

# **Submarkets, Industry Dynamics, and the Evolution of the U.S. Laser Industry**

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### Abstract

In its first 35 years, the U.S. laser industry was characterized by steady growth in output and the number of producers, whereas in the last ten years the number of producers has declined steadily despite continued growth in the industry's output. A model of industry evolution that features the creation, destruction, and fusing of independent submarkets is developed to explain these two eras. We use data on all laser producers to test various implications of the model concerning entry, exit, and innovation. Our findings suggest that an industry's market structure can be fundamentally altered by technological developments that contribute to the emergence of a dominant submarket.

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## **Submarkets, Industry Dynamics, and the Evolution of the U.S. Laser Industry**

### **I. Introduction**

It is common to talk about niches within industries. Until recently, however, the idea of niches, or submarkets in today's economic parlance, has not been prominent in economic modeling. When firms are modeled as producing differentiated products, it is commonly assumed that each firm produces a single product variety from among a continuum of close substitutes. In contrast, submarkets are defined as islands of activity that are insulated from the rest of an industry on both the demand and supply side. Firms can also belong to more than one submarket, and submarkets may come and go over time, giving rise to entry, exit, firm growth, and decline (see, for example, Malerba et al. [1999], Bottazzi et al. [2001], and de Figueiredo and Silverman [2007]).

In this paper we explore the power of submarket dynamics to help explain the determinants of an industry's market structure and the character of innovation. Industries that end up as oligopolies commonly experience a period in their evolution in which the number of firms falls sharply despite robust growth in total industry output. These episodes, which are called shakeouts, have become part of the lexicon of dynamic industry regularities that call out for explanation (Sutton [1997]). There also tends to be a shift from product to process innovation as new industries evolve (Klepper [1996]). We investigate the role of submarket dynamics in bringing about these developments.

Our analysis focuses on the U.S. laser industry, which provides a unique opportunity to explore the role of submarket dynamics in the evolution of market structure and the character of innovation. Figure 1 presents annual data on the number of entrants, exits, producers, and industry (real) sales and output from the inception of the laser industry in 1961 through 2007. The industry effectively spans two eras. In the first era covering the first 35 years of the industry, entry fueled a steady rise in the number of producers, which peaked at 172 in 1996. In the second era that is still going on, the number of firms declined by almost half to 87 as of 2007 despite an acceleration in the rate of growth of industry (real) sales. Seldom if ever has an industry experienced a

pronounced shakeout after such a prolonged period of steady growth in (real) sales and the number of producers (Gort and Klepper [1982]).

To explain these two eras, we develop a model of industry evolution that features the importance of submarkets and R&D competitive dynamics. Sutton [1998] distinguishes between two types of R&D intensive industries in terms of whether R&D is directed toward the creation of new product varieties versus improving the industry's main product(s). We fuse these notions into a single model by combining the framework developed by Klepper and Thompson [2006] to model submarket dynamics and the model of industry evolution developed by Klepper [2002] to explain shakeouts.

In the model, submarkets are created and destroyed over time. Initially submarkets appeal to new buyers and do not compete with other submarkets. Their initial size is limited, which limits incentives to engage in R&D to improve the submarket's products or lower their average cost. If the demand for a submarket's products increases due to exogenous technical developments, it can trigger an escalation of R&D in the submarket, which can lead to further increases in demand at the expense of other submarkets. We show how this can lead to a shakeout within both the growing submarket and the industry. The model has a number of additional, discriminating implications concerning innovation, entry and exit, and firm survival that we use to test it.

It is tempting to describe the expanding submarket as a dominant submarket and its product as a dominant design, thus pitting the emergence of a dominant design as key to the shakeout. But in the laser industry the technological developments that caused the key submarket to expand actually led to the proliferation of products within the submarket, not the ascendancy of a single product to a dominant status. Thus, in contrast to Utterback and Suárez's theory of shakeouts (Utterback and Suárez [1993]), it was not the coalescence of demanders around a dominant design that caused the shakeout. It also does not appear to have been an increase in the minimum efficient size firm, as featured in Jovanovic and MacDonald [1994]. We argue that it was the competitive R&D dynamics unleashed by the expanding submarket that caused the shakeout, consistent with the models of Klepper [1996, 2002] and Sutton [1998]. Prodded by this interpretation, we go back and explore the role similar dynamics may have played in

other industries that experienced shakeouts, particularly the U.S. automobile industry that went through a prolonged shakeout before emerging as a tight oligopoly.

The paper is organized as follows. In Section 2, we present a brief history of the laser industry. In Section 3, we lay out our model and derive various implications from it. In Section 4 we test the implications. In Section 5, we discuss the consistency of our findings with other models of shakeouts and reflect on the evolutionary paths that new industries follow and the role that submarket dynamics play in these paths.

## **2 Overview of the Laser Industry**

The laser is based on the idea that if an electron in an excited state is bombarded by a photon of proper energy, another photon of identical energy will be emitted. Materials in lasers are excited by a suitable energy source and photons of identical energy are built up in a cavity and then released as a tightly collimated beam of light of a single wavelength with all waves in phase. These qualities along with the great potential intensity of laser light make lasers useful for a wide range of applications.

Numerous materials have been made to lase. The material determines the wavelength of the laser light, which in turn dictates the applications serviced by a laser. We distinguish nine broad categories of lasers: solid state (crystals), semiconductor, chemical dye, and six gas lasers, helium neon (HeNe), carbon dioxide (CO<sub>2</sub>), ion, excimer, helium cadmium (HeCd), and a catchall category of other gas lasers. Solid state and semiconductor lasers can be further broken down in terms of the crystals and semiconductor materials used. Distinctions also can be made in each of the nine laser categories according to such factors as power (intensity), continuous versus pulsed operation, longevity, ruggedness, and cost of operation.

These characteristics along with the wavelength of the laser and its overall efficiency dictate its uses. For example, CO<sub>2</sub> lasers emit infrared light that can cut thick sheets of metal, excimer lasers emit ultraviolet light that is useful in semiconductor manufacturing and treating the human eye, HeNe lasers emit red light that is useful in barcode scanning and alignment tools, and semiconductor lasers are small and inexpensive, making them useful in large-scale applications such as CD players and laser printers. At times, existing lasers within a category have been challenged by new ones in

the same category, such as when Ruby crystal lasers were displaced by lasers based on neodymium-doped yttrium aluminum garnet crystals (called Nd:YAG). On rarer occasions an existing laser will be challenged by a new one in another category, such as when semiconductor lasers that emit red light were developed to challenge HeNe lasers in barcode scanning applications. But for the most part, the development of new lasers has brought new users into the industry without affecting the demand for other lasers. While occasionally lasers are successfully challenged by other types of light sources or by non-light sources in certain applications, such as in surgery, over time the industry has grown greatly through the development of new types of lasers.

We will conceptualize this process of growth in terms of the creation and in rarer instances destruction of independent product submarkets. It is an exaggeration to claim no competition or substitution between different types of lasers, as the case of HeNe and semiconductor lasers illustrates. But for the most part differences in the wavelengths and other properties of lasers have tended to differentiate the submarkets they serve and limited the extent of substitutability among them on the demand side. It is also an exaggeration to claim no scope economies across the lasers produced in different submarkets. However, historically the majority of laser firms have specialized in only one or two types of lasers and have coexisted with a small cadre of firms producing a wide range of lasers,<sup>1</sup> which is characteristic of industries characterized by limited scope economies across products.

A novel development beginning around 1988, though, changed in a far-reaching way submarket dynamics in the industry. Lasers need to be excited or “pumped” to initiate laser activity. Different energy sources are used to pump different types of lasers. Historically, solid-state lasers were pumped by flash and arc lamps, but it has long been known that semiconductor lasers are potentially more efficient pumps for solid state lasers. After a long stream of research in universities and government labs combined with improvements in semiconductor lasers, around 1988 practical diode (semiconductor) pumps for solid state lasers emerged. These diode pumps are up to 20 times smaller than

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<sup>1</sup> Among all the entrants through 1994, over their lifetimes 55% produced only one of the nine major types of lasers, 20% two of the types, 23% three to six of the types, and only 2% seven to nine of the types (Klepper and Sleeper [2005]).

lamp pumps of similar technical specifications (DeShazer [1994]). They opened up a rich trajectory of improvements in the efficiency of solid state lasers (Byer [1994] that has greatly expanded their use in two significant ways.

First, steady improvements in diode pumps resulted in decreases in the prices of solid state lasers that made them competitive with other lasers, particularly CO<sub>2</sub> lasers, at their natural wavelengths.<sup>2</sup> Diode pumping also expanded the range of solid state materials that could be used as lasers, leading to the creation of new solid state lasers servicing a wider range of applications (Koechner [2006]). Among these new solid state lasers are a whole new category called fiber lasers. These lasers are composed of special fiber-optic cables that guide and amplify laser light emitted by diode pumps. They are particularly useful for medical and industrial applications where laser light needs to be delivered to hard to reach places.

Second, diode-pumped solid state (DPSS) lasers improved the efficiency of solid state lasers sufficiently that it became feasible to use non-linear optical devices to alter the wavelength of the emitted light to produce *harmonic* wavelengths. Such devices can be used to double the frequency of light, which halves the wavelength, and can be applied repeatedly and in combinations to generate a series of different wavelengths of light from a particular laser. Energy is lost in the process, which along with the cost of the non-linear devices (and in the case of gas lasers, packaging problems) limited the historical use of wavelength conversion. But with the advent of DPSS lasers, it became feasible to use wavelength conversion to create new solid state lasers emitting wavelengths in the visible range, making them competitive with HeNe, ion, dye, and other types of gas lasers.<sup>3</sup> We compiled a list of all the distinct wavelengths supported by DPSS lasers that

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<sup>2</sup> The reduction in the price of solid state lasers brought about by diode pumping enabled them to displace CO<sub>2</sub> lasers in certain metal processing and medical applications where they have a natural advantage over CO<sub>2</sub> lasers (three times more absorption of metals for ND:YAG than CO<sub>2</sub>) due to their shorter wavelengths in the infrared region (Xie et. al. [1997]).

<sup>3</sup> HeNe lasers mainly produce a red colored beam. A small percentage of HeNe lasers used in image recording in commercial printing were displaced by DPSS lasers. Ion lasers produce laser beams in the visible range, including blue (around 475nm) and green (around 510nm). These lasers are bulky and expensive to pump and maintain and were largely displaced by DPSS lasers in several applications, including medical and surgical areas. DPSS lasers have also replaced ion lasers as pumps for other lasers, such as titanium-doped sapphire crystal lasers. Dye lasers can be tuned to generate a laser beam of a wide range of wavelengths. However, they are being displaced by titanium-doped sapphire lasers, which since 1996 have begun to use diode pumping instead of argon ion laser pumps (Matthews [2001a]). Other gas

produce an uninterrupted laser beam from *Laser Focus*. Figure 2 illustrates the broadening of wavelengths offered by solid state lasers with a range of natural wavelengths of 1000nm to 1550nm and harmonic wavelengths spanning 250nm to 800nm.

The modern evolution of solid state lasers has been described as a transformation from producing a ray to a rainbow. Our theoretical model focuses on how this ushered in a new era of competitive dynamics in the industry.

### **3 The Model**

The objective of the model is to explain how the advent of an innovation such as DPSS lasers could trigger a shakeout in an industry previously composed of independent submarkets and a shift in the character of innovation.

The model works as follows. Submarkets are created when exogenous technical advances create the opportunity to develop a variant of the industry's product that appeals to a new class of buyers. Initially the new products are not substitutes for existing ones but buyers of existing products will switch to them if their prices are reduced sufficiently through cost-reducing R&D. There are no scope economies in the sense that a firm's cost of production of a new product does not depend on the mix of other products it produces. Submarkets do not last forever, but can be rendered obsolete by random technical advances in competing products produced in other industries.

Firms engage in product R&D to develop a new product, and those that are successful capture the largest market share of the new product. Eventually other firms imitate the developers of the new product and capture a smaller market share in the new submarket. Firms can also engage in R&D to lower the average cost of production of new products. In the typical submarket, however, even the largest firms are too small for such R&D to be profitable.

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lasers such as nitrogen, carbon monoxide, and metal vapor lasers generate wavelengths in the visible spectrum. A number of DPSS lasers are now available in this part of the spectrum that compete with these lasers.

At some time, an unanticipated technological development increases the size of one submarket, enabling the largest producers in the submarket to grow sufficiently to make cost-reducing R&D profitable. As they invest in cost-reducing R&D, competition causes the price of the submarket's product to fall and demand and output in the submarket, and thus the industry, to rise. Price falls below the cost of other producers in the submarket and they exit the submarket and the industry overall if they were only producing in one submarket. When the price is reduced sufficiently through cost-reducing innovation, buyers in other submarkets are attracted and producers in these submarkets eventually lose their entire output and exit their submarket and the industry. Thus, over time the number of producers in the industry falls and the industry's output rises, giving rise to a shakeout.

The model has a number of other implications that are drawn out below that we use to test its explanation for the shakeout in the laser industry.

### 3.1 Specification of the Model

Let  $t = 0, 1, 2, \dots$  denote the period, where period 0 marks the start of the industry when its first product and thus submarket is created. Let there be  $K$  potential producers in each submarket. For simplicity, these firms are assumed to exist when the industry begins. By definition a firm enters the industry when it enters its first submarket. It exits the industry when it ceases producing in any submarket.

In each period  $t$  there is a probability  $\lambda$  of an (exogenous) technical advance that opens up the possibility of developing a new product. The product can be produced at a cost per unit of  $c$ . Let  $N_t$  denote the number of submarkets at the start of period  $t$ . The total demand for each product  $n = 1, 2, \dots, N_t$  in period  $t$  is given by

$$(1) \quad Q_{nt} = Q(p_{nt}; p_{1t}, p_{2t}, \dots, p_{n-1t}, p_{n+1t}, \dots, p_{N_t t}),$$

where  $p_{jt}$  is the price of product  $j$  in period  $t$  and  $\partial Q_{nt} / \partial p_{nt} < 0$ . When a new submarket  $j$  is created, it is assumed not to be competitive with other submarkets, but if its price can be lowered sufficiently below its initial cost of production  $c$  then it will attract buyers from other submarkets. We capture this by assuming that for submarket  $n$ , if  $p_{nt} = c$  then  $\partial Q_{nt} / \partial p_{jt} > 0$  for  $p_{jt} \leq P^{jn}$  but equals 0 for  $p_{jt} > P^{jn}$ , where the threshold price  $P^{jn} < c$ . Submarkets do not last forever but can be rendered obsolete by improvements in

competing products of other industries. For simplicity, we assume there is a constant hazard  $\gamma$  of a submarket being destroyed each period that is the same across submarkets. If a submarket is destroyed, producers lose their output in the submarket.

When a new product can be developed, the probability of a firm developing it in the next period is  $s(r_p)$ , where  $r_p$  is the firm's R&D spending on the new product,  $s(0) = 0$ ,  $s(r_p) < 1$  for all values of  $r_p$ ,  $s'(0) = \infty$ ,  $s' > 0$ , and  $s'' < 0$  to capture diminishing returns. Successful developers of the new product can produce it at an average cost of  $c$  and have one period before the other potential producers can imitate them and also produce the new product at the same average cost. Before they are imitated, successful developers of the new product play a Cournot-Nash game for one period; hence in that period the price of the new product exceeds  $c$ , all firms produce the same output, and each firm earns positive profits (Tirole [1992]). In the next period when all  $K$  potential producers can produce the product at the same cost  $c$ , competition drives the price to  $c$  and firm profits to zero. Successful developers of the new product retain their original output and capture a share of the increased demand for the product resulting from the decrease in price. Some other, randomly determined potential producers also capture a smaller share of the increased demand for the new product. Firms choose their level of product R&D to maximize their expected profits subject to their choices satisfying a Nash equilibrium. For simplicity, all firms are assumed to have the same probability, denoted by  $\theta$ , of entering each submarket.

Producers of a product can engage in R&D to reduce its cost (or improve its quality holding cost constant). For simplicity, we assume the opportunities to reduce the cost of a submarket's product are the same in each period. Letting  $r_c$  denote the firm's spending on cost-reducing R&D in a submarket in a period, the reduction in its average cost is  $g(r_c)$ , where  $g(0) = 0$ ,  $g'(0)$  is bounded,  $g' > 0$ , and  $g'' < 0$  to capture diminishing returns. The firm can only benefit from the cost reduction by applying it to its own output (i.e., it cannot license its innovations). Furthermore, it is assumed that after one period all cost reductions are costlessly imitated by other producers, limiting the benefits of the R&D to one period. Denoting the firm's output in a submarket as  $Q$ , its profit from cost-reducing R&D then equals  $g(r_c)Q - r_c$ . We assume that for all submarkets  $g'(0)Q^* = 1$ , which implies that cost-reducing R&D (of any amount) is not profitable in a period

unless a firm's output in the submarket exceeds  $Q^*$ . Up to period  $T$ , the output of the largest producers in each submarket (i.e., the original developers of the submarket's product) is assumed to be less than  $Q^*$ .

In period  $T$  an unanticipated technological development improves the quality of product  $d$ . This causes the demand for submarket  $d$  to rise, enabling the largest producers, which are the original developers of product  $d$ , to increase their output above  $Q^*$ . The other producers in submarket  $d$  also increase their output and some (randomly determined) producers that were not in submarket  $d$  capture some of the increased demand, but the output of all of these firms is less than  $Q^*$ . Rather than specify a full model of competition in submarket  $d$ , we just make some assumptions about the nature of the subsequent competition. First, firms take the price of the submarket as given, with the price clearing the submarket in each period. Second, if price exceeds a firm's average cost, it expands, but by a finite amount due to costs of adjustment. Such expansion results in the market-clearing price falling. Third, if price is such that a firm earns negative profits, it exits. Fourth, firms that remain in the submarket expand by the same amount. Fifth, as  $p_{dt}$  falls below  $P^{dn}$ , customers of each producer in submarket  $n$  are equally likely to switch to submarket  $d$ . Sixth, for simplicity we assume that if  $p_{dt}$  falls sufficiently, no new submarket is viable—i.e., if the price of product  $d$  is sufficiently low then the demand for all potential new products is zero, in which case firms cease trying to develop them.

Last, we make two simplifying assumptions about firm decision making. We assume that firms cannot forecast future R&D and other opportunities and thus make decisions each period concerning product and cost reducing R&D to maximize their immediate, one-period profits. We also assume that the costs of acquiring other firms is prohibitive, foreclosing the possibility of acquisitions.

### **3.2 Industry Evolution up to Period $T$**

We first consider the implications of the model for the evolution of the industry up to period  $T$ . In this era firms choose their level of product R&D when it is possible to develop a new product and their level of cost reducing R&D for each product they produce. All other outcomes are randomly determined.

In each period when a new product can be developed, firms have to choose how much R&D,  $r_p$ , to devote to developing the new product. The first-order condition for each firm is

$$(2) \quad s'(r_p)E(\pi) = 1,$$

where  $E(\pi)$  denotes the firm's expected profits from producing the new product in the next period if it successfully develops it.<sup>4</sup> Its expected profits depend on the R&D spending of its rivals; the greater the spending of its rivals then the greater the expected number of producers of the new product in the next period and hence the lower the one-period profits of each firm. Furthermore, the lower  $E(\pi)$  then the smaller the value of  $r_p$  that satisfies (2). Hence the firm's reaction function is such that the greater the R&D spending of its rivals then the lower its R&D spending on developing the new product. Since  $s(r_p)$  is the same for all firms, they have the same reaction functions. Consequently, there exists a value of  $r_p$  for each firm, denoted as  $r^*$ , that defines a Nash equilibrium in which equation (2) is satisfied for every firm with  $E(\pi)$  evaluated at  $r_p = r^*$  for each firm. We assume that  $s(r^*)E(\pi) - r^* \geq 0$  and that this symmetric equilibrium is established. The expected number of successful developers of the new product is  $s(r^*)K < K$  and  $E(\pi) > 0$ . One period later the developers of the new product expand their output and some other firms capture a smaller output of the submarket than the original developers. No firm is large enough for cost-reducing R&D to be profitable and thus the output of each firm in the submarket does not change over time unless the submarket is destroyed and each producer's output in the submarket goes to zero.

Up to period  $T$ , the probability of a submarket being created in each period is the same, as is the probability of a submarket being destroyed. Firms have an equal chance of entering each submarket. Assuming periods are sufficiently small, these conditions conform to the assumptions of the model of submarket dynamics in Klepper and Thompson [2006]. It then follows from Klepper and Thompson [2006] that there is a steady-state distribution for the number of submarkets, firms, and industry output, which implies:

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<sup>4</sup> Since  $s''(r_p) < 0$ , the second-order conditions for a maximum is satisfied.

Result 1: After the start of the industry, the expected number of submarkets, firms, and output rise over time toward their steady-state values.

In each period, at most one submarket is created, so if entry occurs it must be concentrated in a single submarket. If exit occurs in a period, it will be concentrated in submarkets that are destroyed. Therefore, it follows that:

Result 2: In any sub-period, entry and exit will be concentrated in a limited number of submarkets.

The probability of a firm exiting the industry in any given sub-period equals the probability of all of its submarkets being destroyed (and no new ones being created that it enters), which clearly is a decreasing function of the number of submarkets in which it produces. The expected number of submarkets in which a firm produces  $t$  periods after its entry is  $e^{-\gamma t} + \theta\lambda \int_0^t e^{-\gamma x} dx$ , where the first term is the probability that the first submarket it entered is still active after  $t$  periods and the second term is the expected number of additional, new submarkets it entered that are still active after  $t$  periods (cf. Klepper and Thompson [2006, p. 879]). Assuming  $\theta\lambda$  is sufficiently large relative to  $\gamma$ ,<sup>5</sup> the expected number of submarkets rises with  $t$  (the age of the firm) and is independent of when the firm entered the industry. Therefore:

Result 3: The hazard of exit from the industry rises with a firm's age and is independent of its time of entry.

Last, firms can exit a submarket only if it is destroyed. Therefore:

Result 4: The hazard of exit from a submarket is independent of a firm's age and its time of entry into the industry.

### **3.3 Evolution beginning with Period $T$**

We next consider the implications of the model for the evolution of the industry from period  $T$  onward.

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<sup>5</sup> The second term in the expression for the expected number of submarkets rises with  $t$ . The additional assumption is needed to insure that the increase in the expected net number of new submarkets outweighs the expected death of the first one entered, which is required in order for firms on average to grow over time.

In period  $T$ ,  $p_{dT} = c$ , the output of submarket  $d$  rises, incumbent producers in submarket  $d$  expand with the largest expanding above  $Q^*$ , and some firms enter the submarket. In period  $T+1$ , cost reducing R&D is profitable for the largest firms, which were the original entrants into submarket  $d$ . They conduct a level of cost reducing R&D that satisfies the first-order condition:

$$(3) \quad g'(r_c)Q = 1.$$

Consequently, their average cost declines to  $c - g(r_c) < p_{dT}$  and they expand their output. It was assumed that expansion is finite (due to costs of adjustment) and causes the market-clearing price to fall.<sup>6</sup> Therefore,  $p_{dT+1} < c$ , causing total industry demand and hence industry output to rise. The profits of the other producers (with cost  $c$ ) are negative and they exit and the incumbents expand by an equal amount per firm.<sup>7</sup> Therefore, it follows from equation (3) that in period  $T+2$ ,  $r_c$  rises, which must lead to  $p_{dT+2} < p_{dT+1}$  and firm and industry output rising further.<sup>8</sup> This continues until eventually  $p_{dt}$  falls below  $P^{dn}$  for different submarkets  $n$  and buyers switch from these submarkets to submarket  $d$ . With producers in these submarkets equally likely to lose customers, the firms that are expected to exit first are the smallest producers, which are the later entrants in these submarkets. Eventually  $p_{dt}$  falls sufficiently that no new submarkets are viable and firm R&D spending on new products goes to zero, causing entry to cease.

Thus, beginning with period  $T$ , the industry experiences the following evolution: Result 5:  $Q_{dt}$  and total industry output  $\Sigma Q_{jt}$  rise over time, the number of firms in submarket  $d$  initially rises and then falls, the number of firms in other submarkets later declines, and eventually entry ceases.

Total R&D in submarket  $d$ , which equals the sum of product and cost reducing R&D, initially equals  $Kr^*$ , then it drops to 0 until period  $T+1$ , when it becomes positive and then rises over time. Therefore:

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<sup>6</sup> Innovators would earn positive profits if  $p_{dT+1} = c$ . Consequently, the price can fall and still allow producers to earn nonnegative profits, recouping the cost of their R&D in one period.

<sup>7</sup> The price  $p_{dT+1}$  is such that the total expansion of the innovators equals the output of the exiting producers and the increase in the total quantity demanded. See Klepper [2002] for a model of industry evolution in which firms do cost reducing R&D and incur costs to expand, causing the market-clearing price to fall over time and smaller firms to exit.

<sup>8</sup> All firms are identical and we assume they all continue to produce, but given the increasing returns nature of the model this is a knife-edge equilibrium. Allowing for exit and a decline in the number of firms would not alter, though, the key prediction of  $p_{dt}$  continuing to decline over time.

Result 6: Beginning in period  $T+1$ , R&D in submarket  $d$  rises and stays higher than it was in any period after the start of submarket  $d$ .

At time  $T$ , the probability of a firm exiting the industry equals the probability of all its submarkets being destroyed (and no new ones created that it enters). In period  $T+1$  and later periods, firms can also exit from submarket  $d$  and affected submarkets without them being destroyed. Hence:

Result 7: After period  $T$ , the hazard of exit from the industry rises and remains higher than in period  $T$ .

The firms that exit submarket  $d$  in period  $T+1$  are the later entrants into submarket  $d$ . Similarly, the firms that are expected to exit the affected submarkets first are those that entered the submarkets later. Therefore:

Result 8: After period  $T$ , the hazard of exit in submarket  $d$  and affected submarkets is greater for later entrants into the submarkets and hence the hazard of exit from the industry is greater for later entrants.

If no new submarket is developed after period  $T$ , entry initially is concentrated in submarket  $d$  and then ceases. Exit is also initially concentrated in submarket  $d$  and any destroyed submarkets and then occurs in the affected submarkets as well as any that are destroyed. Therefore:

Result 9: Beginning with period  $T$ , entry and exit are initially concentrated in submarket  $d$  and then entry is not (concentrated) in any submarket and exit is dispersed over multiple submarkets.

### **3.4 Testable Implications**

We have data on firms, output, sales, and patents at the level of the nine broad categories of lasers. Each of these categories is likely to contain multiple submarkets. Therefore, we adapt the results above to accommodate the existence of multiple possible submarkets within each of the nine types of lasers. We identify period  $T$  with the advent of DPSS lasers in 1988. As the price of these lasers decreased, they made in-roads into markets serviced by CO<sub>2</sub> lasers. Through wavelength conversion, DPSS lasers also eventually became competitive with primarily HeNe, ion, dye, and other gas lasers. Accordingly, we synthesize the following eight testable hypotheses from the theory.

Hypothesis 1: Entry into the industry initially is positive and output and the number of producers rises. After 1988 output and the number of producers continues to rise at first but eventually the number of producers falls even as the output of the industry continues to rise, giving rise to a shakeout in the industry.

Hypothesis 2: The output and number of producers of solid state lasers rises over time, particularly after the advent of DPSS lasers in 1988, and then at a later point the number of producers declines even as the output of solid state lasers continues to rise.

Hypothesis 3: For CO<sub>2</sub>, HeNe, ion, dye, and other gas lasers, initially entry is positive and output and the number of producers rises. Some time after 1988, entry declines and both output and the number of producers fall in tandem.

Hypothesis 4: Annual R&D expenditures related to solid state lasers rise around 1988 and remain at a higher level in subsequent periods, which gives rise to a greater number of patents and innovations per year related to solid state lasers after 1988. The leading patenters/innovators are the largest producers and hence the earliest producers of solid state lasers.

Hypothesis 5: From the beginning of the industry up to 1988, entry and exit in successive sub-periods are concentrated in a limited number of laser types, with the types of laser differing across sub-periods (and for entrants and exiters within sub-periods). After 1988, at first entry and exit are concentrated in solid state lasers. Subsequently, neither entry nor exit in sub-periods is concentrated in any one type of laser.

Hypothesis 6: At some time after 1988, the hazard of exit from the industry rises and remains at a higher level.

Hypothesis 7: For all entrants, the hazard of exit declines with age. At each age, it is higher for entrants after 1988 than earlier entrants, but among pre-1988 entrants it is unrelated to time of entry (for ages corresponding to years before 1988).

Hypothesis 8: After 1988, the hazard of exit from solid-state, CO<sub>2</sub>, HeNe, ion, dye, and other gas lasers is greater for entrants after 1988 than earlier entrants, whereas before

1988 it is unrelated to time of entry (assuming each type of laser is composed of a single submarket<sup>9</sup>).

## 4 Data Analysis

Data on the U.S. laser producers are compiled using *Laser Focus World's* annual Buyer's Guide, which is based on an annual survey of laser producers. The data, originally collected by Sleeper [1998], are extended to cover the whole period from 1961 to 2007. Many different categories of lasers are listed, and each year we coded the specific lasers produced by each firm. We then aggregated the data up to the level of eight broad laser types,<sup>10</sup> enabling us to identify which of the eight types of lasers firms produced each year.<sup>11</sup> Annual data on global sales and output (since 1986) are collected from the same source.

### 4.1 Shakeouts and Trends in Output and the Number of Producers

As noted in the introduction, Figure 1 indicates that the number of U.S. laser producers increased steadily through 1996 to a peak of 172 and then declined steadily to 87 in 2007.<sup>12</sup> Over this same period global (real) sales of lasers rose steadily,<sup>13</sup> with the average annual rate of growth of (real) sales increasing from 16.8% in 1974-1995 to 20% in 1996-2007. Thus, consistent with hypothesis 1, the laser industry has been undergoing a pronounced shakeout of producers that began after the advent of DPSS lasers.

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<sup>9</sup> If a laser type is composed of multiple submarkets, then on average older firms will be in more of the submarkets. This will reinforce the effect of time of entry on the hazard of exit after 1988 but will also cause the hazard of exit to be greater for later entrants prior to 1988 (not controlling for the age of firms).

<sup>10</sup> Klepper and Sleeper [2005] and Klepper and Thompson [2006] distinguish nine broad categories of lasers through 1994. One of these, Helium Cadmium, remained small and we collapse it into the catchall category of other gas lasers.

<sup>11</sup> Occasionally there was a gap of one or more years over the period a firm was listed as a producer of a particular laser. We used discretion in determining whether this was an error or represented entry and exit from the industry (mostly the former unless the gap was long). Acquisitions of one laser firm by another were treated as an (censored) exit of the acquired firm and continuing production by the acquirer. Firms acquired by non-laser producers were treated as continuing laser producers. Acquisitions were identified from reports in *Laser Focus* and searches of company web sites.

<sup>12</sup> Similar patterns occurred in the total number of laser producers in the world. We restrict our analysis to the U.S. industry where it was manageable to track acquisitions and name and location changes. For an analysis of the German laser industry and its parallels to the U.S., see Buenstorf [2007].

<sup>13</sup> The spike in sales in 2000 (but not output) appears to be due mainly to the strengthening in the Yen relative to the U.S. dollar, which was subsequently reversed (Steele [2002]).

Figure 3 is the analog of Figure 1 for solid state lasers. Apart from a modest decline in the number of producers from 35 in 1967 to 21 in 1978, the number of producers rose over time to a peak of 78 in 1997 and then declined to 50 by 2007.<sup>14</sup> Global production of solid state lasers grew sharply throughout this period, causing solid state lasers to grow from 2% of all non-diode lasers produced in 1994 to 40% in 2007. Nevertheless, consistent with hypothesis 2, the number of producers of solid state lasers went through a pronounced shakeout that is still on-going. These patterns parallel those at the industry level, as predicted.

Figure 4 presents the analogous patterns for CO<sub>2</sub>, HeNe, ion, other gas, and dye lasers. While each is subject to idiosyncratic factors, consistent with hypothesis 3 all of them reflect considerable growth in output and the number of producers from the start of the industry and then a decline in the number of producers since 1997 (if not earlier). Other than CO<sub>2</sub>, the decline in the number of producers was also accompanied by a fall in output, as predicted in hypothesis 3.

#### **4.2 Technological Change Related to Solid State lasers**

We compiled annual data on U.S. patents related to solid state lasers, which includes patents on solid state crystals, diode pumping, and wavelength conversion. The U.S. patent class 372 refers to coherent light generators or simply lasers. Subclasses 21, 22, 41, and 75 refer to wavelength conversion, solid state crystals, and diode pumping. Figure 5 presents the annual number of patents in these DPSS related areas from 1961 to 2002. Also presented for comparison is the annual number of patents in this period for gas and dye lasers corresponding to subclasses 51 to 56 and 58 to 65.<sup>15</sup>

Figure 5 reflects a sharp increase in the number of solid state related patents since 1988. Before 1988 there were less than 25 such patents per year, but after 1988 the

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<sup>14</sup> *Laser Focus Buyer's Guide* does not distinguish diode-pumped and flash-pumped versions of several types of solid state lasers. Only Nd:YAG, Nd:YLF, Nd:YVO<sub>4</sub>, and Cr:LiSAF are explicitly recorded as being diode-pumped. Among these four laser types and a catchall category of diode pumped solid state lasers, the number of producers rose from seven in 1988 to a peak of 48 in 1999 and then declined to 27 in 2007, paralleling the overall trend in solid state lasers. Similarly, even though the number of DPSS laser producers declined, the production of DPSS lasers increased sevenfold from 3,114 units in 1996 to 21,150 units in 2007 while the number of diode lasers sold to pump solid state lasers increased tenfold from 51,813 units in 1999 to 525,355 units in 2006.

<sup>15</sup> Patents are dated based on their year of filing.

annual number of these patents typically exceeded 200. In contrast to this pattern, gas and dye laser related patents experienced their peak activity around 1988 and subsequently declined before recovering. Thus, consistent with hypothesis 4, patenting increased sharply in solid state lasers and related areas after 1988, which contrasts sharply with patenting rates in gas and dye lasers with which DPSS lasers began to compete.

It is also predicted that the leading patenting firms will be the largest firms, which are expected to come from the earliest entrants. Table 1 shows the top five U.S. laser firms in the DPSS-related patent subclasses since 1988 along with the number of years they produced solid state lasers after 1988. Spectra Physics and Coherent are the two leading firms in the industry, Raytheon is another long-lived and important laser producer, and Bell Labs, AT&T's research arm, was an early and sustained research leader in the industry. Amoco Corporation is the only leading patenting firm that did not enter early, but it is a spinoff from Amoco Oil's corporate research lab and the founder recognized the potential of DPSS lasers early (Feder [1988]).<sup>16</sup> Among the 257 producers of solid state lasers in 1989 and later years, Raytheon, Coherent, and Spectra Physics were the first, sixth, and (tied for) eleventh earliest entrants, with Amoco 40<sup>th</sup>, and Raytheon, Coherent, and Spectra Physics ranked among the top ten firms in terms of the total number of years of production of solid state lasers. Thus, consistent with hypothesis 4, patenting in DPSS related areas was led by early and long-lived producers of solid state lasers.

Another measure of technological change pertaining to solid state lasers is the rate of creation of new types of solid state lasers. The number of new categories of solid state lasers averaged 0.60 per year from 1961 to 1987 and then increased to 1.05 per year from 1988 to 2007, consistent with hypothesis 4. Many of these new laser types were made possible by diode pumping and thus shared a common technology. Consequently, they tended to be produced in tandem, especially by the leading solid state producers. For example, Coherent and Spectra Physics, the two leading patenters, produced 17 and 15 different types of solid state lasers respectively. Both were also heavily involved in

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<sup>16</sup> According to *Laser Focus*, Amoco later changed its name to ATx to focus on telecommunications-specific uses of lasers and licensed 24 of its patents to Coherent for non-telecommunications uses in 1995.

producing semiconductor diode arrays for diode pumping. Only two other firms, Schwartz Electro Optics and Excel Technology, produced a comparable number of types of solid state lasers as Coherent and Spectra Physics, but judging from the list of semiconductor producers neither seems to have been as involved as Coherent and Spectra Physics in diode arrays.<sup>17</sup>

Another reflection of the technological change driven by DPSS lasers is the proliferation of new wavelengths of solid state lasers reflected in Figure 2. Before the advent of DPSS lasers, solid state lasers generated wavelengths only in the range of 1,064 nm. Diode pumping led to the creation of new DPSS lasers that generated natural wavelengths in the 1,000 nm to 1,600 nm range and through wavelength conversion harmonic wavelengths in the visible spectrum spanning 250 nm to 800 nm. Not surprisingly, Coherent and Spectra Physics were in the vanguard of the new DPSS lasers. Among the 49 firms in 2006 listed as producing continuous wave DPSS lasers, Coherent and Spectra Physics ranked two and three with 32 and 28 lasers with distinct wavelengths respectively. Only two other firms had lasers with more than ten wavelengths, including Melles Griot with 35 and Lee Laser with 26.<sup>18</sup>

### **4.3 Entry and Exit in Laser Types**

Hypothesis 5 predicts that until fairly recently, entry and exit in short time intervals should be concentrated in just a few types of lasers, with these laser types changing over time. In more recent years, it is expected that entry and exit initially would be concentrated in solid state lasers and then not concentrated in any one laser type.

To test these predictions, following Klepper and Thompson [2006] the history of the industry is divided into five-year intervals, which provide a sufficiently large sample for each time period to carry out statistical tests. The analysis begins in 1970 when all but excimer lasers had been developed, with excimer lasers excluded from the analysis. For

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<sup>17</sup> Consistent with the model, Schwartz (tied for 40<sup>th</sup>) and Excel (60<sup>th</sup>) were relatively early entrants among the 257 firms that produced solid state lasers in the DPSS era (after 1988).

<sup>18</sup> Melles Griot was founded outside of the U.S. and was acquired by a U.S. laser producer in 2007. Lee Laser was originally an OEM supplying Spectra Physics when it entered in 1986 (24<sup>th</sup> among the 257 entrants into solid state lasers) and then expanded to become a full-fledged solid state producer.

entrants and exiters, the laser type(s) produced in the first and the last year respectively are reported in Tables 2 and 3 for each five year interval and for all time periods combined.<sup>19</sup> As the tables indicate, the total number of entrants and exiters producing each laser type over the entire period varies greatly by laser type, reflecting possibly different number of submarkets within each laser type and different sizes of submarkets.

If hypothesis 5 is correct, then the numbers in each cell of Tables 2 and 3 should be close to zero or the total number of entrants (exiters) in the respective time interval, which is denoted as  $Tot_t$ . The alternative, null hypothesis is that the numbers in each cell should equal  $Tot_t$  times the fraction of entrants in all time periods that initially produced the respective laser type, denoted as  $f_i$ . For example, entrants collectively produced 892 lasers in their first year and the fraction of these that were CO2 lasers was  $124/892=0.139$ . Hence, in the time period 1980-1984 when entrants collectively produced 103 lasers in their first year, under the null hypothesis the expected number of entrants producing CO2 lasers is  $0.139 \times 103 = 14.32$ . We can test the null hypothesis using the test statistic  $\sum_{i,t} [(E_{it} - Tot_t * f_i) / Tot_t * f_i]^2$ , where  $E_{it}$  is the actual number of entrants (exits) in Table 2 (3) in laser type  $i$  in time interval  $t$  and  $Tot_t * f_i$  is the expected number under the null hypothesis. It is computed for the first four five-year intervals corresponding to the pre-DPSS era of the industry for entrants and exiters. Ignoring that some firms produced multiple lasers in their first or last year, the test statistic has a  $\chi^2$  distribution with 18 degrees of freedom. For entrants the test statistic equals 52.96, which is significantly different from 0 at the .000 level, and for exiters it equals 32.47, which is significantly different from 0 at the .02 level. Hence the null hypothesis of no significant clustering of entry and exit in the early era is rejected, consistent with hypothesis 5.

It is also predicted that the submarkets where entry and exit are concentrated changes during the early era. Following Klepper and Thompson [2006], laser types where the number of entrants producing a laser type in a time period exceeds the expected number (under the null hypothesis) plus 1.65 standard deviations are identified and

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<sup>19</sup> First and last lasers are defined as laser(s) produced by a firm in the first and last year it was listed in the Buyer's Guide. When more than one laser type is produced in the first year (23% of the entrants produced more than one type in the first year) and the last year (26% of the exiters produced more than one type in the last year), then all laser types are counted.

shown in bold face in Tables 2 and 3.<sup>20</sup> Early on entry and exit are concentrated in HeNe lasers but then shift to other types of lasers, consistent with hypothesis 5.<sup>21</sup>

In the later era we distinguish three time periods, 1990-1994, 1995-1999, and 2000-2007. At some point after 1988 entry was expected to be concentrated in solid state lasers, followed by a concentration of exit in solid state lasers, after which entry and exit were not expected to be concentrated in any one laser. We see that by the 1995-1999 time period, entry was concentrated in solid state lasers and then again solid state lasers and semiconductor lasers in 2000-2007. Exit was not concentrated in any one type of laser in the 1995-1999 period but was concentrated in solid state and semiconductor lasers in the 2000-2007 period. Thus, we do see the predicted concentration of entry and then exit in solid state lasers, but it appears that sufficient time has not yet elapsed for the solid state market to have settled down.

#### **4.4 Hazard of Industry and Submarket Exit**

Hypotheses 6, 7, and 8 predict various changes in firm hazard patterns with the advent of DPSS lasers after 1988.

Hypothesis 6 predicts that the overall hazard rate from the industry will be greater after 1988. Figure 6 reports the annual number of exits expressed as a fraction of firms in the prior year for the period 1965-2007. The fraction of firms exiting is high initially, rising briefly above 20% in 1974, and then declines to a low of around 4% in 1982 before recovering to 10% in 1987. Thereafter the exit rate is markedly higher, varying between 10% and 22% per year. Thus, consistent with hypothesis 6, around 1988 there appears to be a marked increase in the overall industry hazard rate that does not abate over time.

Hypothesis 7 allows for the hazard rate to vary with age and predicts that at comparable ages the hazard of exit should be unrelated to time of entry for entrants prior to 1988 but should be greater for entrants after 1988. To control for age, Kaplan-Meier (K-M) survival curves were estimated for three cohorts of entrants corresponding to the years 1961-1974, 1975-1988, and 1989-2007. These curves, which are presented in

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<sup>20</sup> The standard deviation for laser type  $i$  in time period  $t$  was computed as  $f_i(1-f_i)Tot_t$ .

<sup>21</sup> There is some tendency, though, for entry and exit to be concentrated in the same laser types in each period, which is not predicted by the model.

Figure 7, estimate the probability of entrants surviving to each age.<sup>22</sup> The vertical axis is scaled logarithmically so that the negative of the slope of a K-M curve at a given age is the hazard of exit of the respective cohort at that age. Up to age 15, nearly all exits in the earliest cohort of entrants and most in the middle cohort pertain to the pre-1988 era. Consistent with hypothesis 7, the K-M curves for the two cohorts do not differ much and are not statistically different at the .10 level (p-value 0.7103) based on the log rank test. In contrast, all the exits for the post-1988 entrants correspond to years after 1988. Consistent with hypothesis 7, the K-M curve for the post-1988 entrants is steeper than the other two, reflecting a higher hazard across all ages, and is significantly different from the other two at the .005 level based on the log rank test.

Hypothesis 8 predicts that after 1988, the hazard of exit for solid state producers and for CO<sub>2</sub>, HeNe, ion, dye, and other gas laser producers should be lower for earlier entrants.<sup>23</sup> Consider first the 42 solid-state producers that survived until 1988. Only seven of them entered before 1975, so they are grouped into a single category of early entrants and their survival experience is compared with the 215 solid state producers that entered after 1988. Figure 8 presents K-M survival curves for the two cohorts, where age for the earlier cohort refers to years since 1988 (and age for the second cohort is their chronological age). The survival rate is consistently lower at each age for the later entrants and the curve for the later entrants is significantly different from the one for the earlier entrants at the .01 level based on the log rank test. A similar analysis is done for the producers of CO<sub>2</sub>, HeNe, ion, dye, and other gas lasers; individual observations for CO<sub>2</sub>, HeNe, dye, ion, and other gas lasers are pooled and analogous K-M curves are estimated for entrants before and after 1988. Figure 9 indicates that the K-M curve for the later cohort of entrants lies below that for the earlier cohort of entrants at every age, with the two curves significantly different at the 0.001 level based on the log rank test. Thus, consistent with hypothesis 8, after 1988 the hazard rate of producers of both solid state lasers and CO<sub>2</sub>, HeNe, ion, dye, and other gas lasers is greater for the post-1988 entrants.

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<sup>22</sup> Exits by acquisition are treated as censored in the estimation of the K-M curves.

<sup>23</sup> It also predicts that before 1988 the hazard of exit will be unrelated to time of entry for each type of laser. We tested this by estimating K-M curves for producers of CO<sub>2</sub>, HeNe, dye, ion, and other gas lasers analogous to those at the industry level in Figure 7 and confirmed little difference in the curves for entrants prior to 1989.

## 5 Discussion

For over 30 years, the laser industry was characterized by steady growth in output and the number of producers. Entirely new types of lasers and variants of existing lasers were created that brought new users into the industry. Judging by entry patterns and the rise in the number of producers, these new lasers enabled new firms to enter and compete in the industry. The advent of DPSS lasers around 1988 fundamentally changed these dynamics. A rich trajectory of technological opportunities led to steady improvements in DPSS lasers, fueling a sharp rise in their use both absolutely and as a share of all non-diode lasers produced. Lasers that had always serviced distinct groups of buyers began to experience competition from DPSS lasers, leading producers of these lasers to exit the industry. At the same time, producers of solid state lasers experienced a shakeout that decreased their ranks. The result was a sharp shakeout of producers from the industry that is still on-going.

Before the advent of DPSS lasers, there was little sign of earlier entrants possessing any competitive advantages. But with the onset of DPSS lasers, earlier entrants fared better than later entrants in terms of survival. The earliest entrants into solid state lasers were in the vanguard of the surge in patenting and the creation of new solid state lasers, led by Spectra Physics and Coherent, the long-time leaders of the industry. Our model attributes their leadership to their greater size, which enabled them to earn a greater return from DPSS-related R&D or equivalently to amortize the costs of such R&D over a greater level of output. Indeed, John Ambroseo, the CEO of Coherent, remarked in 2004 (Kincade, and Anderson [2004]) that as the laser industry moved into more mainstream applications, firms needed critical mass to drive engineering programs, which necessitated consolidation.<sup>24</sup>

Quite apart from our particular interpretation of events in the laser industry, it seems clear that the shakeout in the industry was related to technological change. A

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<sup>24</sup> An examination of Coherent's DPSS related patents provides a sense of how its size may have conditioned the return from its engineering programs. Its patents were concentrated in four areas: improvement in diode arrays, particularly the stacking of diode bars in the arrays; heat management in solid state crystals to alleviate thermal stresses; optical devices to focus the output of diode arrays for pumping; and efficient generation of harmonic wavelengths. Innovations in each of these four areas had wide applicability to DPSS lasers of various types and thus would yield profits in proportion to the number of solid state lasers produced.

number of theories portray shakeouts as a reflection of developments related to demand and not technological change (e.g., Horvath, Shivardi, and Woywode [2001], Wang [2008]). To explain the common finding that earlier entrants into shakeout industries tend to survive longer (Klepper [2002]), such theories posit that superior firms enter the industry first, when demand conditions are the least favorable, and thus exit last during the shakeout (Braguinsky, Gabdrakhmanov, and Ohyama [2007], Wang [2008]). However, the fact that the hazard of exit was unrelated to time of entry for the first 30 or so years of the evolution of the laser industry suggests that earlier entrants were not superior firms. It was not until the technological developments brought on by DPSS lasers that advantages of early entry emerged, suggesting these advantages and the shakeout that ensued were fundamentally related to technological change.

The developments in lasers also seem revealing about how technological change contributes to shakeouts. A popular idea is that as industries evolve, demanders coalesce around a particular conception of a product, dubbed a dominant design, which focuses competition and contributes to a shakeout (Utterback and Suárez [1993]). In lasers, the increasing importance of one submarket certainly played an important role in the shakeout in the industry. But the growth of this submarket was fueled by a proliferation of new types of lasers and the adaptation of old ones to markets previously serviced by non-solid state lasers. Rather than buyers coalescing around a dominant design, solid state producers used the technological opportunities opened up by diode pumping to find ways to create new DPSS lasers to service a much wider array of buyers.

Another theory of shakeouts features the role of technological developments in increasing production scale economies and the minimum efficient sized firm (Jovanovic and MacDonald [1994]). Dominant designs are expected to have a similar influence on the scale of production and thus to operate similarly in limiting the number of producers. It is always difficult to assess the nature of the firm average cost curve and the minimum efficient sized firm. But it is noteworthy that diode pumping of solid state lasers led to a proliferation of different types of DPSS lasers, with the leading firms in the vanguard of this process. The key to their success seems to have been based on innovation and development of a wide range of DPSS lasers rather than the production of any one type of laser at a sufficient volume to exploit potential scale economies.

The two eras of the laser industry provide a stark contrast that illuminates how the emergence of a dominant submarket can influence an industry's dynamics and contribute to a shakeout and change in the character of innovation. In reflecting on other innovative industries that have experienced pronounced shakeouts, the lessons from the laser industry may turn out to have broad applicability. The evolution of the historical automobile industry is particularly instructive. Wells [2007] argues that prior to the Model T, different types of cars serviced urban and rural dwellers. Through the use of vanadium steel in the Model T, Ford was able to develop a car that was both light weight and powerful, allowing him to appeal to both urban and rural buyers. The result was a dominant submarket of much larger size, which enabled Ford to invest heavily in cost-reducing R&D, leading to the development of the moving assembly line. Perhaps not surprisingly, the shakeout in the automobile industry began in 1909, one year after the introduction of the Model T (Klepper [2002]), which also marked a pronounced rise in process relative to product innovation (Klepper and Simons [1997]).

Another industry where similar submarket dynamics played an important role in the evolution of market structure was hard disk drives. At a certain point new, smaller disk drives were developed that appealed to new users and thus defined new submarkets. Subsequently the smaller drives were improved sufficiently that they appealed to users of the older, larger drives (Christensen [1993]) and soon after a shakeout ensued. A notable difference from autos and lasers is that new entrants displaced the industry leaders (Christensen, Suárez, and Utterback [1998]), reflecting that the smaller disk drives were pioneered by entrants. This can be readily accommodated in the model by allowing submarket  $d$  to be a new, larger submarket in which the successful developers of the product capture a sufficiently large output for cost-reducing R&D to be profitable from the outset.<sup>25</sup>

Indeed, the model can be modified in a number of ways to accommodate other evolutionary paths. In some new industries, independent submarkets are not prominent, either because demanders are homogeneous or because of economies of scope across submarkets. The former can be accommodated in the model by simply assuming that the

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<sup>25</sup> See Adner [2002] and Adner and Zemsky [2005] for related models of the evolution of the disk drive industry in which firms can behave strategically.

probability of the creation of new submarkets after the first is zero and the initial submarket is large enough to allow for profitable firm cost reducing R&D. Scope economies can be accommodated in the model by assuming that cost reducing R&D can be applied to all of a firm's products, so that a firm's overall size conditions its incentive to engage in cost reducing R&D. In both types of industries, it would be expected that a shakeout would occur earlier than in industries like autos and lasers. Candidate industries where independent submarkets were not prominent are tv receivers and penicillin, both of which experienced shakeouts within ten years of their inception (Klepper [2002]).

When independent submarkets are prominent from the outset, asymmetries in their size and innovative potential will militate toward the eventual emergence of a dominant submarket, paving the way for a shakeout. But there is no technological imperative that rules out innovations that cause an industry to become more fragmented at any point in time. For example, after World War II a single type of camera emerged to service both serious hobbyists and snapshoters, but subsequently two new types of cameras were developed to service each segment of the market, in effect fissuring a dominant submarket into two independent submarkets. Not surprisingly, the result was renewed entry and product innovation, reversing the typical life cycle pattern in which initial entry gives way to a shakeout and R&D shifts from product to process innovation (Windrum [2005]).

We are accustomed to thinking of innovative industries coming from a particular mold regarding the character of innovation and market structure. But the laser industry indicates how quickly an industry can go from one extreme to another. Technological developments can unleash major changes in the nature of an industry's submarkets, with far reaching implications. Sutton [1998], Bottazzi and Secchi [2006], and Klepper and Thompson [2006] show how a wide range of regularities regarding entry, exit, and firm growth could be explained by submarket dynamics. We can now add to the list shakeouts, first-mover advantages, and the nature of technological change.

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## TABLES AND FIGURES

Table 1. Top patenting firms in DPSS lasers since 1988

<i>Patents</i>	<i>Laser Firm</i>	<i>Years of Production After 1988</i>
48	Spectra-Physics Lasers Inc.	20
31	Coherent Inc.	20
24	AT&T Corp.	1
22	Amoco Corporation	8
15	Raytheon Company	7

Table 2: Lasers produced by entering firms in their first year

<i>Period</i>	<i>CO2</i>	<i>Dye</i>	<i>GasOther</i>	<i>HeNe</i>	<i>Ion</i>	<i>Semi</i>	<i>SS</i>	<b>Total</b>
1970-74	12	8	10	<b>24</b>	7	6	14	81
1975-79	3	<b>9</b>	<b>9</b>	<b>16</b>	6	15	6	64
1980-84	<b>27</b>	7	<b>17</b>	14	7	10	21	103
1985-89	22	6	7	18	9	22	41	125
1990-94	15	14	8	14	10	38	59	158
1995-99	26	6	11	11	10	48	<b>82</b>	194
2000-07	19	5	6	7	5	<b>54</b>	<b>71</b>	167
<b>Total</b>	124	55	68	104	54	193	294	892

Table 3: Lasers produced by exiting firms in their last year

<i>Period</i>	<i>CO2</i>	<i>Dye</i>	<i>GasOther</i>	<i>HeNe</i>	<i>Ion</i>	<i>Semi</i>	<i>SS</i>	<b>Total</b>
1970-74	13	7	8	<b>26</b>	9	11	16	90
1975-79	2	3	3	<b>13</b>	2	9	8	40
1980-84	12	6	<b>10</b>	9	5	13	11	66
1985-89	<b>25</b>	6	9	12	10	8	29	99
1990-94	21	<b>14</b>	7	15	7	23	48	135
1995-99	23	3	10	14	11	44	73	178
2000-07	44	12	14	24	17	<b>102</b>	<b>165</b>	378
<b>Total</b>	140	51	61	113	61	210	350	986

Figure 1: Shakeout in the laser industry

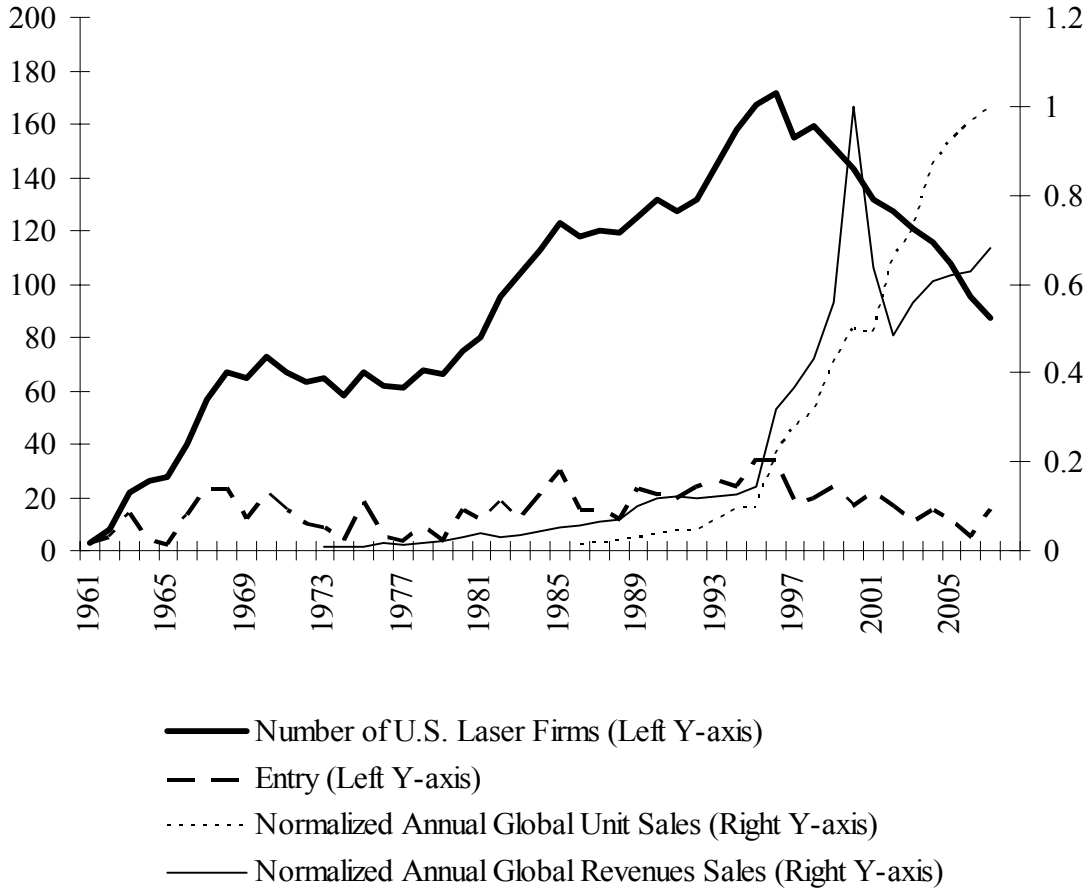


Figure 2. Broadening of wavelengths supported by solid state lasers

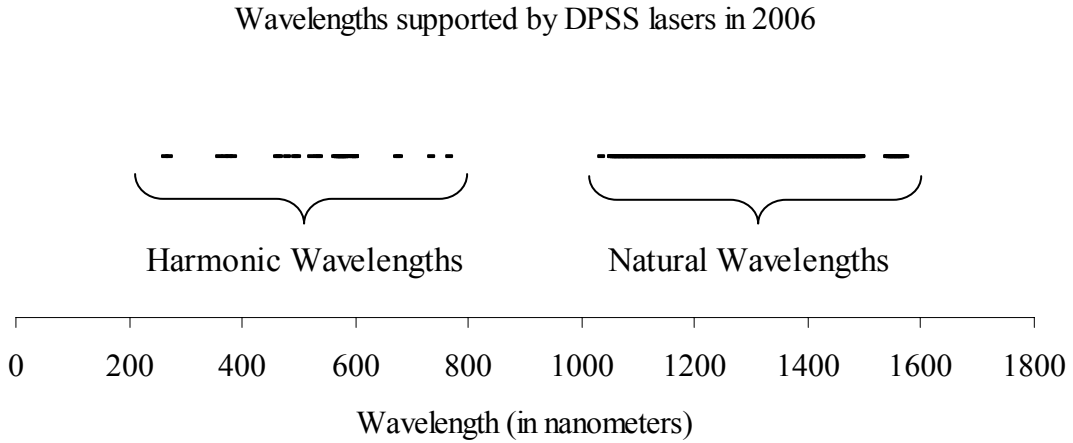


Figure 3: Shakeout in solid-state laser producers

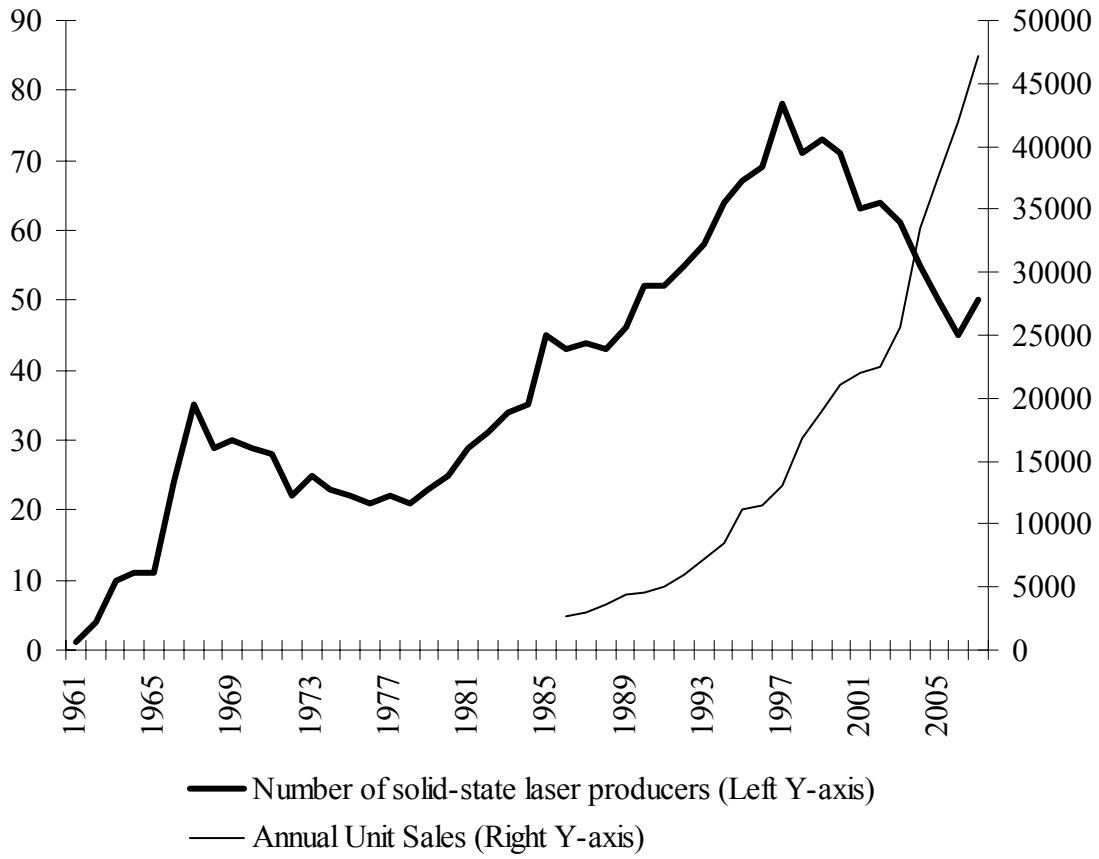


Figure 4: Displacement of CO<sub>2</sub>, HeNe, ion, dye, and other gas laser types

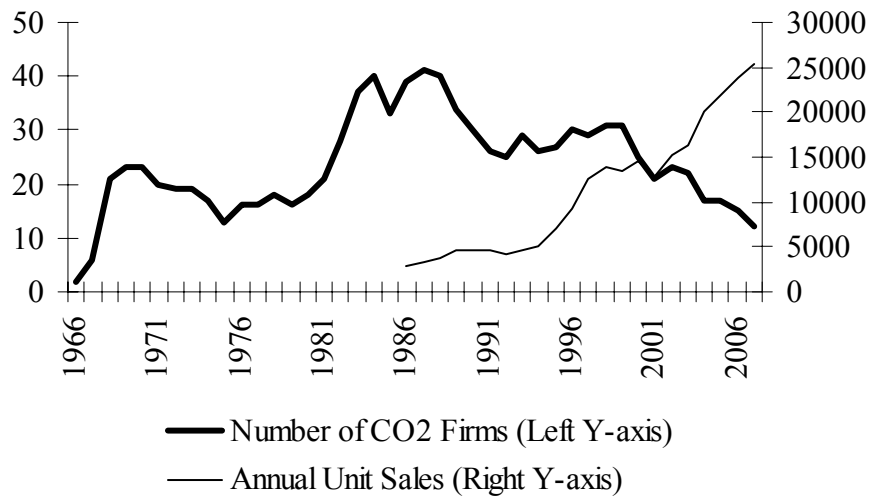
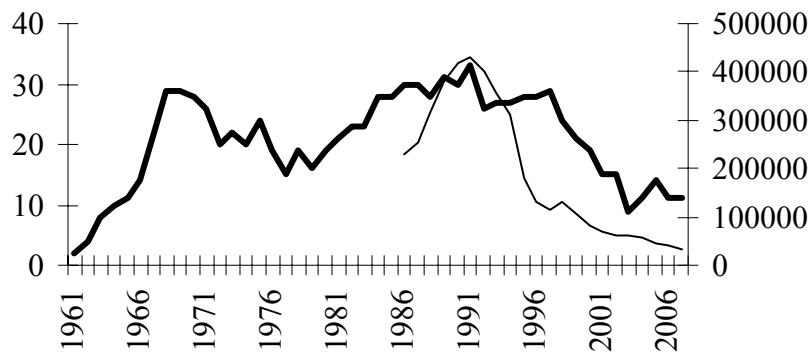
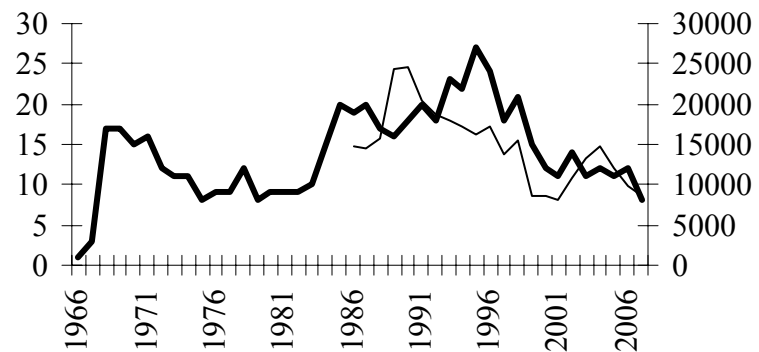


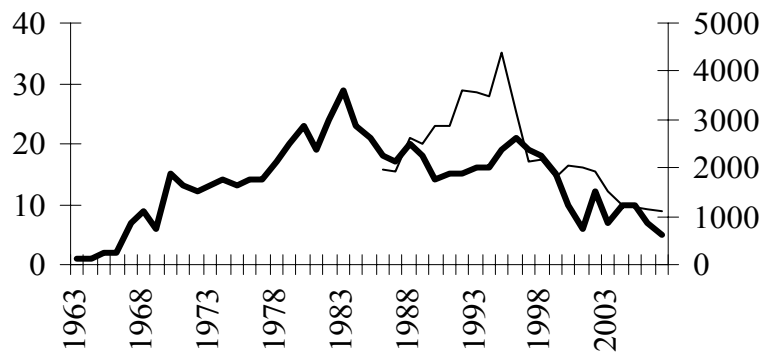
Figure 4 (Continued): Displacement of CO2, HeNe, ion, dye, and other gas laser types



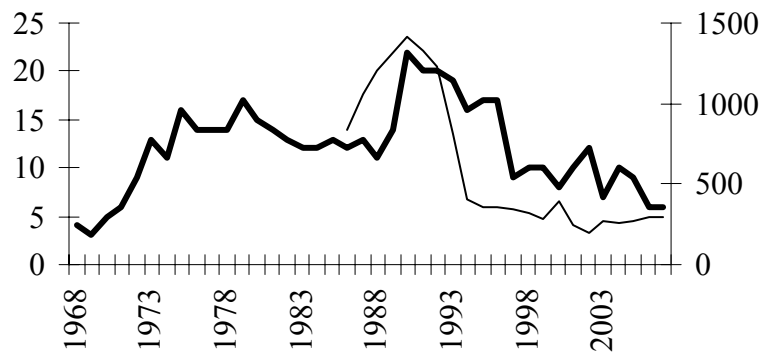
— Number of HeNe Firms (Left Y-axis)  
 - - Annual Unit Sales (Right Y-axis)



— Number of ion laser firms (Left Y-axis)  
 - - Annual Unit Sales (Right Y-axis)

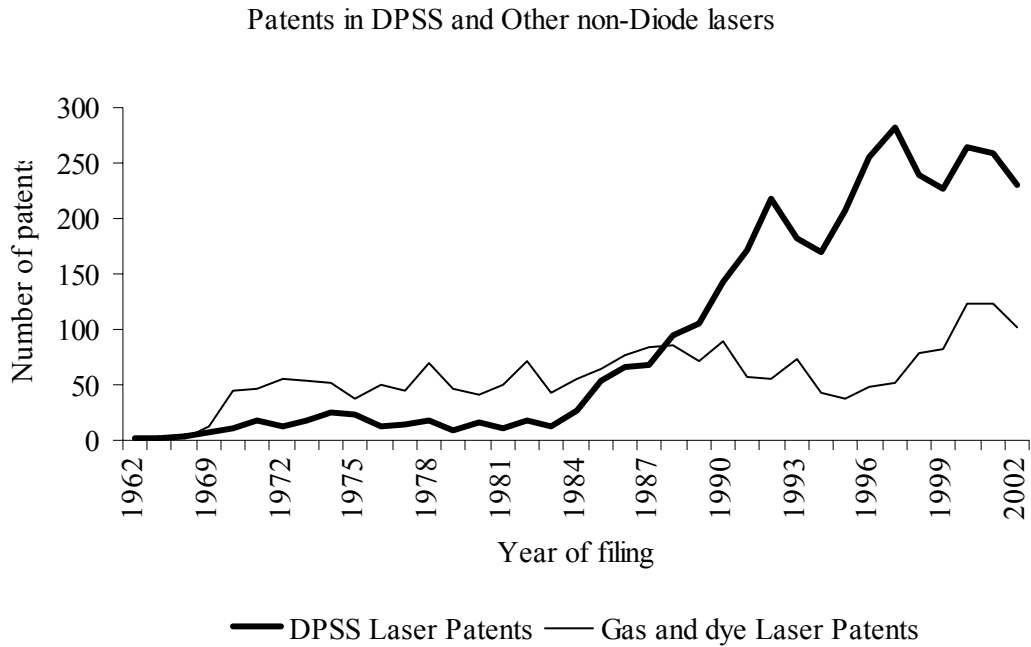


— Number of other gas laser firms (Left Y-axis)  
 - - Annual Unit Sales (Right Y-axis)



— Number of dye laser firms (Left Y-axis)  
 - - Annual Unit Sales (Right Y-axis)

Figure 5: Escalation of Patenting in DPSS lasers relative to other non-diode lasers



Note: Shown in Figure 5 are the number of DPSS related laser patents (subclasses 6, 21, 22, 41, 75, and 96 of 372 patent class); and gas and dye lasers (subclasses 51 to 65).

Figure 6: Annual exits as a percentage of number of firms in the previous year

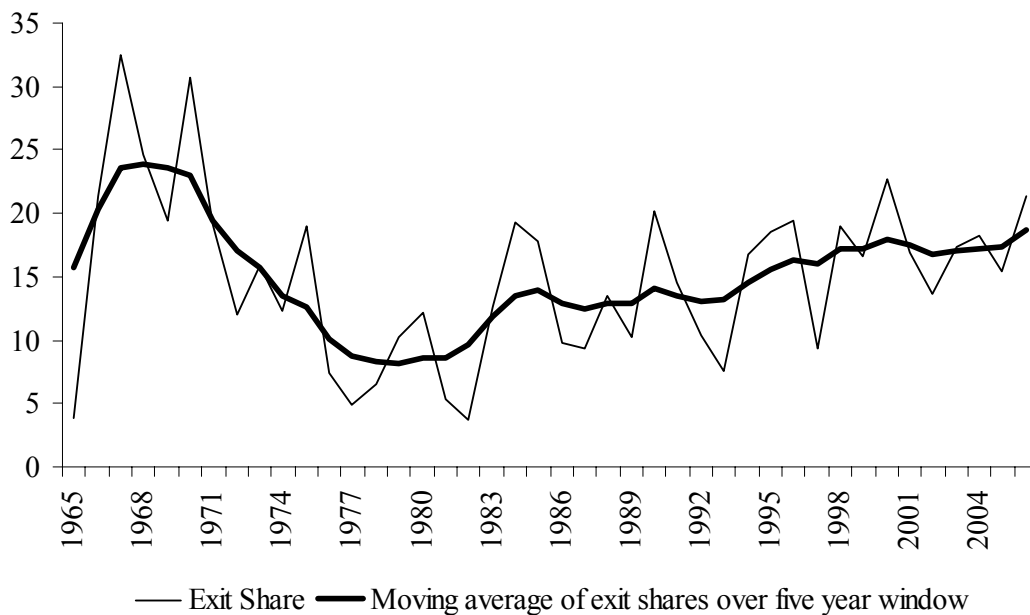


Figure 7: Survival of U.S. laser firms

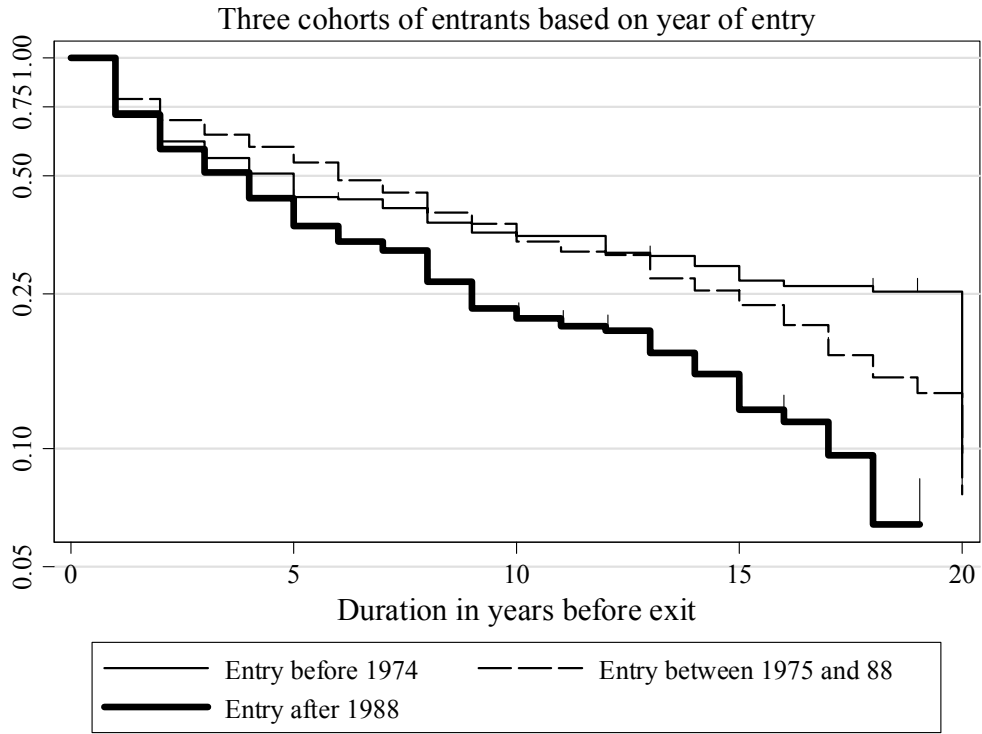


Figure 8: Survival of solid-state laser producers since 1988, by entry time

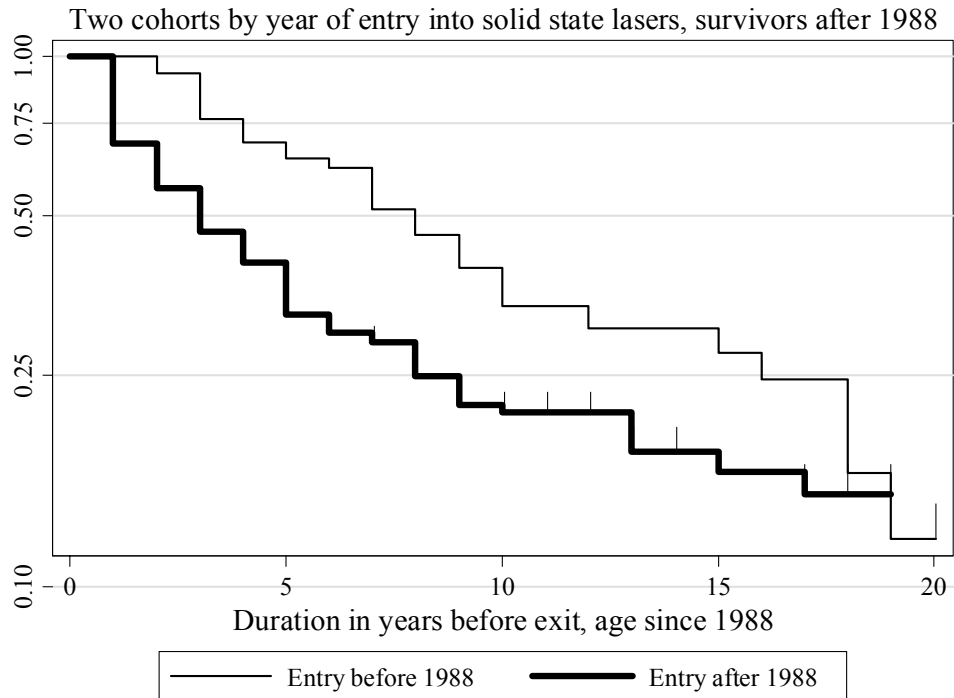


Figure 9: Survival of CO<sub>2</sub>, HeNe, ion, dye, and other gas laser producers since 1988, by entry time

