the 1956-75 period. This procedure affected 267 firm-year observations.

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Table 1
Description of Pooled Annual Observations:
Disk Drive Manufacturers Worldwide 1956-1998

Variables	Min	Max	Mean	Std Dev
Organization's market tenure	0	42	7.90	7.08
Calendar year (1956=0)	0	42	27.33	8.04
Number of low-capacity form-factors produced by organization	0	4	.74	.78
Number of medium- and high-capacity form factors produced by organization	0	9	1.25	1.49
Large Organization (0/1) based on hard-drive sales	0	1	.51	.50
Hard-drive sales ($mil) by organization (large only)	0	11,979	247	982
Organization was founded de novo	0	1	.28	.45
Organization has captive production	0	1	.38	.48
Number of other organizations worldwide in year of organization's founding	0	84	42.46	25.63
Number of other organizations worldwide	0	84	53.77	22.26
(Number of other organizations worldwide)^2/1000	0	7.05	3.38	2.26
Number of other organizations, same region	0	51	20.89	15.16
Overlap with other organizations, same region (by form factor and capacity)	0	22	5.66	4.79
Overlap with low-capacity organizations, same region	0	22	2.84	4.18
Overlap with medium- and high-capacity organizations, same region	0	22	2.82	3.59
Non-overlap with other organizations, same region	0	51	15.23	12.86
Organization's competitive experience	0	167.5	31.46	37.55
Overlap with other organizations, same region, weighted by rivals' competitive experience	0	1103.9	272.99	286.18
Overlap with other organizations, same region, times calendar year/1000 (1956=0)	0	.616	.161	.141
Number of other organizations, other regions	0	84	32.87	20.09
Overlap with other organizations, other regions (by form factor and capacity)	0	45	10.27	9.07
Overlap with other organizations, other regions, weighted by rivals' competitive experience	0	1903.2	389.84	426.99
Overlap with other organizations, other regions, times calendar year/1000 (1956=0)	0	1.3	.30	0.28

Note: The data cover 1511 organization-years, 169 organizations and 155 exits.

Table 2
Estimates of Market Exit Rates Among Disk Drive Manufacturers Worldwide 1956-1998

Independent Variables	Models (1)	(2)	(3)
Organization's market tenure 0 to 1 year	-6.103**	-4.816**	-5.283**
	(.6945)	(.6745)	(.7377)
Organization's market tenure 1 to 3 years	-4.649**	-3.099**	-3.551**
	(.5213)	(.5010)	(.5814)
Organization's market tenure 3 to 5 years	-4.465**	-2.860**	-3.328**
	(.5341)	(.5159)	(.5984)
Organization's market tenure 5 to 10 years	-4.432**	-2.655**	-3.121**
	(.5384)	(.5360)	(.6198)
Organization's market tenure 10 to 20 years	-4.427**	-2.306**	-2.781**
	(.5805)	(.5863)	(.6749)
Organization's market tenure above 20 years	-4.198**	-1.841**	-2.417**
	(.6491)	(.6704)	(.7842)
Calendar year (1956=0)	.1030**	.0568**	.0639**
	(.0171)	(.0165)	(.0178)
Japanese organization	-.1628	-.4762*	-.4353
	(.2455)	(.2493)	(.2681)
Eastern-European organization	-.6046	-1.135*	-1.055*
	(.6151)	(.6167)	(.6209)
Western-European organization	-.2456	-.4269	-.3907
	(.2844)	(.2845)	(.2917)
South American organization	-.4577	-.8528**	-.8599**
	(.3521)	(.3535)	(.3630)
Asian (other than Japan) organization	.1669	.0972	.0021
	(.3722)	(.3749)	(.3837)
Organization produces 1.8-inch form factor	-.1681	-.4175	-.4135
	(.5646)	(.5973)	(.5973)
Organization produces 2.5-inch form factor	-.1176	-.1370	-.1493
	(.4914)	(.4780)	(.4807)
Organization produces 3.5-inch form factor	.2925	.4044	.5002
	(.3362)	(.3614)	(.3622)
Organization produces 5.25-inch form factor	.3848	.2545	.3425
	(.3056)	(.3319)	(.3362)
Organization produces 8-inch form factor	.4693	.1045	.1390
	(.3653)	(.3921)	(.3950)
Organization produces 14-inch (or above) form factor	.2973	-.0846	.1081
	(.3205)	(.3403)	(.3582)
Number of low-capacity form-factors produced by organization	-.6064**	-.3734	-.3838
	(.2268)	(.2349)	(.2343)
Number of medium- and high-capacity form factors produced by organization	-.6409** (.1471)	-.2053 (.1555)	-.2325 (.1548)
Large organization (0/1) based on hard-drive sales		-1.838**	-1.928**
		(.3149)	(.3214)
Hard-drive sales ($mil) by organization (large only)		-.0023*	-.0024
		(.0014)	(.0015)
Organization was founded de novo			.2571
			(.2105)
Organization has captive production			.3839
			(.2554)
Likelihood-ratio chi-squared (Df)	114.43(14)	213.32(16)	216.28(18)

*p<.10, **p<.05. Standard errors are in parentheses.
Note: For region effects, the U.S. is the left-out category. The data cover 1511 organization-years, 169 organizations and 155 exits. Chi-squared values compare to a model with only tenure effects.

Table 3a
Models of Technology-Based Competition Among Disk Drive Manufacturers Worldwide

Independent Variables	Models (4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Japanese organization	-.4390	-.4381	.4515	.3657	.3437	.2326	.1752	.1946
	.2698)	(.2687)	(.3847)	(.3899)	(.3901)	(.3946)	(.4035)	(.3983)
Eastern-European organization	-1.109*	-1.065*	.6037	.5808	.4733	-.1284	-.1973	-.1393
	(.6266)	(.6232)	(.8008)	(.8046)	(.8126)	(.8587)	(.8635)	(.8590)
Western-European organization	-.4196	-.3857	.7992*	.8619*	.8369*	.4395	.3656	.3437
	(.2977)	(.2931)	(.4600)	(.4642)	(.4646)	(.4989)	(.5099)	(.5170)
South American organization	-.8523**	-.8649**	.4250	.5075	.4403	.1282	-.0268	.0313
	(.3682)	(.3640)	(.5343)	(.5382)	(.5406)	(.5544)	(.5944)	(.5703)
Asian (other than Japan) organization	-.0177	-.0013	1.380**	1.504**	1.464**	1.237**	1.107*	1.081*
	(.3876)	(.3844)	(.5641)	(.5683)	(.5753)	(.5755)	(.6027)	(.6128)
Number of low-capacity form-factors produced by organization	-.3749	-.3777	-.4090*	-.4186*	-.2446	-.1941	-.2062	-.2107
	(.2369)	(.2368)	(.2365)	(.2364)	(.2733)	(.2712)	(.2712)	(.2726)
Number of medium- and high-capacity form factors produced by organization	-.2414	-.2306	-.2215	-.1795	-.2463	-.2461	-.2361	-.2399
	(.1561)	(.1551)	(.1547)	(.1583)	(.1673)	(.1670)	(.1676)	(.1673)
Large organization (0/1) based on hard-drive sales	-1.943**	-1.931**	-2.043**	-2.048**	-2.086**	-2.129**	-2.137**	-2.126**
	(.3231)	(.3221)	(.3261)	(.3258)	(.3271)	(.3278)	(.3274)	(.3274)
Hard-drive sales ($mil) by organization (large only)	-.0024	-.0024	-.0025*	-.0025*	-.0024	-.0027*	-.0027*	-.0027*
	(.0015)	(.0015)	(.0015)	(.0015)	(.0015)	(.0015)	(.0015)	(.0015)
Organization was founded de novo	.2326	.2574	.2440	.2273	.2471	.2292	.2244	.2269
	(.2140)	(.2104)	(.2094)	(.2086)	(.2090)	(.2104)	(.2109)	(.2105)
Organization has captive production	.3510	.3868	.4217	.5021*	.5359**	.4558*	.4529*	.4525*
	(.2617)	(.2556)	(.2607)	(.2622)	(.2628)	(.2655)	(.2638)	(.2642)
Number of other organizations worldwide in year of organization's founding	-.0042							
	(.0065)							
Number of other organizations worldwide	.0089	.0008						
	(.0278)	(.0044)						
(Number of other organizations worldwide)^2/1000	-.0674							
	(.2643)							
Number of other organizations, same region			.0327**					
			(.0105)					
Overlap with other organizations, same region (by form factor and capacity)				.0648**				
				(.0236)				
Overlap with low-capacity organizations, same region					.0507*	.0557**	.0797*	.1349
					(.0267)	(.0261)	(.0419)	(.1114)
Overlap with medium- and high-capacity organizations, same region					.0966**	.1004**	.1206**	.1757*
					(.0340)	(.0339)	(.0434)	(.1082)
Non-overlap with other organizations, same region				.0255**	.0239**	.0240**	.0235**	.0224*
				(.0117)	(.0118)	(.0117)	(.0117)	(.0119)
Organization's competitive experience						-.0157**	-.0069*	-.0068*
						(.0075)	(.0036)	(.0036)
Overlap with other orgs., same region weighted by rivals' comp. experience							-.0005	
							(.0007)	
Overlap with other orgs., same region, times calendar year/1000 (1956=0)								-2.801
								(3.829)
Number of other organizations, other regions			-.0188**	-.0191**	-.0176**	-.0157**	-.0151**	-.0143*
			(.0075)	(.0075)	(.0076)	(.0075)	(.0075)	(.0077)
Likelihood-ratio chi-squared	216.73	216.31	226.79	229.08	230.70	235.41	235.95	235.94
(Degrees of freedom)	(21)	(19)	(20)	(21)	(22)	(23)	(24)	(24)

***p<.10, **p<.05. Standard errors are in parentheses.**
Note: Each model also includes market tenure, calendar year, and form-factor fixed effects as shown in Table 3b. For region effects, the U.S. is the left-out category. The data cover 1511 organization-years, 169 organizations and 155 exits. Chi-squared values compare to a model with only tenure effects.

Table 3b

Estimated Market Tenure, Calendar Year, and Form-Factor Fixed Effects from the Models in Table 3a

Independent Variables	Models (4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Organization's market tenure 0 to 1 year	-5.443**	-5.320**	-6.056**	-6.211**	-6.289**	-6.559**	-6.691**	-6.709**
	(.9080)	(.7676)	(.8210)	(.8360)	(.8426)	(.8578)	(.8825)	(.8919)
Organization's market tenure 1 to 3 years	-3.711**	-3.587**	-4.266**	-4.434**	-4.497**	-4.667**	-4.799**	-4.828**
	(.7880)	(.6175)	(.6756)	(.6937)	(.6984)	(.7059)	(.7360)	(.7516)
Organization's market tenure 3 to 5 years	-3.490**	-3.364**	-4.006**	-4.183**	-4.218**	-4.296**	-4.429**	-4.459**
	(.7949)	(.6340)	(.6874)	(.7057)	(.7084)	(.7091)	(.7398)	(.7555)
Organization's market tenure 5 to 10 years	-3.294**	-3.157**	-3.783**	-3.942**	-3.987**	-3.912**	-4.042**	-4.083**
	(.8286)	(.6523)	(.7010)	(.7160)	(.7190)	(.7178)	(.7472)	(.7674)
Organization's market tenure 10 to 20 years	-3.017**	-2.818**	-3.439**	-3.537**	-3.540**	-3.235**	-3.399**	-3.435**
	(.8792)	(.7086)	(.7584)	(.7680)	(.7696)	(.7725)	(.8120)	(.8300)
Organization's market tenure above 20 years	-2.767**	-2.456**	-2.972**	-3.051**	-3.063**	-2.503**	-2.730**	-2.784**
	(1.034)	(.8156)	(.8675)	(.8763)	(.8771)	(.8979)	(.9555)	(.9878)
Calendar year (1956=0)	.0695**	.0637**	.0687**	.0743**	.0740**	.0827**	.0886**	.0898**
	(.0203)	(.0179)	(.0184)	(.0191)	(.0192)	(.0193)	(.0211)	(.0219)
Organization produces 1.8-inch form factor	-.4102	-.4004	-.4806	-.5722	-.4859	-.5493	-.6109	-.5896
	(.6030)	(.6020)	(.6071)	(.6162)	(.6175)	(.6113)	(.6174)	(.6137)
Organization produces 2.5-inch form factor	-.1351	-.1411	-.0458	-.0884	-.1598	-.3209	-.3129	-.2950
	(.4824)	(.4831)	(.4844)	(.4898)	(.4935)	(.4961)	(.4961)	(.4960)
Organization produces 3.5-inch form factor	.5342	.4979	.5563	.3652	.2720	.2898	.2975	.3371
	(.3661)	(.3624)	(.3663)	(.3934)	(.3997)	(.3921)	(.3923)	(.3971)
Organization produces 5.25-inch form factor	.3542	.3296	.4305	.2538	.1907	.1493	.1406	.1510
	(.3448)	(.3434)	(.3457)	(.3697)	(.3722)	(.3689)	(.3690)	(.3688)
Organization produces 8-inch form factor	.1126	.1248	.0876	.0303	-.0670	-.0418	-.0407	-.0613
	(.4025)	(.4027)	(.3964)	(.4016)	(.4084)	(.4043)	(.4035)	(.4051)
Organization produces 14-inch (or above) form factor	.0780	.1049	.0880	.0496	.0098	.0476	.0418	-.0341
	(.3610)	(.3585)	(.3566)	(.3620)	(.3644)	(.3650)	(.3662)	(.3853)

***p<.10, **p<.05. Standard errors are in parentheses.**

Table 4a
Models of Global Competition Among Disk Drive Manufacturers Worldwide

Independent Variables	Models (12)	(13)	(14)	(15)
Japanese organization	-.1787	-.0837	-.0574	-.2971
	(.3418)	(.3454)	(.3419)	(.2930)
Eastern-European organization	-1.041	-.9289	-.9029	-1.265*
	(.7406)	(.7522)	(.7523)	(.7020)
Western-European organization	-.1090	.0038	.0636	-.2240
	(.4752)	(.4759)	(.4605)	(.4116)
South American organization	-.7605	-.5964	-.4512	-.7072
	(.5733)	(.5756)	(.5174)	(.4820)
Asian (other than Japan) organization	.4944	.5556	.6559	.3878
	(.6056)	(.6038)	(.5772)	(.5459)
Number of low-capacity form-factors produced by organization	-.0974	-.1200	-.1264	-.1471
	(.2681)	(.2706)	(.2708)	(.2697)
Number of medium- and high-capacity form factors produced by organization	-.2671	-.2508	-.2472	-.2477
	(.1673)	(.1677)	(.1676)	(.1685)
Large organization (0/1) based on hard-drive sales	-2.078**	-2.032**	-2.029**	-1.985**
	(.3281)	(.3302)	(.3301)	(.3277)
Hard-drive sales ($mil) by organization (large only)	-.0026*	-.0028*	-.0028*	-.0027*
	(.0015)	(.0015)	(.0015)	(.0015)
Organization was founded de novo	.2698	.2929	.2905	.2796
	(.2113)	(.2110)	(.2109)	(.2109)
Organization has captive production	.4896*	.5230**	.5151*	.5239**
	(.2607)	(.2629)	(.2634)	(.2613)
Overlap with low-capacity organizations, same region	.0895**	.0895**	.0821**	.0816**
	(.0347)	(.0364)	(.0342)	(.0343)
Overlap with medium- and high-capacity organizations, same region	.1294**	.1379**	.1343**	.1364**
	(.0375)	(.0383)	(.0377)	(.0377)
Non-overlap with other organizations, same region	.0182*	.0168	.0154	
	(.0109)	(.0112)	(.0110)	
Organization's competitive experience	-.0069**	-.0084**	-.0088**	-.0084**
	(.0035)	(.0036)	(.0036)	(.0035)
Overlap with other organizations, other regions (by form factor and capacity)	-.0806**	-.2691**	-.2881**	-.2755**
	(.0355)	(.1130)	(.1078)	(.1050)
Overlap with other organizations, other regions, weighted by rivals' competitive experience	.0016**	.0006		
	(.0008)	(.0010)		
Overlap with other organizations, other regions, times calendar year/1000 (1956=0)		7.355*	8.695**	8.350**
		(4.099)	(3.392)	(3.311)
Likelihood-ratio chi-squared	236.64	239.97	239.62	237.71
(Degrees of freedom)	(24)	(25)	(24)	(23)

*p<.10, **p<.05. Standard errors are in parentheses.
Note: Each model also includes market tenure, calendar year, and form-factor fixed effects as shown in Table 4b. For region effects, the U.S. is the left-out category. The data cover 1511 organization-years, 169 organizations and 155 exits. Chi-squared values compare to a model with only tenure effects.

Table 4b
Estimated Market Tenure, Calendar Year, and Form-Factor Fixed Effects from the Models in Table 4a

Independent Variables	Models (12)	(13)	(14)	(15)
Organization's market tenure 0 to 1 year	-6.179**	-5.959**	-5.977**	-5.720**
	(.8590)	(.8455)	(.8448)	(.8135)
Organization's market tenure 1 to 3 years	-4.329**	-4.119**	-4.133**	-3.888**
	(.7056)	(.6879)	(.6872)	(.6491)
Organization's market tenure 3 to 5 years	-3.981**	-3.748**	-3.754**	-3.531**
	(.7069)	(.6918)	(.6913)	(.6580)
Organization's market tenure 5 to 10 years	-3.610**	-3.388**	-3.396**	-3.183**
	(.7133)	(.6960)	(.6953)	(.6640)
Organization's market tenure 10 to 20 years	-2.999**	-2.693**	-2.672**	-2.430**
	(.7623)	(.7518)	(.7494)	(.7130)
Organization's market tenure above 20 years	-2.331**	-1.923**	-1.874**	-1.669**
	(.8645)	(.8726)	(.8712)	(.8417)
Calendar year (1956=0)	.0629**	.0527**	.0542**	.0584**
	(.0208)	(.0212)	(.0210)	(.0203)
Organization produces 1.8-inch form factor	-.1253	-.1517	-.2318	-.3235
	(.6209)	(.6263)	(.6124)	(.6090)
Organization produces 2.5-inch form factor	-.4058	-.2975	-.2603	-.3612
	(.5010)	(.5059)	(.5013)	(.4973)
Organization produces 3.5-inch form factor	.0893	-.0448	-.0161	-.1132
	(.4093)	(.4236)	(.4201)	(.4172)
Organization produces 5.25-inch form factor	.1523	.1416	.1244	.0854
	(.3704)	(.3749)	(.3741)	(.3756)
Organization produces 8-inch form factor	-.2206	-.0779	-.0267	.0413
	(.4078)	(.4177)	(.4083)	(.4075)
Organization produces 14-inch (or above) form factor	.0676	.2479	.2762	.2782
	(.3633)	(.3759)	(.3729)	(.3782)

***p<.10, **p<.05. Standard errors are in parentheses.**

Figure 1: Hard Disk Drive Manufacturers Worldwide

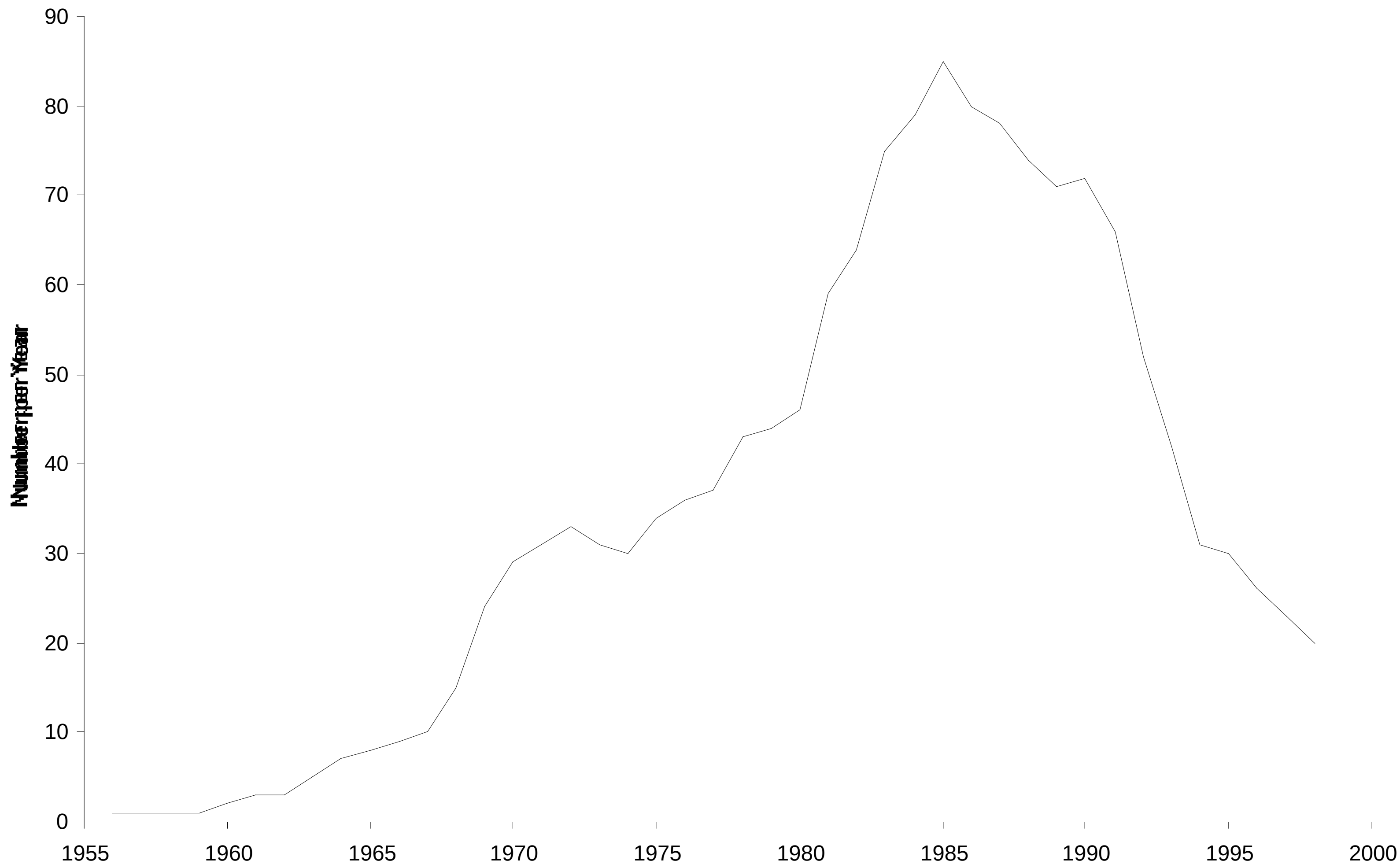

Figure 2: Hard Disk Drive Manufacturers by Home Region

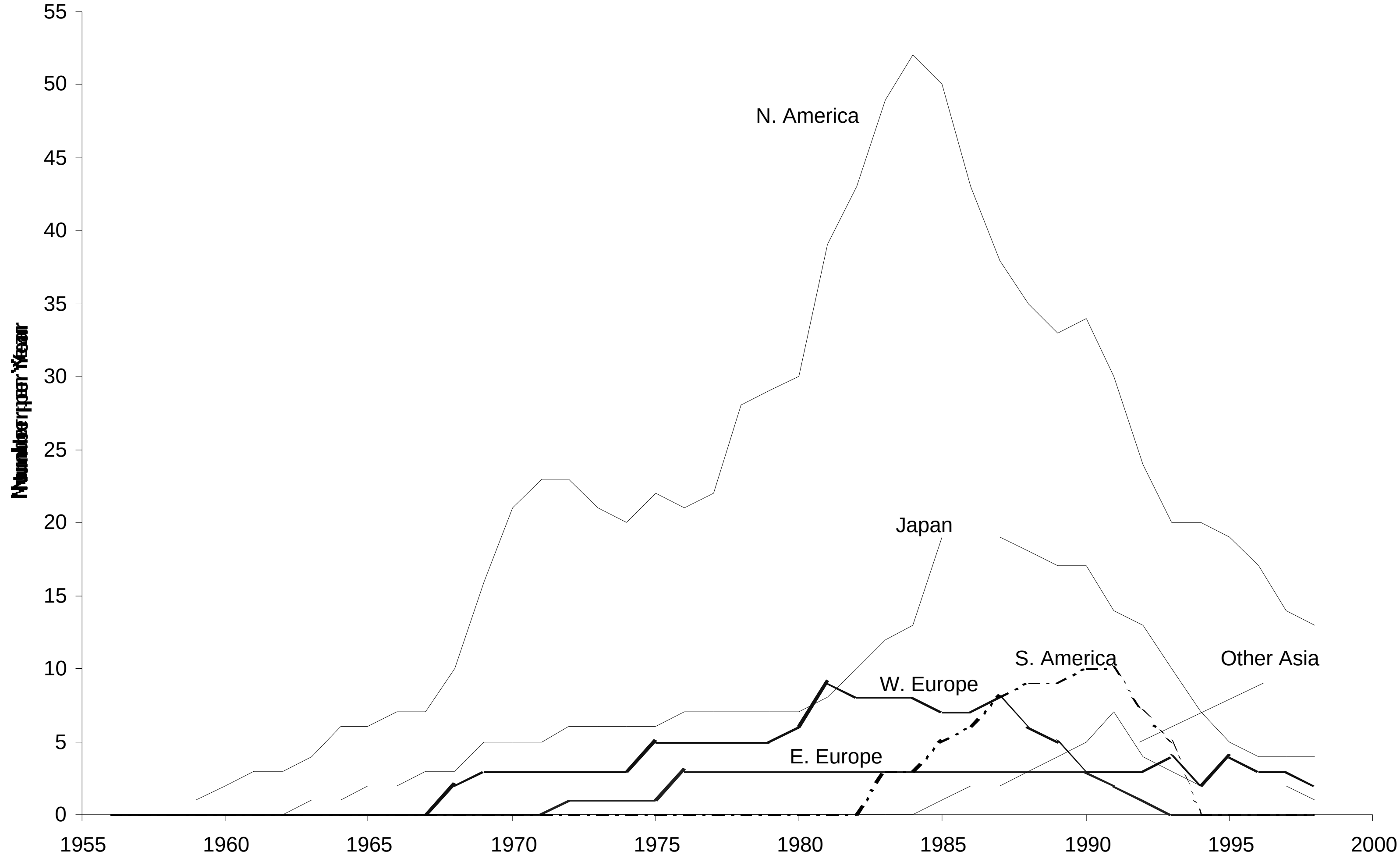

Figure 3: Entries and Exits of Hard Disk Drive Manufacturers Worldwide

Figure 4: Effects of Age and Competitive Experience on the Exit Rate
(Based on the Estimates in Model 15)

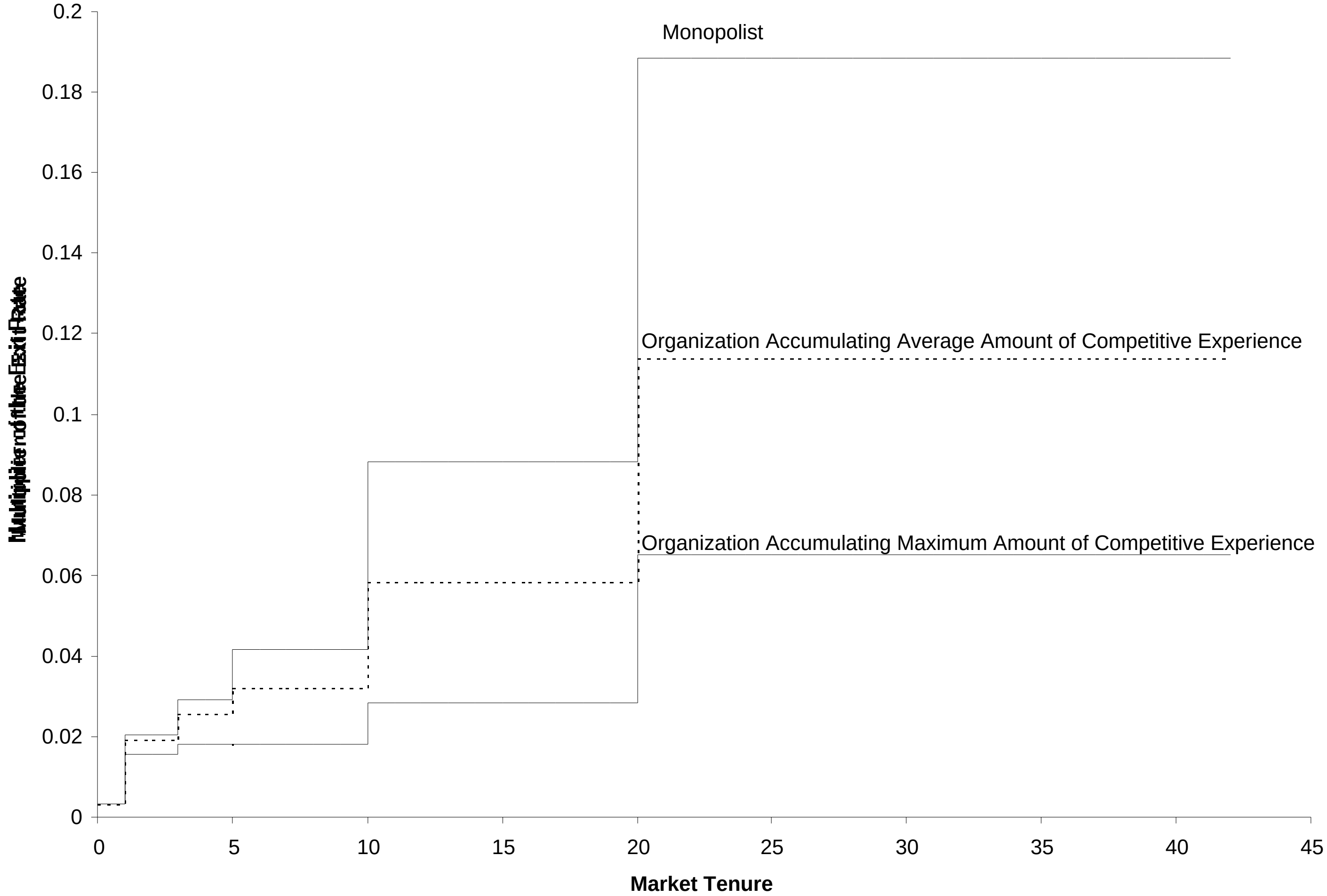

Figure 5: Effects of Competition on the Exit Rate
(Based on the Estimates in Model 15)

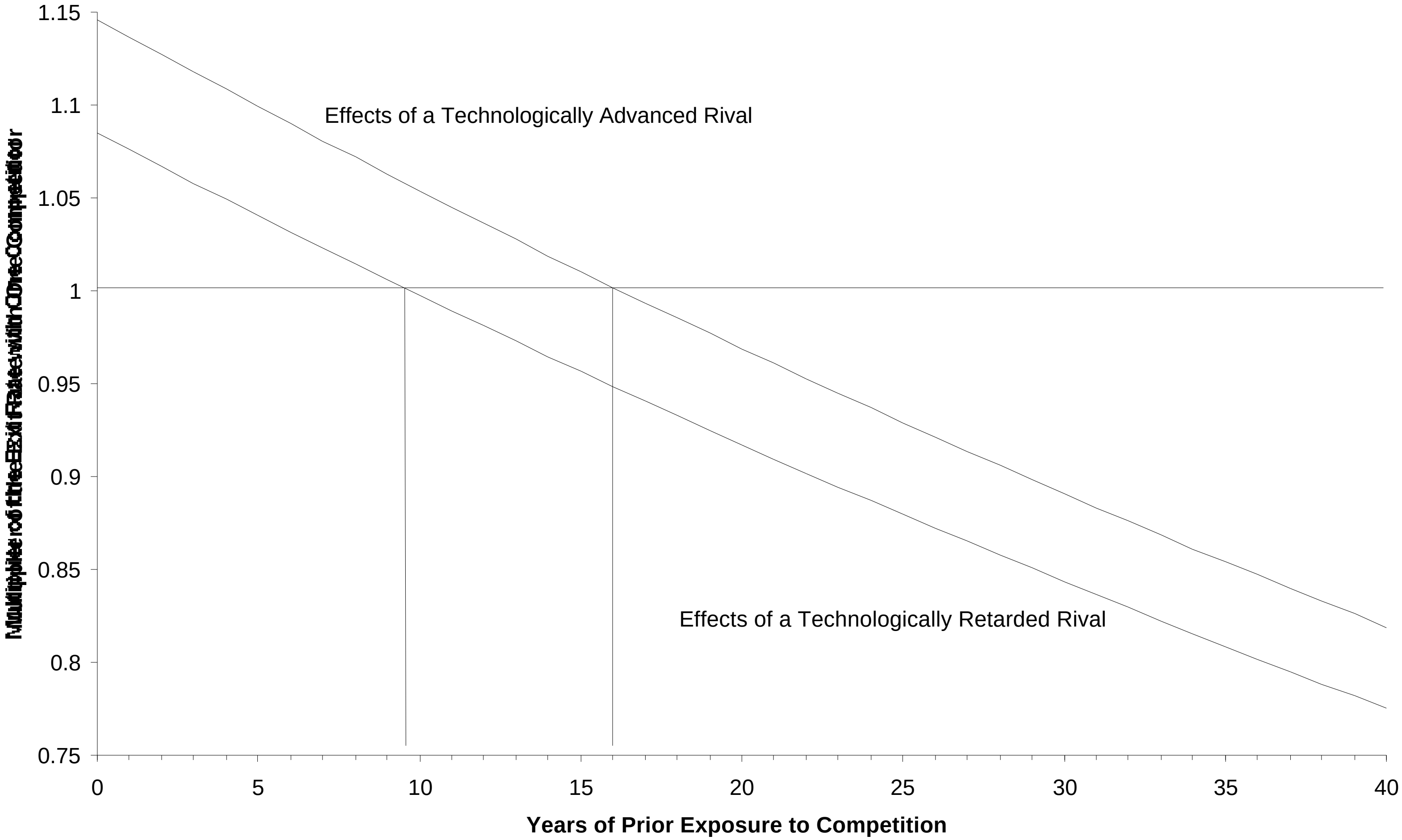

Figure 6: The Development of Global Competition Among Disk Drive Manufacturers (Based on the Estimates in Model 15)