The economics of predation: What drives pricing when there is learning-by-doing?*

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Abstract

Predatory pricing—a deliberate strategy of pricing aggressively in order to eliminate competitors—is one of the more contentious areas of antitrust policy and its existence and efficacy are widely debated. The purpose of this paper is to formally characterize predatory pricing in a modern industry-dynamics framework that endogenizes competitive advantage and industry structure. Our framework encompasses important phenomena such as learning-by-doing, network effects, switching costs, dynamic demand, and certain types of adjustment costs. Due to its prominent role in legal cases involving alleged predation, we examine learning-by-doing in more detail.

We first show that predation-like behavior arises routinely in our learning-by-doing model. Equilibria involving predation-like behavior typically coexist with equilibria involving much less aggressive pricing. To disentangle predatory pricing from mere competition for efficiency on a learning curve we next decompose the equilibrium pricing condition and develop alternative characterizations of a firm's predatory pricing incentives. We finally measure the impact of these incentives on industry structure, conduct, and performance. We show that forcing a firm to ignore the predatory incentives in setting its price can have a large impact and that this impact stems from eliminating equilibria with predation-like behavior. Along with the predation-like behavior, however, a fair amount of competition for the market is eliminated.

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1 Introduction

Predatory pricing—a deliberate strategy of pricing aggressively in order to eliminate competitors—is one of the more contentious areas of antitrust policy. Scholars such as Edlin (2010) argue that predatory pricing can, under certain circumstances, be a profitable business strategy. Others—commonly associated with the Chicago School—suggest that predatory pricing is rarely rational and thus unlikely to be practiced or, as Baker (1994) puts it, somewhere between a white tiger and a unicorn—a rarity and a myth.

At the core of predatory pricing is a trade-off between lower profit in the short run due to aggressive pricing and higher profit in the long run due to reduced competition. But as the debate over the efficacy—and even the existence—of predatory pricing suggests, it is not necessarily straightforward to translate this intuitive understanding into a more precise characterization of what predatory pricing actually is.[1]

Characterizing predatory pricing is especially complicated when firms face other intertemporal trade-offs such as learning-by-doing, network effects, or switching costs that can give rise to aggressive pricing with subsequent recoupment.[2] The empirical literature provides ample evidence that the marginal cost of production decreases with cumulative experience in a variety of industrial settings,[3] and the resulting tension between predatory pricing and mere competition for efficiency on a learning curve often comes to the fore when predation is alleged. It was, for example, a key issue in the policy debate about the "semiconductor wars" between the U.S. and Japan during the 1970s and 1980s (Flamm 1993, Flamm 1996, Dick 1991). Similarly, the predatory pricing that U.S. color television producers accused Japanese producers of during the 1960s and 1970s may have reflected a strategy of acquiring competitive advantage by exploiting learning economies (Developing World Industry and Technology, Inc. 1978, Yamamura & Vandenberg 1986). The European Commission case against Intel in 2009 over the use of loyalty reward payments to computer manufacturers (that lead to a record-breaking fine of $1.5 billion) likewise revolved around whether Intel's behavior was exclusionary or efficiency enhancing (Willig, Orszag & Levin 2009).[4] More generally, contractual arrangements such as nonlinear pricing

[1]Edlin (2002) provides a comprehensive overview of the current law on predatory pricing. Bolton, Brodley & Riordan (2000) and Edlin (2010) provide excellent reviews of the theoretical and empirical literature.

[2]This point has been made previously by Farrell & Katz (2005): "Distinguishing competition from predation is even harder in network markets than in others. With intertemporal increasing returns, there may innocently be intense initial competition as firms fight to make initial sales and benefit from the increasing returns." (p. 204).

[3]See the references in footnote 2 of Besanko, Doraszelski, Kryukov & Satterthwaite (2010).

[4]For example, Intel CEO Paul Otellini argued "[w]e have ... consistently invested in innovation, in manufacturing and in developing leadership technology. The result is that we can discount our products to compete in a highly competitive marketplace, passing along to consumers everywhere the efficiencies of being the world's leading volume manufacturer of microprocessors." http://www.zdnet.com/blog/btl/ec-intel-abused-dominant-position-vs-amd-fined-record-145-billion-in-antitrust-case/17884 (accessed on June 7, 2011).

and exclusive dealing that can be exclusionary are often also efficiency enhancing (Jacobson & Sher 2006, Melamed 2006).

While predatory pricing is difficult to disentangle from pricing aggressively to pursue efficiency, being able to do so is important in legal cases involving alleged predation. Moreover, if one entertains the possibility that predatory pricing is a viable business strategy, then a characterization of predatory pricing is required to allow economists, legal scholars, and antitrust practitioners to detect its presence and measure its extent.

The purpose of this paper is to formally characterize predatory pricing in a modern industry-dynamics framework along the lines of Ericson & Pakes (1995). To this end, we develop a dynamic pricing model with endogenous competitive advantage and industry structure. The model is general enough to embrace a number of specific applications besides learning-by-doing, including network effects, switching costs, dynamic demand, and certain types of adjustment costs. We ask three interrelated questions. First, what drives pricing and, in particular, how can we separate predatory incentives for pricing aggressively from efficiency-enhancing incentives in a dynamic pricing model with endogenous competitive advantage and industry structure? Second, when does predation-like behavior arise? Third, what is the impact of the predatory incentives on industry structure, conduct, and performance? We discuss these questions—and our answers to them—in turn.

What drives pricing? Unlike much of the previous literature, we do not attempt to deliver an ironclad definition of predation. Instead, our contribution is to show that we can isolate a firm's predatory incentives by analytically decomposing the equilibrium pricing condition. Our decomposition is reminiscent of that of Ordover & Saloner (1989), but it extends to the complex strategic interactions that arise in the Markov perfect equilibrium of a dynamic stochastic game. The cornerstone of our decomposition is the insight that the price set by a firm reflects two goals besides short-run profit. First, by pricing aggressively, the firm may move further down its learning curve and improve its competitive position in the future, giving rise to what we call the *advantage-building motive*. Second, the firm may prevent its rival from moving further down its learning curve and becoming a more formidable competitor, giving rise to the *advantage-denying motive*.

Due to its prominent role in predation cases, we examine learning-by-doing in more detail in a model similar to those in Cabral & Riordan (1994) and Besanko et al. (2010). Decomposing the equilibrium pricing condition with even more granularity reveals that the probability that the rival exits the industry—the linchpin of any notion of predatory pricing—affects both the advantage-building and advantage-denying motives. One component of the advantage-building motive is, for example, the *advantage-building/exit motive*. This is the marginal benefit to the firm from the increase in the probability of rival exit that results if the firm moves further down its learning curve. Similarly, the *advantage-denying/exit motive* is the marginal benefit from preventing the decrease in the probability of rival exit that results if the rival moves further down its learning curve. Other terms in the decomposed equilibrium pricing condition capture the impact of the firm's pricing decision on its competitive position, its rival's competitive position, and so on. In this way our decomposition corresponds to the common practice of antitrust authorities to question the intent behind a business strategy. Most importantly, our decomposition provides us with a coherent and flexible way to develop alternative characterizations of a firm's predatory pricing incentives, some of which are motivated by the existing literature while others are novel.

To detect the presence of predatory pricing antitrust, authorities routinely ask whether a firm sacrifices current profit in exchange for the expectation of higher future profit following the exit of its rival. One way to test for sacrifice is to determine whether the derivative of a profit function that "incorporate[s] everything except effects on competition" is positive at the price the firm has chosen (Edlin & Farrell 2004, p. 510). Our alternative characterizations correspond to different operationalizations of this everything-except-effects-on-competition profit function and identify clusters of terms in our decomposition as the firm's predatory pricing incentives.

When does predation-like behavior arise? While there is a sizeable literature that attempts to rationalize predatory pricing as an equilibrium phenomenon by means of reputation effects (Kreps, Milgrom, Roberts & Wilson 1982), informational asymmetries (Fudenberg & Tirole 1986), or financial constraints (Bolton & Sharfstein 1990), our learning-by-doing model forgoes these features and "stacks the deck" against predatory pricing. Our numerical analysis nevertheless reveals the widespread existence of equilibria involving behavior that resembles conventional notions of predatory pricing in the sense that aggressive pricing in the short run is associated with reduced competition in the long run. The fact that predation-like behavior arises routinely and without requiring extreme or unusual parameterizations calls into question the idea that economic theory provides *prima facie* evidence that predatory pricing is a rare phenomenon.

Our paper relates to earlier work by Cabral & Riordan (1994), who establish analytically the possibility that predation-like behavior can arise in a model of learning-by-doing, and Snider (2008), who uses the Ericson & Pakes (1995) framework to explore whether American Airlines engaged in predatory capacity expansion in the Dallas-Fort Worth to Wichita market in the late 1990s. We go beyond establishing possibility by way of an example or a case study by showing just how common predation-like behavior is.

We moreover reinforce and formalize a point made by Edlin (2010) that predatory pricing is common "if business folk think so" (p. 9). Equilibria involving predation-like behavior typically coexist in our model with equilibria involving much less aggressive pricing. Multiple equilibria arise in our model if, for given demand and cost fundamentals, there is more than one set of firms' expectations regarding the value of continued play that is consistent with rational expectations about equilibrium behavior and industry dynamics.[5] Which of these equilibria is realized depends on firms' expectations. Loosely speaking, if firms anticipate that predatory pricing may work, they have an incentive to choose the extremely aggressive prices that, in turn, ensure that predatory pricing does work.

In providing a formal connection between predatory pricing and multiple equilibria, our paper relates to independent work by Shalem, Spiegel & Stahl (2011). Their model admits an equilibrium in which a strong firm prices aggressively to drive a weak firm out of the market and another equilibrium in which the strong firm accommodates its current competitor as well as all subsequent entrants. In contrast to our model, competitive advantage is exogenous in their model and aggressive pricing is predatory by default (as it cannot improve a firm's competitive position).

What is the impact of predatory incentives? While much of the previous literature has argued for—or against—the merits of particular definitions of predation on conceptual grounds, we instead directly measure the impact of a firm's predatory pricing incentives on industry structure, conduct, and performance. Our alternative characterizations provide us with a menu of conduct restrictions of different severity. A conduct restriction can in principle be imposed by forcing the firm to ignore the predatory incentives in setting its price. We compute equilibria of the counterfactual game with the conduct restriction in place and compare them to equilibria of the actual game across a wide range of parameterizations.

We show that less severe conduct restrictions, such as forcing a firm to ignore the advantage-denying/exit motive, have on average a smaller impact on industry structure, conduct, and performance than more severe conduct restrictions, such as forcing a firm to ignore the advantage-building and advantage-denying motives in their entirety. The more severe conduct restrictions have a larger impact because they eliminate equilibria with predation-like behavior, paving the way for lower concentration, lower prices, and higher consumer and total surplus in the long run. In contrast, even the more severe conduct restrictions cause little change in equilibria involving less aggressive pricing.

Our analysis further reveals a tension between reducing predation-like behavior and reducing the intense competition for the market that gives rise to high levels of consumer surplus in the short run. Indeed, the price of making future consumers better off is often to

[5]Multiple equilibria can potentially also arise in our model if the best replies of the one-shot game that is being played given continuation values intersect more than once. This cannot happen in the model in Besanko et al. (2010).

make current consumers worse off.

Finally, our analysis shows that there may be sensible ways of disentangling efficiency-enhancing motives from predatory motives in pricing. From the menu of conduct restrictions, those that emphasize advantage denying as the basis for predation come closest to being unambiguously beneficial for consumers and society at large in both the short run and the long run. In contrast to aggressive pricing behavior that is primarily driven by the benefits from acquiring competitive advantage, aggressive pricing behavior that is primarily driven by the benefits from preventing the rival from acquiring competitive advantage or overcoming competitive disadvantage is predatory. While there is some latitude in where exactly to draw the line between mere competition for efficiency on a learning curve and predatory pricing, our analysis highlights that this distinction is closely related to that between advantage-building and advantage-denying motives. These motives, in turn, can be isolated and measured using our decomposition.

2 Model

Because predatory pricing is an inherently dynamic phenomenon, we consider a discrete-time, infinite-horizon dynamic stochastic game between two firms. We first lay out a fairly general dynamic pricing model with endogenous competitive advantage and industry structure that gives rise to an advantage-building motive and an advantage-denying motive. To gain further insight into how these motives operate we then tailor the model to an industry with learning-by-doing.

2.1 Setup

At any point in time, firm $n \in \{1, 2\}$ is described by its state $e_n \in \{0, 1, \ldots, M\}$. A firm in state $e_n = 0$ is a potential entrant, and a firm in state $e_n \in \{1, \ldots, M\}$ is an incumbent firm that competes in the product market and jostles for competitive advantage. State $e_n \in \{1, \ldots, M\}$ indicates the competitive position of incumbent firm n. A state $e_n \in \{1, \ldots, M\}$ indicates the level of a valuable firm-specific resource such as a cost or demand advantage. In an industry with learning-by-doing, for example, state $e_n \in \{1, \ldots, M\}$ indicates the cumulative experience or stock of know-how of incumbent firm n which, in turn, determines its production cost. With network effects or switching costs, it indicates the installed base or the number of captive customers. We return to other possible applications below.

The industry's state is the vector of firms' states $\mathbf{e} = (e_1, e_2) \in \{0, 1, \ldots, M\}^2$. In each period, firms first set prices and then decide on exit and entry. During the price-setting phase the industry's state changes from $\mathbf{e}$ to $\mathbf{e}'$ depending on the pricing decisions of the incumbent firms. During the exit-entry phase, the state further changes from $\mathbf{e}'$ to $\mathbf{e}''$ depending on the exit decisions of the incumbent firms and the entry decisions of the potential entrants. The state at the end of the current period finally becomes the state at the beginning of the subsequent period.

Before analyzing firms' decisions, we describe the remaining primitives of our dynamic stochastic game.

Product market and competitive advantage. As incumbent firm n competes in the product market, its profit in the current period is $\pi_n(\mathbf{p}, \mathbf{e})$ given the vector of firms' prices $\mathbf{p} = (p_1, p_2)$ and the industry's state $\mathbf{e}$.[6]

Besides competing in the product market, incumbent firm n jostles for competitive advantage by adjusting its price in the current period to influence the industry's state in the subsequent period. Competitive advantage is therefore determined endogenously. Specifically, we model the probability that the industry's state changes from $\mathbf{e}$ to $\mathbf{e}'$ during the price-setting phase as $\Pr(\mathbf{e}'|\mathbf{e}, \mathbf{q})$ given the vector $\mathbf{q} = (q_1, q_2)$ and the industry's state $\mathbf{e}$, where $q_n = D_n(\mathbf{p}, \mathbf{e})$ is itself a function of prices $\mathbf{p}$ and the industry's state $\mathbf{e}$. As the notation suggests, we think of $\mathbf{q}$ as (realized or expected) quantities or market shares and of $D_n(\cdot)$ as the demand function of incumbent firm n. More generally, however, $\mathbf{q}$ can be anything resulting from the pricing decisions of the incumbent firms such as the probability of making a sale or the profit from competing in the product market.

Exit and entry. We model entry as a transition from state $e'_n = 0$ to state $e''_n = 1$ and exit as a transition from state $e'_n \geq 1$ to state $e''_n = 0$ so that the exit of an incumbent firm creates an opportunity for a new firm to enter the industry. Re-entry is therefore possible.

If incumbent firm n exits the industry, it receives a scrap value X_n drawn from a symmetric triangular distribution $F_X(\cdot)$ with support $[\overline{X} - \Delta_X, \overline{X} + \Delta_X]$, where $E_X(X_n) = \overline{X}$ and $\Delta_X > 0$ is a scale parameter. If potential entrant n enters the industry, it incurs a setup cost S_n drawn from a symmetric triangular distribution $F_S(\cdot)$ with support $[\overline{S} - \Delta_S, \overline{S} + \Delta_S]$, where $E_S(S_n) = \overline{S}$ and $\Delta_S > 0$ is a scale parameter. Scrap values and setup costs are independently and identically distributed across firms and periods, and their realization is observed by the firm but not its rival.

2.2 Firms' decisions

To analyze the pricing decision $p_n(\mathbf{e})$ of incumbent firm n, the exit decision $\phi_n(\mathbf{e}', X_n) \in \{0, 1\}$ of incumbent firm n with scrap value X_n, and the entry decision $\phi_n(\mathbf{e}', S_n) \in \{0, 1\}$ of potential entrant n with setup cost S_n, we work backwards from the exit-entry phase to the price-setting phase. Because scrap values and setup costs are private to a firm, its

[6] To conserve on notation, we take the price of a potential entrant to be infinity.

rival remains uncertain about the firm's decision. Combining exit and entry decisions, we let $\phi_n(\mathbf{e}')$ denote the probability, as viewed from the perspective of its rival, that firm n decides *not* to operate in state $\mathbf{e}'$: If $e_n \neq 0$ so that firm n is an incumbent, then $\phi_n(\mathbf{e}') = E_X\left[\phi_n(\mathbf{e}', X_n)\right]$ is the probability of exiting; if $e'_n = 0$ so that firm n is an entrant, then $\phi_n(\mathbf{e}') = E_S\left[\phi_n(\mathbf{e}', S_n)\right]$ is the probability of not entering.

We use $V_n(\mathbf{e})$ to denote the expected net present value (NPV) of future cash flows to firm n in state $\mathbf{e}$ at the beginning of the period and $U_n(\mathbf{e}')$ to denote the expected NPV of future cash flows to firm n in state $\mathbf{e}'$ *after* pricing decisions but *before* exit and entry decisions are made. The price-setting phase determines the value function $V_n(\mathbf{e})$ along with the policy function $p_n(\mathbf{e})$; the exit-entry phase determines the value function $U_n(\mathbf{e}')$ along with the policy function $\phi_n(\mathbf{e}')$.

Exit decision of incumbent firm. To simplify the exposition, we focus on firm 1; the derivations for firm 2 are analogous. If incumbent firm 1 exits the industry, it receives the scrap value X_1 in the current period and perishes. If it does not exit and remains a going concern in the subsequent period, its expected NPV is

$$\widehat{X}_1(\mathbf{e}') = \beta\left[V_1(\mathbf{e}')(1-\phi_2(\mathbf{e}')) + V_1(e'_1, 0)\phi_2(\mathbf{e}')\right],$$

where $\beta \in [0, 1)$ is the discount factor. Incumbent firm 1's decision to exit the industry in state $\mathbf{e}'$ is thus $\phi_1(\mathbf{e}', X_1) = 1\left[X_1 \geq \widehat{X}_1(\mathbf{e}')\right]$, where $1[\cdot]$ is the indicator function and $\widehat{X}_1(\mathbf{e}')$ the critical level of the scrap value above which exit occurs. The probability of incumbent firm 1 exiting is $\phi_1(\mathbf{e}') = 1 - F_X(\widehat{X}_1(\mathbf{e}'))$. It follows that *before* incumbent firm 1 observes a particular draw of the scrap value, its expected NPV is given by the Bellman equation

$$\begin{aligned} U_1(\mathbf{e}') &= E_X\left[\max\left\{\widehat{X}_1(\mathbf{e}'), X_1\right\}\right] \\ &= (1-\phi_1(\mathbf{e}'))\beta\left[V_1(\mathbf{e}')(1-\phi_2(\mathbf{e}')) + V_1(e'_1, 0)\phi_2(\mathbf{e}')\right] + \phi_1(\mathbf{e}')E_X\left[X_1 | X_1 \geq \widehat{X}_1(\mathbf{e}')\right], \end{aligned} \quad (1)$$

where $E_X\left[X_1 | X_1 \geq \widehat{X}_1(\mathbf{e}')\right]$ is the expectation of the scrap value conditional on exiting the industry.

Entry decision of potential entrant. If potential entrant 1 does not enter the industry, it perishes. If it enters and becomes an incumbent firm (in the initial state 1) in the subsequent period, its expected NPV is

$$\widehat{S}_1(\mathbf{e}') = \beta\left[V_1(1, e'_2)(1-\phi_2(\mathbf{e}')) + V_1(1, 0)\phi_2(\mathbf{e}')\right].$$

In addition, it incurs the setup cost S_1 in the current period. Potential entrant 1's decision to not enter the industry in state $\mathbf{e}'$ is thus $\phi_1(\mathbf{e}', S_1) = 1\left[S_1 \geq \widehat{S}_1(\mathbf{e}')\right]$, where $\widehat{S}_1(\mathbf{e}')$ is the critical level of the setup cost. The probability of potential entrant 1 not entering is $\phi_1(\mathbf{e}') = 1 - F_S(\widehat{S}_1(\mathbf{e}'))$ and *before* potential entrant 1 observes a particular draw of the setup cost, its expected NPV is given by the Bellman equation

$$\begin{aligned} U_1(\mathbf{e}') &= E_S\left[\max\left\{\widehat{S}_1(\mathbf{e}') - S_1, 0\right\}\right] \\ &= (1-\phi_1(\mathbf{e}'))\left\{\beta[V_1(1,e_2')(1-\phi_2(\mathbf{e}')) + V_1(1,0)\phi_2(\mathbf{e}')] - E_S\left[S_1 | S_1 \leq \widehat{S}_1(\mathbf{e}')\right]\right\}, \end{aligned} \tag{2}$$

where $E_S\left[S_1 | S_1 \leq \widehat{S}_1(\mathbf{e}')\right]$ is the expectation of the setup cost conditional on entering the industry.[7]

Pricing decision of incumbent firm. In the price-setting phase, the expected NPV of incumbent firm 1 is

$$V_1(\mathbf{e}) = \max_{p_1} \pi_1(p_1, p_2(\mathbf{e}), \mathbf{e}) + \sum_{\mathbf{e}'} U_1(\mathbf{e}') \Pr\left(\mathbf{e}' | \mathbf{e}, D_1(p_1, p_2(\mathbf{e}), \mathbf{e}), D_2(p_1, p_2(\mathbf{e}), \mathbf{e})\right). \tag{3}$$

Because $\sum_{\mathbf{e}'} \Pr(\mathbf{e}' | \mathbf{e}, \mathbf{q}) = 1$, we can equivalently formulate the maximization problem on the right-hand side of the Bellman equation (3) as $\max_{p_1} \Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})$, where

$$\begin{aligned} \Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e}) &= \pi_1(p_1, p_2(\mathbf{e}), \mathbf{e}) + U_1(\mathbf{e}) \\ &+ \sum_{\mathbf{e}' \neq \mathbf{e}} \left[U_1(\mathbf{e}') - U_1(\mathbf{e})\right] \Pr\left(\mathbf{e}' | \mathbf{e}, D_1(p_1, p_2(\mathbf{e}), \mathbf{e}), D_2(p_1, p_2(\mathbf{e}), \mathbf{e})\right) \end{aligned} \tag{4}$$

is the long-run profit of incumbent firm 1. The first-order condition for the pricing decision $p_1(\mathbf{e})$ of incumbent firm 1 is

$$\begin{aligned} 0 &= \frac{\partial \pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})}{\partial p_1} \\ &+ \sum_{\mathbf{e}' \neq \mathbf{e}} \left[U_1(\mathbf{e}') - U_1(\mathbf{e})\right] \frac{\partial \Pr\left(\mathbf{e}' | \mathbf{e}, D_1(p_1, p_2(\mathbf{e}), \mathbf{e}), D_2(p_1, p_2(\mathbf{e}), \mathbf{e})\right)}{\partial q_1} \frac{\partial D_1(p_1, p_2(\mathbf{e}), \mathbf{e})}{\partial p_1} \\ &+ \sum_{\mathbf{e}' \neq \mathbf{e}} \left[U_1(\mathbf{e}) - U_1(\mathbf{e}')\right] \frac{\partial \Pr\left(\mathbf{e}' | \mathbf{e}, D_1(p_1, p_2(\mathbf{e}), \mathbf{e}), D_2(p_1, p_2(\mathbf{e}), \mathbf{e})\right)}{\partial q_2} \frac{\partial\left(-D_2\right)(p_1, p_2(\mathbf{e}), \mathbf{e})}{\partial p_1}, \end{aligned} \tag{5}$$

[7]See the Online Appendix for closed-form expressions for $E_X\left[X_1 | X_1 \geq \widehat{X}_1(\mathbf{e}')\right]$ in equation (1) and $E_S\left[S_1 | S_1 \leq \widehat{S}_1(\mathbf{e}')\right]$ in equation (2).

where in the last line we take the derivative of $(-D_2)(p_1, p_2(\mathbf{e}))$ instead of $D_2(p_1, \mathbf{e}))$ with respect to p_1 to make the sign comparable to that of the derivative of $D_1(p_1, p_2(\mathbf{e}))$.

The pricing decision $p_1(\mathbf{e})$ of incumbent firm 1 is akin to an investment decision in that it encompasses its short-run profit $\pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})$ and its long-run competitive position *vis-à-vis* that of its rival. Competitive advantage changes as the industry's state changes. Equation (5) shows that the firm's price p_1 affects the transitions in the industry's state from $\mathbf{e}$ to $\mathbf{e}'$ through two distinct channels: first, through the impact that p_1 has on the firm's quantity q_1 and, second, through the impact that p_1 has on its rival's quantity q_2. We call the first channel the *advantage-building motive* and the second channel the *advantage-denying motive*. Loosely speaking, the advantage-building motive captures the idea that a lower price p_1 may—by way of a higher quantity q_1—change the industry's state in a way that is more favorable to incumbent firm 1. The advantage-denying motive captures the idea that a lower price p_1 may—by way of a lower quantity q_2—prevent the industry's state from changing in a way that is less favorable to incumbent firm 1. Gaining further insight into how these motives operate requires putting additional structure on our dynamic stochastic game.

2.3 Learning-by-doing

Because learning-by-doing is important in many industries where allegations of predation have surfaced in the past, we use it to provide context for our dynamic stochastic game. Our learning-by-doing model is closely related to Cabral & Riordan (1994) and Besanko et al. (2010) but more general by allowing for exit and entry. In contrast to Besanko et al. (2010), our model abstracts from organizational forgetting.[8]

Learning-by-doing and production cost. State $e_n \in \{1, \ldots, M\}$ indicates the cumulative experience or stock of know-how of incumbent firm n. Its marginal cost of production $c(e_n)$ is given by

$$c(e_n) = \begin{cases} \kappa\rho^{\log_2 e_n} & \text{if} \quad 1 \leq e_n < m, \\ \kappa\rho^{\log_2 m} & \text{if} \quad m \leq e_n \leq M, \end{cases}$$

where $\kappa > 0$ is the marginal cost for a firm without prior experience, and $\rho \in [0, 1]$ is the progress ratio. Marginal cost decreases by $100(1 - \rho)\%$ as the stock of know-how doubles, so that a lower progress ratio implies a steeper learning curve. As a firm makes sales, it adds to

[8]Empirical studies show that organizations can forget the know-how gained through learning-by-doing due to labor turnover, periods of inactivity, and failure to institutionalize tacit knowledge (Argote, Beckman & Epple 1990, Darr, Argote & Epple 1995, Benkard 2000, Shafer, Nembhard & Uzumeri 2001, Thompson 2007). Besanko et al. (2010) show that organizational forgetting predisposes firms to price aggressively. Omitting organizational forgetting from the model therefore "stacks the deck" against finding predation-like behavior.

its stock of know-how and lowers its production cost in subsequent periods. Once the firm reaches state m, the learning curve "bottoms out" and there are no further experience-based cost reductions.[9]

Demand. The industry draws customers from a large pool of potential buyers. In each period, one buyer enters the market and purchases one unit of either one of the "inside goods" that are offered by the incumbent firms at prices $\mathbf{p}$ or an "outside good" at an exogenously given price p_0. The probability that incumbent firm n makes the sale is given by the logit specification

$$q_n = D_n(\mathbf{p}) = \frac{\exp(\frac{-p_n}{\sigma})}{\sum_{k=0}^{2} \exp(\frac{-p_k}{\sigma})}, \tag{6}$$

where $\sigma > 0$ is a scale parameter that governs the degree of product differentiation. As $\sigma \to 0$, goods become homogeneous.

Pricing decision of incumbent firm. Figure 1 illustrates the possible state-to-state transitions in our learning-by-doing model.[10] The long-run profit of incumbent firm 1 in equation (4) accordingly simplifies to

$$\begin{aligned} \Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e}) &= (p_1 - c(e_1))D_1(p_1, p_2(\mathbf{e})) + U_1(\mathbf{e}) \\ &+ D_1(p_1, p_2(\mathbf{e}))\left[U_1(e_1+1, e_2) - U_1(\mathbf{e})\right] + D_2(p_1, p_2(\mathbf{e}))\left[U_1(e_1, e_2+1) - U_1(\mathbf{e})\right]. \end{aligned} \tag{7}$$

Because $\Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})$ is strictly quasiconcave in p_1 (given $p_2(\mathbf{e})$ and $\mathbf{e}$), the pricing decision $p_1(\mathbf{e})$ is uniquely determined by a first-order condition analogous to equation (5)

$$mr_1(p_1, p_2(\mathbf{e})) - c(e_1) + [U_1(e_1+1, e_2) - U_1(\mathbf{e})] + \Upsilon(p_2(\mathbf{e}))\left[U_1(\mathbf{e}) - U_1(e_1, e_2+1)\right] = 0, \tag{8}$$

[9] We obviously have to ensure $e_n \leq M$. To simplify the exposition we abstract from boundary issues in what follows.

[10] Formally, our learning-by-doing model is a special case of the general model with the probability that the industry's state changes from $\mathbf{e}$ to $\mathbf{e}'$ during the price-setting phase set to

$$\Pr\left(\mathbf{e}'|\mathbf{e}, \mathbf{q}\right) = \begin{cases} q_1 & \text{if} \quad \mathbf{e}' = (e_1+1, e_2), \\ q_2 & \text{if} \quad \mathbf{e}' = (e_1, e_2+1), \\ 1 - q_1 - q_2 & \text{if} \quad \mathbf{e}' = \mathbf{e}, \end{cases}$$

where q_n is the probability that incumbent firm n makes the sale as given in equation (6).

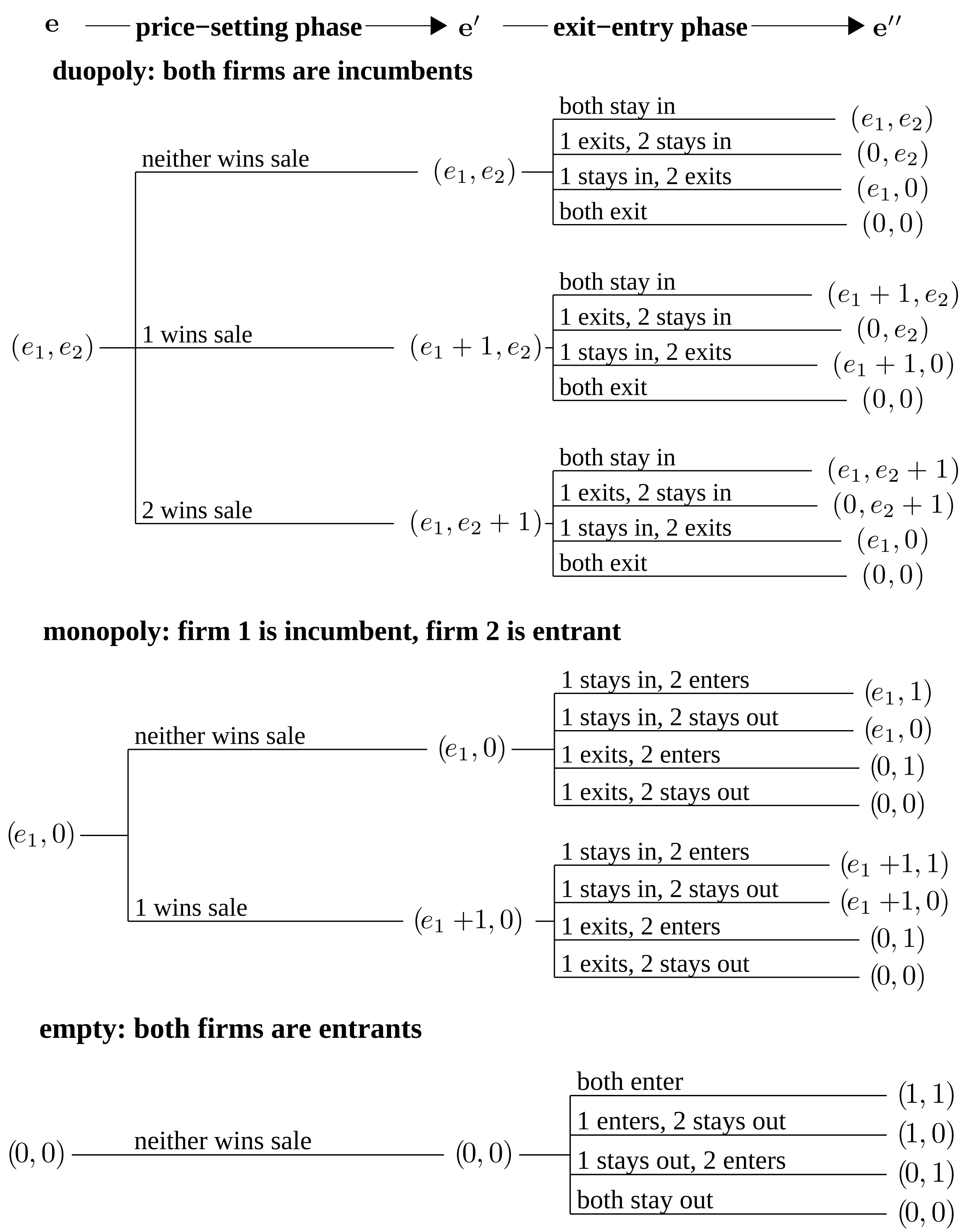

Figure 1: Possible state-to-state transitions.

where $mr_1(p_1, p_2(\mathbf{e})) = p_1 - \frac{\sigma}{1-D_1(p_1,p_2(\mathbf{e}))}$ is the marginal revenue of incumbent firm 1, or what Edlin (2010) calls *inclusive price*,[11] and

$$\Upsilon(p_2(\mathbf{e})) = \frac{\frac{\partial(-D_2)(p_1,p_2(\mathbf{e}))}{\partial p_1}}{\frac{\partial D_1(p_1,p_2(\mathbf{e}))}{\partial p_1}} = \frac{D_2(p_1, p_2(\mathbf{e}))}{1 - D_1(p_1, p_2(\mathbf{e}))} = \frac{\exp\left(-\frac{p_2(\mathbf{e})}{\sigma}\right)}{\exp\left(-\frac{p_0}{\sigma}\right) + \exp\left(-\frac{p_2(\mathbf{e})}{\sigma}\right)}$$

is the probability of firm 2 making a sale conditional on firm 1 not making a sale. Note that we have rescaled equation (5) by

$$\frac{\partial \Pr(e_1 + 1, e_2 | \mathbf{e}, D_1(p_1, p_2(\mathbf{e})), D_2(p_1, p_2(\mathbf{e})))}{\partial q_1} \frac{\partial D_1(p_1, p_2(\mathbf{e}))}{\partial p_1} = -\frac{1}{\sigma} D_1(p_1, p_2(\mathbf{e}))\left(1 - D_1(p_1, p_2(\mathbf{e}))\right)$$

to ensure that the various terms in equation (8) are expressed in monetary units.

Equation (8) isolates the two distinct channels through with the firm's price p_1 affects the transitions in the industry's state from $\mathbf{e}$ to $\mathbf{e}'$ in the learning-by-doing model. First, by winning the sale in the current period, the firm moves further down its learning curve and improves its future competitive position. The reward that the firm thereby receives is the *advantage-building motive* $[U_1(e_1 + 1, e_2) - U_1(\mathbf{e})]$. Second, by winning the sale in the current period, the firm *prevents* its rival from moving down its learning curve and becoming a more formidable competitor in the future. The penalty that the firm thereby *avoids* is the *advantage-denying motive* $[U_1(\mathbf{e}) - U_1(e_1, e_2 + 1)]$.

Because $mr_1(p_1, p_2(\mathbf{e}))$ is strictly increasing in p_1, equation (8) implies that any increase in the advantage-building or advantage-denying motives makes the firm more aggressive in pricing. To the extent that an improvement in the firm's competitive position is beneficial and an improvement in the rival's competition position is harmful, i.e., $[U_1(e_1 + 1, e_2) - U_1(\mathbf{e})] > 0$ and $[U_1(\mathbf{e}) - U_1(e_1, e_2 + 1)] > 0$, the inclusive price is less than marginal cost and the firm charges a price below the static optimum.[12] If these motives are sufficiently large, price may be below marginal cost.

2.4 Key assumptions and other applications

Before further analyzing our learning-by-doing model, we briefly return to the general model. The advantage-building motive and the advantage-denying motive arise because of two key assumptions. First, whereas the literature on dynamic stochastic games (see, e.g., Filar & Vrieze 1997, Basar & Olsder 1999) specifies the transition probabilities $\Pr(\mathbf{e}'|\mathbf{e}, \mathbf{p})$ to

[11] See the Online Appendix for details.

[12] The value function $U_1(\mathbf{e})$ is endogenously determined in equilibrium. For some parameterizations, the advantage-building and advantage-denying motives fail to be positive. For example, if the industry moves into a state with aggressive price competition as the firm wins the sale, then we may have $U_1(e_1 + 1, e_2) < U_1(\mathbf{e})$ and we may have $U_1(\mathbf{e}) < U_1(e_1, e_2 + 1)$ if the industry moves out of such a state as the rival wins the sale; see Section 6.1 of Besanko et al. (2010) for details.

depend directly on players' actions (in our case, firms' prices) $\mathbf{p}$, we restrict the transition probabilities $\Pr(\mathbf{e}'|\mathbf{e},\mathbf{q})$ to depend on $\mathbf{p}$ through the demand system $q_1 = D_1(\mathbf{p},\mathbf{e})$ and $q_2 = D_2(\mathbf{p},\mathbf{e})$.

Our second assumption is that firms set prices rather than quantities. With quantity-setting, the long-run profit of incumbent firm 1 in equation (4) becomes

$$\begin{aligned}\Pi_1(q_1, q_2(\mathbf{e}), \mathbf{e}) = \pi_1(P_1(q_1, q_2(\mathbf{e}), \mathbf{e}), P_2(q_1, q_2(\mathbf{e}), \mathbf{e}), \mathbf{e}) + U_1(\mathbf{e}) \\ + \sum_{\mathbf{e}' \neq \mathbf{e}} \left[U_1(\mathbf{e}') - U_1(\mathbf{e})\right] \Pr\left(\mathbf{e}'|\mathbf{e}, q_1, q_2(\mathbf{e})\right),\end{aligned}$$

where $p_1 = P_1(\mathbf{q},\mathbf{e})$ and $p_2 = P_2(\mathbf{q},\mathbf{e})$ is the inverse demand system, and the first-order condition (5) becomes

$$\begin{aligned}0 = &\frac{\partial \pi_1(P_1(q_1, q_2(\mathbf{e}), \mathbf{e}), P_2(q_1, q_2(\mathbf{e}), \mathbf{e}), \mathbf{e})}{\partial p_1} \frac{\partial P_1(q_1, q_2(\mathbf{e}), \mathbf{e})}{\partial q_1} \\ &+ \frac{\partial \pi_1(P_1(q_1, q_2(\mathbf{e}), \mathbf{e}), P_2(q_1, q_2(\mathbf{e}), \mathbf{e}), \mathbf{e})}{\partial p_2} \frac{\partial P_2(q_1, q_2(\mathbf{e}), \mathbf{e})}{\partial q_1} \\ &+ \sum_{\mathbf{e}' \neq \mathbf{e}} \left[U_1(\mathbf{e}') - U_1(\mathbf{e})\right] \frac{\partial \Pr\left(\mathbf{e}'|\mathbf{e}, q_1, q_2(\mathbf{e})\right)}{\partial q_1}.\end{aligned}$$

The advantage-denying motive disappears because, in contrast to the firm's price, the firm's quantity has no direct effect on its rival's quantity.[13]

Within the confines of these assumptions, the general model has many applications besides learning-by-doing.The models of network effects in Mitchell & Skrzypacz (2006), Chen, Doraszelski & Harrington (2009), Dube, Hitsch & Chintagunta (2010), and Cabral (2011) and habit formation (Bergemann & Välimäki 2006) are closely related, as are the models of switching costs in Dube, Hitsch & Rossi (2009) and Chen (2011).

More generally, in models of dynamic demand the sales in the current period determine the state of demand in the subsequent period. To the extent that firms compete for sales, a firm's price thus affects its rival's competitive position, and this gives rise to an advantage-denying motive. Demand may be dynamic in markets with durable goods (Goettler & Gordon 2011, Gowrisankaran & Rysman 2012), storable goods (Erdem, Imai & Keane 2003, Hendel & Nevo 2006), and experience goods (Bergemann & Välimäki 1996, Ching 2010). A difference with our general model is that consumers are typically forward-looking in models

[13] While the early literature on learning-by-doing has used quantity-setting models with homogeneous products and deterministic demand (e.g., Spence 1981, Fudenberg & Tirole 1983, Ghemawat & Spence 1985, Ross 1986, Dasgupta & Stiglitz 1988, Cabral & Riordan 1997), the more recent literature has moved to price-setting models with differentiated products and stochastic demand (e.g., Habermeier 1992, Cabral & Riordan 1994, Besanko et al. 2010). As Cabral & Riordan (1994) note, price-setting models may be well-suited to capture the closed competitive price negotiations that are typical for many industries where learning-by-doing matters (see Flamm (1996) for DRAM chips and Newhouse (1982, 2002) for commercial airframes).

of dynamic demand.

Price-setting models with costly quantity—or capacity—adjustment are another application of our general model, as are—perhaps more surprisingly—quantity-setting models with costly price adjustments (menu costs). This is because in these latter models a firm's quantity has a direct effect on its rival's price in the current period and thus competitive position in the subsequent period (see Lapham & Ware (1994) and Jun & Vives (2004) and the references therein). On the other hand, neither price-setting models with costly price adjustment nor quantity-setting models with costly quantity adjustment give rise to an advantage-denying motive.

Finally, some investment-type models such as advertising models where goodwill accumulates according to a firm's "share of voice" or advertising is combative (see Jorgensen & Zaccour (2004) and the references therein) give rise to an advantage-denying motive. More generally, the advantage-denying motive is present whenever a firm's investment directly and immediately spills over into its rival's competitive position.

3 Equilibrium and computation

Because the demand and cost specification is symmetric, we restrict ourselves to symmetric Markov perfect equilibria in pure strategies of our learning-by-doing model.[14] Existence follows from the arguments in Doraszelski & Satterthwaite (2010). In a symmetric equilibrium, the decisions taken by firm 2 in state $\mathbf{e} = (e_1, e_2)$ are identical to the decisions taken by firm 1 in state (e_2, e_1). It therefore suffices to determine the value and policy functions of firm 1.

We use the homotopy or path-following method in Besanko et al. (2010) to compute the symmetric Markov perfect equilibria of our learning-by-doing model. Although it cannot be guaranteed to find all equilibria, the advantage of this method is its ability to explore the equilibrium correspondence and search for multiple equilibria in a systematic fashion.

To explain the homotopy method, consider a single equation $H(x, \omega) = 0$ in a unknown variable x and a known parameter ω. To the extent that there is more than one x that solves $H(x, \omega) = 0$ given ω, the mapping $H^{-1}(\omega) = \{x | H(x, \omega) = 0\}$ from parameters into variables is a correspondence. We think of $H(x, \omega) = 0$ as the equilibrium condition and of $H^{-1}(\omega) = \{x | H(x, \omega) = 0\}$ as the equilibrium correspondence. This correspondence takes the form of one or more "paths" through (x, ω)-space, and the homotopy method seeks to trace out these paths.

It does so by introducing an auxiliary variable s to define a parametric curve $(x(s), \omega(s)) \in H^{-1}(\omega) = \{x | H(x, \omega) = 0\}$. Differentiating $H(x(s), \omega(s)) = 0$ with respect to s yields

[14] The focus on symmetric equilibria does not imply that the industry inevitably evolves towards a symmetric structure. Depending on how successful a firm is in moving down its learning curve, it may have a cost and charge a price different from that of its rival.

$\frac{\partial H(x(s),\omega(s)}{\partial x} x'(s) + \frac{\partial H(x(s),\omega(s)}{\partial x} \omega'(s) = 0$. Starting from a point $(x(s), \omega(s))$ on the path, this differential equation prescribes how x and ω must change to obtain another point on the path. The homotopy method reduces the task of solving the equation $H(x, \omega) = 0$ to the task of solving this differential equation. This requires an initial condition in the form of a known point on the path. We may not be able to trace out a particular path in $H^{-1}(\omega) = \{(x, \omega)|H(x, \omega) = 0\}$, and therefore miss some solutions to $H(x, \omega) = 0$, if we do not have an initial condition for it.

Computing the equilibria of our learning-by-doing model mirrors the above example except that it involves many equilibrium conditions $\mathbf{H}(\mathbf{x}, \boldsymbol{\omega}) = 0$ (Bellman equations and optimality conditions), many variables $\mathbf{x} = (\mathbf{V}_1, \mathbf{U}_1, \mathbf{p}_1, \boldsymbol{\phi}_1)$ (values and policies), and many parameters $\boldsymbol{\omega} = (\rho, \sigma, \overline{X}, \ldots)$.[15] To explore the equilibrium correspondence $\mathbf{H}^{-1}(\boldsymbol{\omega}) = \{\mathbf{x}|\mathbf{H}(\mathbf{x}, \boldsymbol{\omega}) = 0\}$, we compute slices of it by varying a parameter of the model such as the progress ratio ρ while holding the remaining parameters fixed. We denote a slice of the equilibrium correspondence along ρ by $\mathbf{H}^{-1}(\rho)$ in what follows.

To try and identify as many equilibria as possible, we proceed in an intuitively appealing but potentially fallible way. Just as we can vary the progress ratio ρ while holding the remaining parameters fixed, we can vary the degree of product differentiation σ while holding the remaining parameters fixed. We "criss-cross" the parameter space in an orderly fashion by using the equilibria on the ρ-slices as initial conditions to generate σ-slices. A σ-slice must either intersect with all ρ-slices or lead us to an additional equilibrium that, in turn, gives us an initial condition to generate an additional ρ-slice. We continue this process until all σ- and ρ-slices "match up." We denote the resulting two-dimensional slice through the equilibrium correspondence by $\mathbf{H}^{-1}(\rho, \sigma)$.

3.1 Baseline parameterization

To compute a slice of the equilibrium correspondence along one or more parameters of interest, we hold the remaining parameters fixed at the values in Table 1. While this baseline parameterization is not intended to be representative of any particular industry, it is neither entirely unrepresentative nor extreme. The discount factor is consistent with discount rates and product life cycle lengths in high-tech industries where learning-by-doing may be particularly important (Besanko et al. 2010). The baseline value for the progress ratio lies well within the range of empirical estimates (Dutton & Thomas 1984). Setup costs are about three times scrap values and therefore largely sunk. Scrap values and setup costs are reasonably variable.

Under the baseline parameterization, an *emerging firm* in state $e_n = 1$ has a reasonable

[15] See Besanko et al. (2010) and Borkovsky, Doraszelski & Kryukov (2010, 2012) for details. Our codes are available upon request.

parameter	value
maximum stock of know-how M	30
price of outside good p_0	10
product differentiation σ	1
cost at top of learning curve κ	10
bottom of learning curve m	15
progress ratio ρ	0.75
scrap value $\overline{X}$, Δ_X	1.5, 1.5
setup cost $\overline{S}$, Δ_S	4.5, 1.5
discount factor β	0.95

Table 1: Baseline parameterization.

shot at gaining traction and a *mature firm* in state $e_n \geq m$ enjoys a modest degree of market power. Profit opportunities are reasonably good; in a *mature duopoly* in state $\mathbf{e} \geq (m, m)$ the annual rate of return on the investment of setup costs is about 22% at static Nash equilibrium prices.

4 Predation-like behavior

To illustrate the types of behavior that can emerge in our learning-by-doing model, we examine the equilibria that arise for the baseline parameterization in Table 1. For two of these three equilibria Figure 2 shows the pricing decision of firm 1, the non-operating probability of firm 2, and the time path of the probability distribution over industry structures (empty, monopoly, and duopoly).[16]

The upper panels of Figure 2 exemplify what we call an *aggressive equilibrium*. The pricing decision in the upper left panel exhibits a deep well in state $(1, 1)$ with $p_1(1, 1) = -34.78$. A *well* is a preemption battle where firms vie to be the first to move down from the top of their learning curves. The pricing decision further exhibits a deep trench along the e_1-axis with $p_1(e_1, 1)$ ranging from 0.08 to 1.24 for $e_1 \in \{2, \ldots, 30\}$.[17] A *trench* is a price war that the leader (firm 1) wages against the follower (firm 2). One can think of a trench as an endogenously arising mobility barrier in the sense of Caves & Porter (1977). In the trench the follower exits the industry with a positive probability of $\phi_2(e_1, 1) = 0.22$ for $e_1 \in \{2, \ldots, 30\}$ as the upper middle panel shows. The follower remains in this exit zone as long as it does not win the sale. Once the follower exits, the leader raises its price and the industry becomes an entrenched monopoly.[18] This sequence of events resembles conventional

[16] The third equilibrium is essentially intermediate between the two shown in Figure 2.

[17] Because prices are strategic complements, there is also a shallow trench along the e_2-axis with $p_1(1, e_2)$ ranging from 3.63 to 4.90 for $e_2 \in \{2, \ldots, 30\}$.

[18] While our model allows for re-entry, whether it actually occurs depends on how a potential entrant

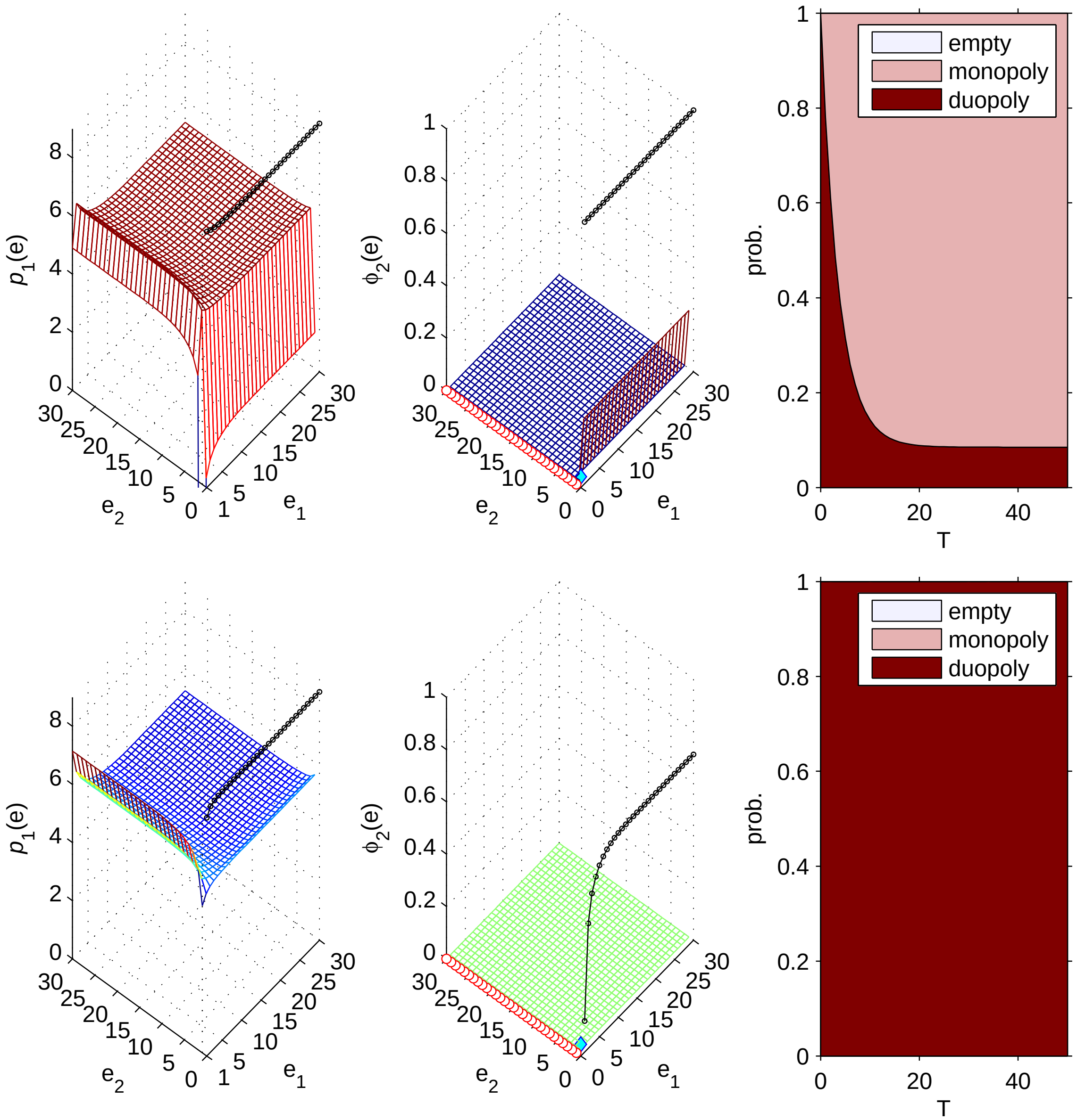

Figure 2: Pricing decision of firm 1 (left panels), non-operating probability of firm 2 (middle panels), and time path of probability distribution over industry structures, starting from $\mathbf{e} = (1, 1)$ at $T = 0$ (right panels). Aggressive (upper panels) and accommodative (lower panels) equilibria.

notions of predatory pricing. The industry may also evolve into a mature duopoly if the follower manages to crash through the mobility barrier by winning the sale but, as the upper right panel of Figure 2 shows, this is far less likely than an entrenched monopoly.

The lower panels of Figure 2 are typical for an *accommodative equilibrium.* There is a shallow well in state $(1, 1)$ with $p_1(1, 1) = 5.05$ as the lower left panel shows. Without mobility barriers in the form of trenches, however, any competitive advantage is temporary and the industry evolves into a mature duopoly as the lower right panel shows.

To further illustrate how industry dynamics differ between the aggressive and accommodative equilibria, we use the policy functions $\mathbf{p}_1$ and $\boldsymbol{\phi}_1$ for a particular equilibrium to construct the matrix of state-to-state transition probabilities that characterizes the Markov process of industry dynamics. From this, we compute the transient distribution over states in period T, $\boldsymbol{\mu}^T$, starting from state $(1, 1)$ in period 0. This tells us how likely each possible industry structure is in period T given that the game began as an emerging duopoly. Depending on T, the transient distributions can capture short-run or long-run (steady-state) dynamics. We think of period 1000 as the long run and, with a slight abuse of notation, denote $\boldsymbol{\mu}^{1000}$ by $\boldsymbol{\mu}^{\infty}$. We use the transient distribution in period 1000 rather than the limiting (or ergodic) distribution to capture long-run dynamics because the Markov process implied by the equilibrium under consideration may have multiple closed communicating classes.[19]

For the aggressive equilibrium, the left panel of Table 2 reports the most likely industry structure at various times T as given by the mode of the transient distribution $\boldsymbol{\mu}^T$ along with firms' pricing decisions and non-operating probabilities. After the industry has emerged from the preemption battle, in period 1 the leader (firm 1) prices aggressively in order to keep the follower (firm 2) in the exit zone. By period 4 the follower has most likely exited the industry and the leader raises its price. From thereon, the industry remains an entrenched monopoly. For the accommodative equilibrium, after the industry emerges from the preemption battle in period 1, the leader enjoys a competitive advantage over the follower. As can be seen in the right panel, this advantage is temporary: after period 5 the most likely industry structure is symmetric (or almost symmetric). The industry ultimately becomes a mature duopoly.

assesses its prospects in the industry. In this particular equilibrium, $\phi_2(e_1, 0) = 1.00$ for $e_1 \in \{2, \ldots, 30\}$, so that the potential entrant does not enter if the incumbent firm has moved down from the top of its learning curve.

[19] The multiple closed communicating classes that may arise for a particular equilibrium are conceptually different from multiple equilibria. A closed communicating class is a set of states from which there is no escape once the industry has entered it. The transient distribution in period 1000 accounts for the probability of reaching any one of these classes, starting from state $(1, 1)$ in period 0.

T	aggressive equilibrium $\mathbf{e}$	$p_1(\mathbf{e})$	$p_2(\mathbf{e})$	$\phi_1(\mathbf{e})$	$\phi_2(\mathbf{e})$	accommodative equilibrium $\mathbf{e}$	$p_1(\mathbf{e})$	$p_2(\mathbf{e})$	$\phi_1(\mathbf{e})$	$\phi_2(\mathbf{e})$
0	(1, 1)	-34.78	-34.78	0.00	0.00	(1, 1)	5.05	5.05	0.00	0.00
1	(2, 1)	0.08	3.63	0.00	0.22	(2, 1)	5.34	6.29	0.00	0.00
2	(3, 1)	0.56	4.15	0.00	0.22	(3, 1)	5.45	6.65	0.00	0.00
3	(4, 1)	0.80	4.41	0.00	0.22	(4, 1)	5.51	6.82	0.00	0.00
4	(5, 0)	8.62	–	0.00	1.00	(5, 1)	5.54	6.93	0.00	0.00
5	(6, 0)	8.60	–	0.00	1.00	(6, 1)	5.56	7.00	0.00	0.00
6	(7, 0)	8.59	–	0.00	1.00	(4, 4)	5.65	5.65	0.00	0.00
7	(8, 0)	8.58	–	0.00	1.00	(5, 4)	5.56	5.68	0.00	0.00
8	(9, 0)	8.57	–	0.00	1.00	(5, 5)	5.57	5.57	0.00	0.00
9	(9, 0)	8.57	–	0.00	1.00	(6, 5)	5.50	5.59	0.00	0.00
10	(10, 0)	8.56	–	0.00	1.00	(6, 6)	5.51	5.51	0.00	0.00
20	(18, 0)	8.54	–	0.00	1.00	(11,11)	5.29	5.29	0.00	0.00
50	(30, 0)	8.54	–	0.00	1.00	(26,26)	5.24	5.24	0.00	0.00
∞	(30, 0)	8.54	–	0.00	1.00	(30,30)	5.24	5.24	0.00	0.00

Table 2: Most likely industry structure, pricing decisions, and non-operating probabilities. Restricted to mode with $e_1 \geq e_2$. Aggressive and accommodative equilibria.

4.1 Industry structure, conduct, and performance

To succinctly describe an equilibrium we use six metrics of industry structure, conduct, and performance (SCP).

Structure. *Expected long-run Herfindahl index:*

$$HHI^{\infty} = \sum_{\mathbf{e}\geq(0,0)} \frac{\mu^{\infty}(\mathbf{e})}{1-\mu^{\infty}(0,0)} HHI(\mathbf{e}),$$

where the Herfindahl index in state $\mathbf{e}$ is

$$HHI(\mathbf{e}) = \sum_{n=1}^{2} \left[\frac{D_n(p_1(\mathbf{e}), p_2(\mathbf{e}))}{D_1(p_1(\mathbf{e}), p_2(\mathbf{e})) + D_2(p_1(\mathbf{e}), p_2(\mathbf{e}))} \right]^2.$$

The expected long-run Herfindahl index is a summary measure of industry concentration. If $HHI^{\infty} > 0.5$, then an asymmetric industry structure arises and persists.

Conduct. *Expected long-run average price:*

$$\overline{p}^{\infty} = \sum_{\mathbf{e}\geq(0,0)} \frac{\mu^{\infty}(\mathbf{e})}{1-\mu^{\infty}(0,0)} \overline{p}(\mathbf{e}),$$

where the (share-weighted) average price in state $\mathbf{e}$ is

$$\overline{p}(\mathbf{e}) = \sum_{n=1}^{2} \frac{D_n(p_1(\mathbf{e}), p_2(\mathbf{e}))}{D_1(p_1(\mathbf{e}), p_2(\mathbf{e})) + D_2(p_1(\mathbf{e}), p_2(\mathbf{e}))} p_n(\mathbf{e}).$$

Performance. *Expected long-run consumer surplus:*

$$CS^{\infty} = \sum_{\mathbf{e}} \mu^{\infty}(\mathbf{e})\, CS(\mathbf{e}),$$

where $CS(\mathbf{e})$ is consumer surplus in state $\mathbf{e}$.
Expected long-run total surplus:

$$TS^{\infty} = \sum_{\mathbf{e}} \mu^{\infty}(\mathbf{e}) \left\{ CS(\mathbf{e}) + \sum_{n=1}^{2} PS_n(\mathbf{e}) \right\},$$

where $PS_n(\mathbf{e})$ is the producer surplus of firm n in state $\mathbf{e}$.[20]
Expected discounted consumer surplus:

$$CS^{NPV} = \sum_{T=0}^{\infty} \beta^T \sum_{\mathbf{e}} \mu^T(\mathbf{e})\, CS(\mathbf{e}).$$

Expected discounted total surplus:

$$TS^{NPV} = \sum_{T=0}^{\infty} \beta^T \sum_{\mathbf{e}} \mu^T(\mathbf{e}) \left\{ CS(\mathbf{e}) + \sum_{n=1}^{2} PS_n(\mathbf{e}) \right\}.$$

By focusing on the states that arise in the long run (as given by $\boldsymbol{\mu}^{\infty}$), CS^{∞} and TS^{∞} summarize the long-run implications of equilibrium behavior for industry performance. In contrast, CS^{NPV} and TS^{NPV} summarize the short-run and the long-run implications that arise along entire time paths of states (as given by $\boldsymbol{\mu}^0$, $\boldsymbol{\mu}^1$, ...). Hence, CS^{NPV} and TS^{NPV} reflect any short-run *competition for the market* as well as any long-run *competition in the market.*

Table 3 illustrates the SCP metrics for the equilibria at the beginning of Section 4. The Herfindahl index reflects that the industry is substantially more likely to be monopolized under the aggressive equilibrium than under the accommodative equilibrium. Prices are higher, and consumer and total surplus are lower, under the aggressive equilibrium than under the accommodative equilibrium. The difference between the equilibria is smaller for CS^{NPV} than for CS^{∞} because the former metric accounts for the competition for the

[20] See the Online Appendix for expressions for $CS(\mathbf{e})$ and $PS_n(\mathbf{e})$.

	aggressive equilibrium	accommodative equilibrium
HHI^{∞}	0.96	0.50
$\overline{p}^{\infty}$	8.26	5.24
CS^{∞}	1.99	5.46
TS^{∞}	6.09	7.44
CS^{NPV}	104.17	109.07
TS^{NPV}	110.33	121.14

Table 3: Industry structure, conduct, and performance. Aggressive and accommodative equilibria.

market in the short run that manifests itself in the deep well and trench of the aggressive equilibrium. The competition for the market in the short run mitigates to some extent the lack of competition in the market in the long run.

4.2 Equilibrium correspondence

For clarity, we focus on one-dimensional slices through the equilibrium correspondence and our metric of industry structure. See the Online Appendix for additional figures and tables.

Progress ratio. The upper panel of Figure 3 illustrates the equilibrium correspondence by plotting HHI^{∞} against ρ. If $\rho = 1$ there is no learning-by-doing, while if $\rho = 0$ the learning economies become infinitely strong in the sense that the marginal cost of production jumps from κ for the first unit to 0 for any further unit. The progress ratio ρ therefore determines the possible extent of efficiency gains from pricing aggressively in order to move down the learning curve.

There are multiple equilibria for ρ from 0 to 0.80. $\mathbf{H}^{-1}(\rho)$ involves a main path (labeled MP) with one equilibrium for ρ from 0 to 1, a semi-loop (SL) with two equilibria for ρ from 0 to 0.80, and three loops (L_1, L_2, and L_3) each with two equilibria for ρ from 0.25 to 0.70, 0.35 to 0.65, and 0.36 to 0.53, respectively.

The equilibria on MP are accommodative. The industry evolves into a mature duopoly with $HHI^{\infty} = 0.5$ as in the accommodative equilibrium at the beginning of Section 4. The equilibria on the lower fold of SL similarly involve an almost symmetric industry structure. The equilibria on the upper fold of SL as well as those on L_1, L_2, and L_3 are aggressive. As in the aggressive equilibrium at the beginning of Section 4, the industry evolves into an entrenched monopoly with $HHI^{\infty} \approx 1.0$.[21]

[21] Aggressive equilibria can arise even if there is practically no learning-by-doing, e.g., if $\rho = 0.99$ and $\sigma = 0.10$ or $\rho = 0.98$ and $\sigma = 0.30$. See the Online Appendix for details.

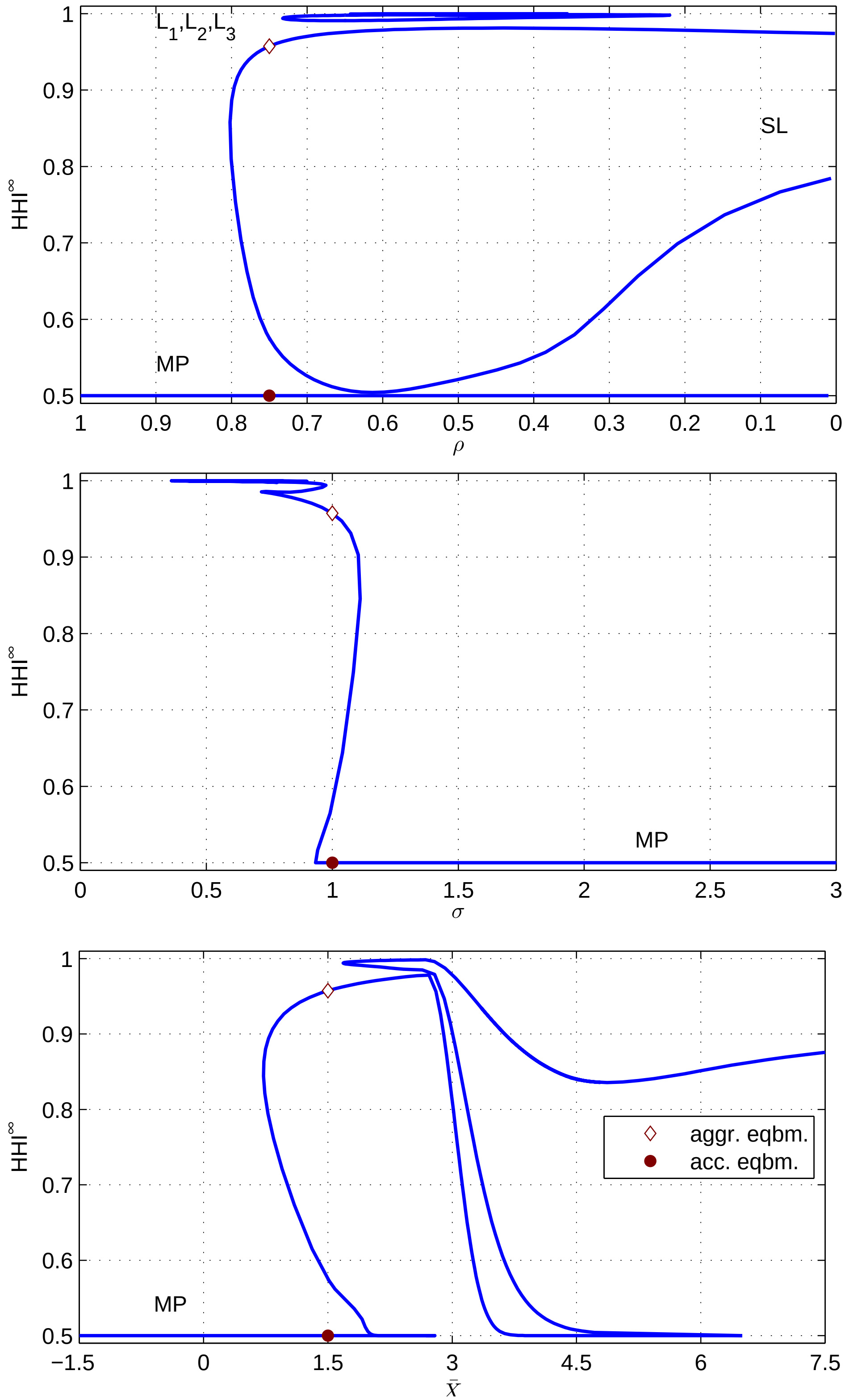

Figure 3: Expected long-run Herfindahl index. Equilibrium correspondence: slice along $\rho \in [0, 1]$ (upper panel), $\sigma \in [0, 3]$ (middle panel), and $\overline{X} \in [-1.5, 7.5]$ (lower panel).

Product differentiation. The middle panel of Figure 3 plots HHI^{∞} against σ. The degree of product differentiation σ influences how desirable it is for a firm to induce its rival to exit the industry: As $\sigma \to 0$ the goods become homogenous, competition intensifies, and profits fall. Product differentiation is already very weak for $\sigma = 0.3$ and moderately strong for $\sigma = 3$.[22]

There are multiple equilibria for σ below 1.10. While $\mathbf{H}^{-1}(\sigma)$ involves just a main path (labeled MP), multiple equilibria arise as this path bends back on itself. The equilibria on the lower fold of MP are accommodative and the industry evolves into a mature duopoly. The equilibria on the upper fold of MP are aggressive and the industry evolves into an entrenched monopoly.

Scrap value. The lower panel of Figure 3 plots HHI^{∞} against the $\overline{X}$. The expected scrap value $\overline{X}$ determines how easy it is for a firm to induce its rival to exit the industry. Because a firm can always guarantee itself a nonnegative short-run profit, exit is impossible if $\overline{X} + \Delta_X < 0 \Leftrightarrow \overline{X} < -1.5$. As $\overline{X} \to \infty$, exit becomes inevitable. At the same time, however, exit is immediately followed by entry. In particular, if $\overline{X} - \Delta_X > \overline{S} + \Delta_S \Leftrightarrow \overline{X} > 7.5$, then a potential entrant has an incentive to incur the setup cost for the exclusive purpose of receiving the scrap value.[23]

There are multiple equilibria for $\overline{X}$ from 0.7 to 6.5. $\mathbf{H}^{-1}(\overline{X})$ involves a main path (labeled MP) that bends back on itself. The equilibria on the lower fold of MP are accommodative and the industry evolves into a mature duopoly. The equilibria on the upper fold of MP are aggressive and the industry evolves into an entrenched monopoly.

Overall, many equilibria are aggressive. In these equilibria, predation-like behavior arises. Generally speaking, aggressive equilibria tend to arise with a lower progress ratio ρ, a lower degree of product differentiation σ, and a higher expected scrap value $\overline{X}$.[24] Aggressive equilibria typically coexist with accommodative equilibria, and multiplicity of equilibria is the norm rather than the exception. The sheer number of equilibria can be staggering; we have found up to 181 equilibria for some parameterizations.[25] However, the number of

[22] The homotopy algorithm sometimes fails for σ below 0.3. For $\sigma = 0.3$ in an emerging duopoly the own- and cross-price elasticities of demand are -28.17 and 6.38, respectively, at static Nash equilibrium prices and -6.42 and 6.42 in a mature duopoly. For $\sigma = 3$ the own- and cross-price elasticities are -3.72 and 0.84, respectively, in an emerging duopoly, and -1.66 and 1.07 in a mature duopoly.

[23] Our model cannot capture perfect contestability which requires $\Delta_X = \Delta_S = 0$ in addition to $\overline{X} = \overline{S}$.

[24] With more than two firms, the incentive to price aggressively may be muted because it is costly and eliminating a competitor from the industry benefits all surviving firms. A firm may thus prefer another firm to price aggressively rather than to do so itself. This externality is well-understood in merger analysis (Stigler 1950). Because the benefits of focusing on two firms are substantial, both in terms of computational burden and in terms of presenting the results, we leave it to future work to extend the analysis to more firms.

[25] Many of these equilibria differ in the number, location, or depth of the trenches and corresponding exit zones but induce broadly similar industry dynamics.

equilibria varies widely across parameterizations; see the Online Appendix for details.

5 Isolating predatory incentives

To detect the presence of predatory pricing, antitrust authorities routinely ask whether a firm sacrifices current profit in exchange for the expectation of higher future profit following the exit of its rival. This sacrifice test thus views predation as an "investment in monopoly profit" (Bork 1978).[26]

Edlin & Farrell (2004) point out that one way to test for sacrifice is to determine whether the derivative of a suitably defined profit function is positive at the price the firm has chosen, which indicates that the chosen price is less than the price that maximizes profit. Moreover, "[i]n principle this profit function should incorporate *everything except effects on competition*" (p. 510, our italics).

To formalize the sacrifice test and relate it to our model, we partition the profit function $\Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})$ in equation (7) into an everything-except-effects-on-competition (EEEC) profit function $\Pi_1^0(p_1, p_2(\mathbf{e}), \mathbf{e})$ and a remainder $\Omega_1(p_1, p_2(\mathbf{e}), \mathbf{e}) = \Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e}) - \Pi_1^0(p_1, p_2(\mathbf{e}), \mathbf{e})$ that by definition reflects the effects on competition. Because $\frac{\partial \Pi_1(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})}{\partial p_1} = 0$ in equilibrium, the sacrifice test $\frac{\partial \Pi_1^0(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})}{\partial p_1} > 0$ is equivalent to

$$-\frac{\partial \Omega_1(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})}{\partial p_1} = \frac{\partial \Omega_1(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})}{\partial (-p_1)} > 0. \tag{9}$$

$\frac{\partial \Omega_1(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})}{\partial (-p_1)}$ is the marginal return to a price cut in the current period due to changes in the competitive environment. If profit is sacrificed, then inequality (9) tells us that these changes in the competitive environment are to the firm's advantage. In this sense, $\frac{\partial \Omega_1(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})}{\partial (-p_1)}$ is the marginal return to the "investment in monopoly profit" and thus a natural measure of the firm's predatory pricing incentives.

We next turn to characterizing the firm's predatory pricing incentives $\frac{\partial \Omega_1(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})}{\partial (-p_1)}$ for a variety of plausible specifications of the EEEC profit function.

Short-run profit. Expanding the above quote from Edlin & Farrell (2004) "[i]n principle this profit function should incorporate everything except effects on competition, *but in practice sacrifice tests often use short-run data*, and we will often follow the conventional shorthand of calling it short-run profit" (p. 510, our italics). Defining $\Pi_1^0(p_1, p_2(\mathbf{e}), \mathbf{e}) =$

[26] A sacrifice test is closely related to the "no economic sense" test that holds that "conduct is not exclusionary or predatory unless it would make no economic sense for the defendant but for the tendency to eliminate or lessen competition" (Werden 2006, p. 417). Both tests have been criticized for "not generally [being] a reliable indicator of the impact of allegedly exclusionary conduct on consumer welfare—the primary focus of antitrust laws" (Salop 2006, p. 313).

$(p_1 - c(e_1))D_1(p_1, p_2(\mathbf{e}))$ to be short-run profit, it follows from the sacrifice test (9) that $\frac{\partial \Omega_1(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})}{\partial(-p_1)} > 0$ if and only if $[U_1(e_1+1, e_2) - U_1(\mathbf{e})] + \Upsilon(p_2(\mathbf{e}))\,[U_1(\mathbf{e}) - U_1(e_1, e_2+1)] > 0$. Our first definition of predatory incentives thus comprises the advantage-building motive and the advantage-denying motive:

Definition 1 (short-run profit) *The firm's predatory pricing incentives are* $[U_1(e_1+1, e_2) - U_1(\mathbf{e})] + \Upsilon(p_2(\mathbf{e}))\,[U_1(\mathbf{e}) - U_1(e_1, e_2+1)]$.

The sacrifice test based on Definition 1 is equivalent to the inclusive price $mr_1(p_1(\mathbf{e}), p_2(\mathbf{e}))$ being less than *short-run* marginal cost $c(e_1)$.[27] Because $mr_1(p_1(\mathbf{e}), p_2(\mathbf{e})) \to p_1(\mathbf{e})$ as $\sigma \to 0$, in an industry with very weak product differentiation it is also nearly equivalent to the classic Areeda & Turner (1975) test that equates predatory pricing with below-cost pricing and underpins the current *Brooke Group* standard for predatory pricing in the U.S.

Dynamic competitive vacuum. Definition 1 may be too severe as it forces a static model of profit maximization onto a dynamic world. In particular, it denies the efficiency gains from pricing aggressively in order to move down the learning curve.

Farrell & Katz (2005) argue forcefully that an action is predatory to the extent that it weakens the rival (see, in particular, p. 219 and p. 226). A firm should therefore behave as if it were operating in a "dynamic competitive vacuum" in the sense that the firm takes as given the competitive position of its rival in the current period but ignores that its current price can affect the evolution of the competitive position of its rival beyond the current period. We accordingly define the EEEC profit function to be $\Pi_1^0(p_1, p_2(\mathbf{e}), \mathbf{e}) = (p_1 - c(e_1))D_1(p_1, p_2(\mathbf{e})) + U_1(\mathbf{e}) + D_1(p_1, p_2(\mathbf{e}))\,[U_1(e_1+1, e_2) - U_1(\mathbf{e})]$.[28] It follows from the sacrifice test (9) that $\frac{\partial \Omega_1(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})}{\partial(-p_1)} > 0$ if and only if $[U_1(\mathbf{e}) - U_1(e_1, e_2+1)] > 0$. The advantage-denying motive thus constitutes our second definition of predatory incentives:

Definition 2 (dynamic competitive vacuum) *The firm's predatory pricing incentives are* $[U_1(\mathbf{e}) - U_1(e_1, e_2+1)]$.

Definition 2 provides a way to disentangle predatory incentives from standard dynamic pricing incentives under learning-by-doing that would lead even a monopolist to set inclusive price below short-run marginal cost. The sacrifice test based on Definition 2 is equivalent to the inclusive price $mr_1(p_1(\mathbf{e}), p_2(\mathbf{e}))$ being less than *long-run* marginal cost

[27] Edlin (2010) interprets the arguments of the U.S. Department of Justice in a predatory pricing case against American Airlines in the mid 1990s as implicitly advocating such a sacrifice test. Edlin & Farrell (2004) and Snider (2008) provide detailed analyses of this case.

[28] We assume that from the subsequent period onward play returns to equilibrium. To us, this best captures the idea that the firm is sacrificing something now in exchange for a later improvement in the competitive environment.

$c(e_1) - [U_1(e_1+1, e_2) - U_1(\mathbf{e})]$. Note that a lower bound on long-run marginal cost $c(e_1) - [U_1(e_1+1, e_2) - U_1(\mathbf{e})]$ is out-of-pocket cost at the bottom of the learning curve $c(m)$ (Spence 1981). Hence, if $mr_1(p_1(\mathbf{e}), p_2(\mathbf{e})) < c(m)$, then $mr_1(p_1(\mathbf{e}), p_2(\mathbf{e})) < c(e_1) - [U_1(e_1+1, e_2) - U_1(\mathbf{e})]$. This provides a one-way test for sacrifice that can be operationalized given some basic knowledge of demand and cost.

Rival exit. In contrast to Definitions 1 and 2, the economic definitions of predation formulated in the existing literature focus more narrowly on the impact of a price cut on rival exit. According to Ordover & Willig (1981), "[p]redatory behavior is a response to a rival that sacrifices part of the profit that could be earned under competitive circumstances were the rival to remain viable, in order to induce exit and gain consequent additional monopoly profit" (pp. 9–10). Cabral & Riordan (1997) relatedly call "an action predatory if (1) a different action would increase the probability that rivals remain viable and (2) the different action would be more profitable under the counterfactual hypothesis that the rival's viability were unaffected" (p. 160).

Moving from the two-period model in Cabral & Riordan (1997) to our infinite-horizon dynamic stochastic game, we take the "rival's viability" to refer to the probability that the rival exits the industry in the current period. This probability, in turn, is part of both the advantage-building motive $[U_1(e_1+1, e_2) - U_1(\mathbf{e})]$ and the advantage-denying motive $[U_1(\mathbf{e}) - U_1(e_1, e_2+1)]$ as can be seen by using equation (1) to express $U_1(\mathbf{e})$ in terms of $V_1(\mathbf{e})$. To isolate the impact of a price cut on rival exit, we therefore further decompose the equilibrium pricing condition (8) as

$$mr_1(p_1, p_2(\mathbf{e})) - c(e_1) + \underbrace{\left[\sum_{k=1}^{5} \Gamma_1^k(\mathbf{e})\right]}_{=[U_1(e_1+1,e_2)-U_1(\mathbf{e})]} + \Upsilon(p_2(\mathbf{e})) \underbrace{\left[\sum_{k=1}^{4} \Theta_1^k(\mathbf{e})\right]}_{=[U_1(\mathbf{e})-U_1(e_1,e_2+1)]} = 0. \tag{10}$$

The decomposed advantage-building motives $\Gamma_1^k(\mathbf{e})$ summarized in Table 4 are the various sources of marginal benefit to the firm from winning the sale in the current period and moving further down its learning curve. The decomposed advantage-denying motives $\Theta_1^k(\mathbf{e})$ summarized in Table 5 are the various sources of marginal benefit to the firm from winning the sale in the current period and, in so doing, preventing its rival from moving further down its learning curve. The decomposed advantage-denying motives differ from the decomposed advantage-building motives in that they focus not on the firm becoming more efficient but on the firm preventing its rival from becoming more efficient.[29]

[29]The decomposition (10) applies to an industry with two incumbent firms in state $\mathbf{e} \geq (1,1)$ and we focus on firm 1. Because $\Gamma_1^k(\mathbf{e})$ and $\Theta_1^k(\mathbf{e})$ are typically positive, we refer to them as marginal benefits. To streamline the exposition, we further presume monotonicity of the value and policy functions. For some parameterizations these assumptions fail.

advantage-building	definition	if the firm wins the sale and moves further down its learning curve, then the firm...
baseline	$\Gamma_1^1(\mathbf{e}) = (1-\phi_1(\mathbf{e}))\beta\left[V_1(e_1+1,e_2) - V_1(\mathbf{e})\right]$	... improves its competitive position within the duopoly
exit	$\Gamma_1^2(\mathbf{e}) = (1-\phi_1(\mathbf{e}))\left[\phi_2(e_1+1,e_2) - \phi_2(\mathbf{e})\right] \times \beta[V_1(e_1+1,0) - V_1(e_1+1,e_2)]$	... increases its rival's exit probability
survival	$\Gamma_1^3(\mathbf{e}) = [\phi_1(\mathbf{e}) - \phi_1(e_1+1,e_2)] \times \beta\Big[\phi_2(e_1+1,e_2)V_1(e_1+1,0) + (1-\phi_2(e_1+1,e_2))V_1(e_1+1,e_2)\Big]$	... decreases its exit probability
scrap value	$\Gamma_1^4(\mathbf{e}) = \phi_1(e_1+1,e_2)E_X\left[X_1 \mid X_1 \geq \widehat{X}_1(e_1+1,e_2)\right] - \phi_1(\mathbf{e})E_X\left[X_1 \mid X_1 \geq \widehat{X}_1(\mathbf{e})\right]$	... increases its expected scrap value
market structure	$\Gamma_1^5(\mathbf{e}) = (1-\phi_1(\mathbf{e}))\phi_2(\mathbf{e}) \beta\Big\{[V_1(e_1+1,0) - V_1(e_1,0)] - [V_1(e_1+1,e_2) - V_1(\mathbf{e})]\Big\}$	... gains from an improved competitive position as a monopolist versus as a duopolist

Table 4: Decomposed advantage-building motives.

advantage-denying	definition	if the firm wins the sale and prevents its rival from moving further down its learning curve, then the firm ...
baseline	$\Theta_1^1(\mathbf{e}) = (1-\phi_1(\mathbf{e}))(1-\phi_2(e_1,e_2+1)) \times \beta\left[V_1(\mathbf{e}) - V_1(e_1,e_2+1)\right]$	... prevents its rival from improving its competitive position within the duopoly
exit	$\Theta_1^2(\mathbf{e}) = (1-\phi_1(\mathbf{e}))[\phi_2(\mathbf{e}) - \phi_2(e_1,e_2+1)] \times \beta[V_1(e_1,0) - V_1(\mathbf{e})]$	... prevents its rival's exit probability from decreasing
survival	$\Theta_1^3(\mathbf{e}) = [\phi_1(e_1,e_2+1) - \phi_1(\mathbf{e})] \times \beta\Big[\phi_2(e_1,e_2+1)V_1(e_1,0) + (1-\phi_2(e_1,e_2+1))V_1(e_1,e_2+1)\Big]$	... prevents its exit probability from increasing
scrap value	$\Theta_1^4(\mathbf{e}) = \phi_1(\mathbf{e})E_X\left[X_1 \mid X_1 \geq \widehat{X}_1(\mathbf{e})\right] - \phi_1(e_1,e_2+1)E_X\left[X_1 \mid X_1 \geq \widehat{X}_1(e_1,e_2+1)\right]$	... prevents its expected scrap value from decreasing

Table 5: Decomposed advantage-denying motives.

The impact of a price cut on rival exit is reflected in $\Gamma_1^2(\mathbf{e})$ and $\Theta_1^2(\mathbf{e})$. The *advantage-building/exit motive*

$$\Gamma_1^2(\mathbf{e}) = (1-\phi_1(\mathbf{e}))\left[\phi_2(e_1+1,e_2)-\phi_2(\mathbf{e})\right]\beta[V_1(e_1+1,0)-V_1(e_1+1,e_2)]$$

is the marginal benefit to the firm from increasing its rival's exit probability from $\phi_2(\mathbf{e})$ to $\phi_2(e_1+1,e_2)$. The increase in the firm's expected NPV, $[V_1(e_1+1,0)-V_1(e_1+1,e_2)]$, is deflated by the probability $(1-\phi_1(\mathbf{e}))$ that the firm remains in the industry in the current period because otherwise the benefit is nil. The *advantage-denying/exit motive*

$$\Theta_1^2(\mathbf{e}) = (1-\phi_1(\mathbf{e}))[\phi_2(\mathbf{e})-\phi_2(e_1,e_2+1)]\beta[V_1(e_1,0)-V_1(\mathbf{e})]$$

is the marginal benefit to the firm from preventing its rival's exit probability from decreasing from $\phi_2(\mathbf{e})$ to $\phi_2(e_1,e_2+1)$. The increase in the firm's expected NPV, $[V_1(e_1,0)-V_1(\mathbf{e})]$, is again deflated by the probability $(1-\phi_1(\mathbf{e}))$ that the firm remains in the industry. Our third definition of predatory incentives therefore is:

Definition 3 (rival exit I) *The firm's predatory pricing incentives are* $\Gamma_1^2(\mathbf{e})+\Upsilon(p_2(\mathbf{e}))\Theta_1^2(\mathbf{e})$.[30]

Note that a verbatim translation of the Ordover & Willig (1981) and Cabral & Riordan (1997) definitions of predation into our model involves other decomposed advantage-building and advantage-denying motives as well; see the Online Appendix for details.

Our final definition of the firm's predatory pricing incentives comes from partitioning the predatory incentives in Definition 3 more finely by maintaining that the truly exclusionary effect on competition is the one aimed at inducing exit by preventing the rival from winning the sale and moving further down its learning curve:[31]

Definition 4 (rival exit II) *The firm's predatory pricing incentives are* $\Theta_1^2(\mathbf{e})$.

The types of behavior—in particular, the wells and trenches—that can emerge in our model are closely linked to the decomposed advantage-building and advantage-denying motives that Definitions 3 and 4 focus on. The upper left and middle panels of Table 6 illustrate the decomposition (10) for the aggressive equilibrium at the beginning of Section 4 for a set of states $(e_1,1)$ with $e_1 \in \{1,\ldots,30\}$ where firm 2 is emerging. The competition for the market in the well in state $(1,1)$ is driven mostly by the baseline advantage-building motive

[30] The corresponding EEEC profit function is $\Pi^0(p_1,p_2(\mathbf{e}),\mathbf{e}) = (p_1-c(e_1))D_1(p_1,p_2(\mathbf{e}))+U_1(\mathbf{e})+D_1(p_1,p_2(\mathbf{e}))\left[\sum_{k\neq 2}\Gamma_1^k(\mathbf{e})\right]-D_2(p_1,p_2(\mathbf{e}))\left[\sum_{k\neq 2}\Theta_1^k(\mathbf{e})\right]$.

[31] An alternative to Definition 4 is to define $\Gamma_1^2(\mathbf{e})$ as the firm's predatory pricing incentives. This definition is used by Snider (2008) to explore whether American Airlines engaged in predatory capacity expansion in the Dallas-Fort Worth to Wichita market in the late 1990s.

$\Gamma_1^1(1,1)$ and the advantage-building/exit motive $\Gamma_1^2(1,1)$. In contrast, the competition for the market in the trench in states $(e_1, 1)$ with $e_1 \in \{2, \ldots, 30\}$ is driven mostly by the baseline advantage-denying motive $\Theta_1^1(e_1, 1)$ and the advantage-denying/exit motive $\Theta_1^2(e_1, 1)$. The predation-like behavior in the trench thus does not arise because by becoming more efficient the leader increases the probability that the follower exits the industry. It arises because by preventing the follower from becoming more efficient, the leader keeps the follower in the trench and thus prone to exit. Another way to put this is that the leader makes the cost to the follower of attempting to move down its learning curve comparable to the benefit to the follower of doing so, so that exit is in the follower's interest. Viewed this way, the aggressive pricing in the trench can be viewed as raising the rival's cost of remaining in the industry.

For a set of states $(e_1, 4)$ with $e_1 \in \{1, \ldots, 30\}$ where firm 2 has already gained some traction, in contrast, neither the decomposed advantage-building motives nor the decomposed advantage-denying motives are very large. Our computations show that for all parameterizations and equilibria the decomposed advantage-denying motives vanish entirely once firm 2 has reached the bottom of its learning curve in states (e_1, e_2) with $e_2 \in \{16, \ldots, 30\}$.[32] As can be seen in the lower left and middle panels of Table 6, to the extent that the price is below the static optimum in the aggressive equilibrium this is due mostly to the baseline advantage-building motive $\Gamma_1^1(e_1, 4)$.

Our definitions of predatory incentives are in what intuitively seems to be decreasing order of severity. The right panels of Table 6 illustrate this point at the example of the aggressive equilibrium at the beginning of Section 4. A sacrifice test based on a later definition has indeed a lesser tendency to identify a price as predatory.

6 Economic significance of predatory incentives

Is predatory pricing detrimental to consumers and society at large? We use our model to address this question by implementing an ideal conduct restriction that eliminates the predatory incentives. We imagine an omniscient regulator who can instantly flag a profit sacrifice and prevent a firm from pricing to achieve that sacrifice by forcing it to ignore the predatory incentives. The various definitions of predatory incentives in Section 5 accordingly restrict the range of the firm's price, e.g., Definition 1 prohibits the inclusive price—and thus also the actual price—from being less than marginal cost.

We formalize a conduct restriction as a constraint $\Xi_1(p_1, p_2(\mathbf{e}), \mathbf{e}) = 0$ on the maximization problem on the right-hand side of the Bellman equation (3) that the firm solves in the price-setting phase. We form the constraint from our decomposition (10) by "switching

[32] Similarly, the decomposed advantage-building motives vanish entirely once firm 1 has reached the bottom of its learning curve in states (e_1, e_2) with $e_1 \in \{16, \ldots, 30\}$.

												sacrifice test			
			advantage-building					advantage-denying				1	2	3	4
$\mathbf{e}$	$p_1(\mathbf{e})$	$c(e_1)$	$\Gamma_1^1(\mathbf{e})$	$\Gamma_1^2(\mathbf{e})$	$\Gamma_1^3(\mathbf{e})$	$\Gamma_1^4(\mathbf{e})$	$\Gamma_1^5(\mathbf{e})$	$\Theta_1^1(\mathbf{e})$	$\Theta_1^2(\mathbf{e})$	$\Theta_1^3(\mathbf{e})$	$\Theta_1^4(\mathbf{e})$	SRP	DCV	REI	REII
(1,1)	-34.78	10.00	39.45	6.44	0.02	0.00	-0.01	0.93	0.03	0.44	-0.51	$\surd\surd$	$\surd\surd$	$\surd\surd$	$\surd$
(2,1)	0.08	7.50	4.27	0.02	0.00	0.00	-0.20	32.93	6.45	0.00	0.00	$\surd\surd$	$\surd\surd$	$\surd\surd$	$\surd\surd$
(3,1)	0.56	6.34	2.94	0.01	0.00	0.00	-0.12	33.96	6.27	0.00	0.00	$\surd\surd$	$\surd\surd$	$\surd\surd$	$\surd\surd$
(4,1)	0.80	5.63	2.20	0.01	0.00	0.00	-0.08	34.54	6.17	0.00	0.00	$\surd\surd$	$\surd\surd$	$\surd\surd$	$\surd\surd$
(5,1)	0.95	5.13	1.71	0.01	0.00	0.00	-0.05	34.91	6.10	0.00	0.00	$\surd\surd$	$\surd\surd$	$\surd\surd$	$\surd\surd$
(6,1)	1.05	4.75	1.36	0.00	0.00	0.00	-0.04	35.17	6.06	0.00	0.00	$\surd\surd$	$\surd\surd$	$\surd\surd$	$\surd\surd$
(7,1)	1.11	4.46	1.09	0.00	0.00	0.00	-0.03	35.35	6.02	0.00	0.00	$\surd\surd$	$\surd\surd$	$\surd\surd$	$\surd\surd$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
(14,1)	1.24	3.34	0.09	0.00	0.00	0.00	0.00	35.71	5.96	0.00	0.00	$\surd\surd$	$\surd\surd$	$\surd\surd$	$\surd\surd$
(15,1)	1.24	3.25	0.00	0.00	0.00	0.00	0.00	35.71	5.96	0.00	0.00	$\surd\surd$	$\surd\surd$	$\surd\surd$	$\surd\surd$
(16,1)	1.24	3.25	0.00	0.00	0.00	0.00	0.00	35.71	5.96	0.00	0.00	$\surd\surd$	$\surd\surd$	$\surd\surd$	$\surd\surd$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
(30,1)	1.24	3.25	0.00	0.00	0.00	0.00	0.00	35.71	5.96	0.00	0.00	$\surd\surd$	$\surd\surd$	$\surd\surd$	$\surd\surd$
(1,4)	4.41	10.00	5.21	0.00	1.92	-0.52	0.00	0.00	0.00	0.00	0.00	$\surd\surd$	$\surd$		
(2,4)	6.06	7.50	2.87	0.00	0.00	0.00	0.00	0.16	0.00	0.00	0.00	$\surd\surd$	$\surd$		
(3,4)	5.79	6.34	2.12	0.00	0.00	0.00	0.00	0.24	0.00	0.00	0.00	$\surd\surd$	$\surd$		
(4,4)	5.65	5.63	1.66	0.00	0.00	0.00	0.00	0.31	0.00	0.00	0.00	$\surd\surd$	$\surd$		
(5,4)	5.56	5.13	1.34	0.00	0.00	0.00	0.00	0.35	0.00	0.00	0.00	$\surd\surd$	$\surd$		
(6,4)	5.49	4.75	1.10	0.00	0.00	0.00	0.00	0.39	0.00	0.00	0.00	$\surd\surd$	$\surd$		
(7,4)	5.45	4.46	0.90	0.00	0.00	0.00	0.00	0.41	0.00	0.00	0.00	$\surd\surd$	$\surd$		
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
(14,4)	5.32	3.34	0.09	0.00	0.00	0.00	0.00	0.47	0.00	0.00	0.00	$\surd\surd$	$\surd$		
(15,4)	5.32	3.25	0.00	0.00	0.00	0.00	0.00	0.47	0.00	0.00	0.00	$\surd$	$\surd$		
(16,4)	5.32	3.25	0.00	0.00	0.00	0.00	0.00	0.47	0.00	0.00	0.00	$\surd$	$\surd$		
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
(30,4)	5.32	3.25	0.00	0.00	0.00	0.00	0.00	0.47	0.00	0.00	0.00	$\surd$	$\surd$		

Table 6: Decomposed advantage-building and advantage-denying motives (left and middle panels) and sacrifice test for Definitions 1–4 (right panels). $\surd\surd$ means that the weighted sum of the predatory incentives is larger than 0.5, $\surd$ that the weighted sum is between 0 and 0.5, and a blank that the weighted sum smaller or equal to 0. Aggressive equilibrium.

off" the predatory incentives according to a particular definition. For example, Definition 2 forces the firm to ignore $\sum_{k=1}^{4} \Theta_1^k(\mathbf{e}) = [U_1(\mathbf{e}) - U_1(e_1, e_2+1)]$ in setting its price, so the constraint is $\Xi_1(p_1, p_2(\mathbf{e}), \mathbf{e}) = mr_1(p_1, p_2(\mathbf{e})) - c(e_1) + \left[\sum_{k=1}^{5} \Gamma_1^k(\mathbf{e})\right] = mr_1(p_1, p_2(\mathbf{e})) - c(e_1) + [U_1(e_1+1, e_2) - U_1(\mathbf{e})] = 0$. We use the homotopy method to compute the symmetric Markov perfect equilibria of the counterfactual game with a conduct restriction (according to a particular definition) in place. Comparing the SCP metrics between the counterfactuals and equilibria tells us how much bite the predatory incentives have.

6.1 Counterfactual and equilibrium correspondences

As with the equilibrium correspondence in Section 4.2, we compute two-dimensional slices along (ρ, σ), $(\rho, \overline{X})$, and $(\sigma, \overline{X})$ through the counterfactual correspondence. Our computations show that for all parameterizations the counterfactual is unique for Definition 1 but not necessarily for Definitions 2, 3, and 4 where we have found up to 3, 103, and 151 counterfactuals for some parameterizations. Even for Definitions 3 and 4, however, there tend to be less counterfactuals than equilibria for a given parameterization.

Figure 4 illustrates the counterfactual correspondence for Definitions 1–4 by plotting HHI^{∞} against ρ. We superimpose the equilibrium correspondence $\mathbf{H}^{-1}(\rho)$ from Figure 3.

For Definitions 1 and 2, the counterfactual correspondence consists of a main path. In the counterfactuals the industry evolves into a mature duopoly with $HHI^{\infty} = 0.5$. Further inspection shows that the counterfactuals are accommodative. While the accommodative equilibria on MP and the lower fold of SL have a counterfactual "nearby," the aggressive equilibria on the upper fold of SL as well as those on L_1, L_2, and L_3 do not. For example, for the baseline parameterization, the accommodative but not the aggressive equilibrium seems to have a counterfactual counterpart.

By contrast, the counterfactual correspondence for Definitions 3 and 4 resembles the equilibrium correspondence and consists of a main path, a semi-loop, and one loop. The counterfactuals span the same range of industry structures as the equilibria. Most, but not all, equilibria have a counterfactual "nearby."

6.2 Eliminated and surviving equilibria

By illustrating that there are equilibria that do not have a counterfactual counterpart, Figure 4 suggests that a conduct restriction eliminates some equilibria while other equilibria survive it. To formalize this intuition, we use the homotopy method to match equilibria with counterfactuals. Instead of abruptly "switching off" the predatory incentives in our decomposition (10), we gradually drive them to zero. For Definition 2, for example, we put a weight λ on $\sum_{k=1}^{4} \Theta_1^k(\mathbf{e}) = [U_1(\mathbf{e}) - U_1(e_1, e_2+1)]$, and we then allow the homotopy method to vary λ (along with the vector of values and policies $\mathbf{x} = (\mathbf{V}_1, \mathbf{U}_1, \mathbf{p}_1, \boldsymbol{\phi}_1)$). At

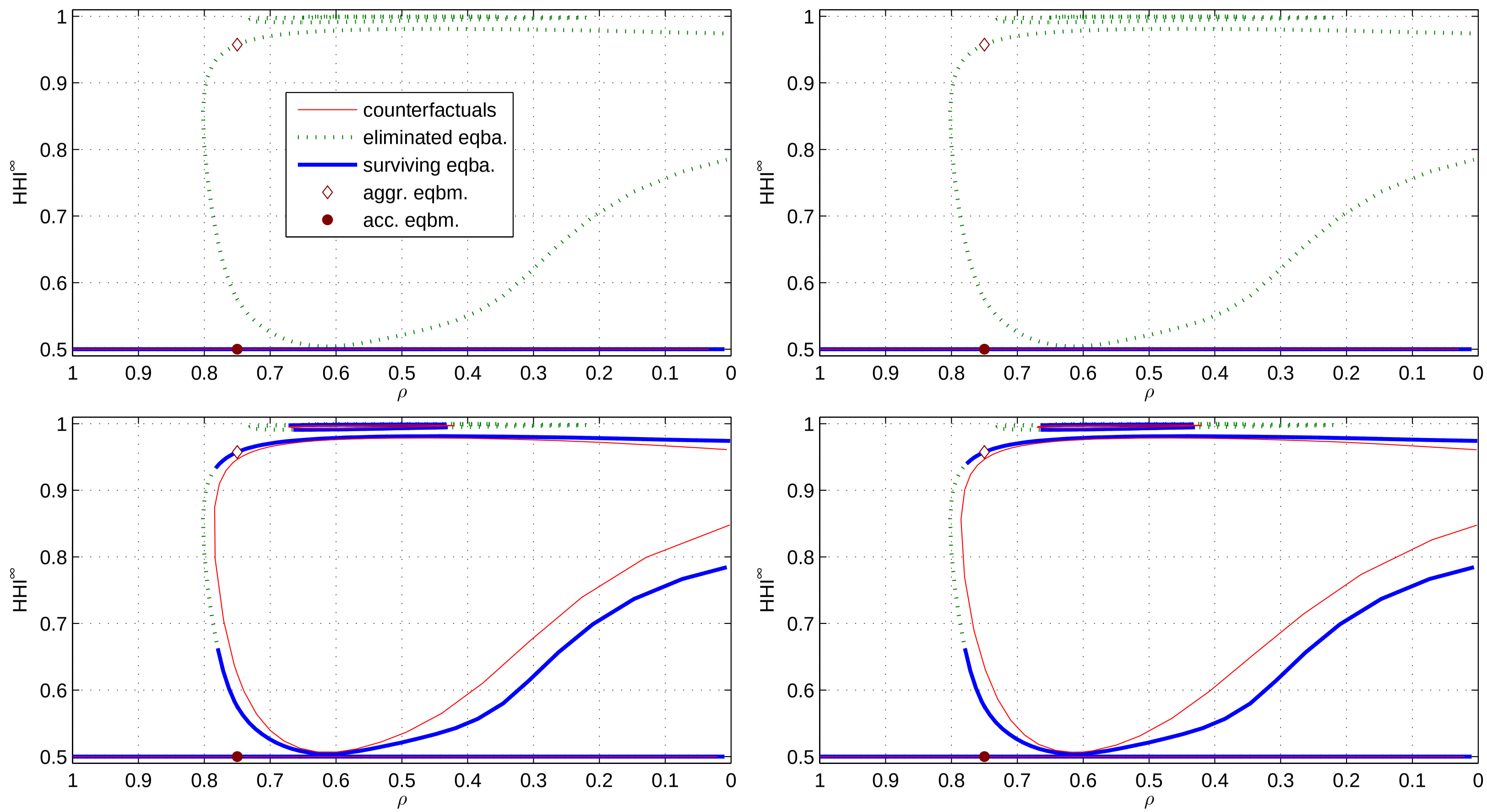

Figure 4: Expected long-run Herfindahl index. Counterfactual (solid red line) and equilibrium correspondences for Definitions 1–4 (upper left, upper right, lower left, and lower right panels) along with eliminated (dashed green line) and surviving (solid blue line) equilibria. Slice along $\rho \in [0, 1]$.

$\lambda = 1$ we have an equilibrium and at $\lambda = 0$ we have a counterfactual. We say that an equilibrium *survives* the conduct restriction if, starting from $\lambda = 1$, the homotopy reaches the counterfactual correspondence. A surviving equilibrium smoothly deforms into a symmetric Markov perfect equilibrium of the counterfactual game by gradually tightening the conduct restriction. We say that an equilibrium is *eliminated* by the conduct restriction if the homotopy algorithm returns to the equilibrium correspondence.[33]

Figure 4 distinguishes between eliminated and surviving equilibria for Definitions 1–4. Definitions 1 and 2 eliminate the aggressive equilibria that are associated with higher expected long-run Herfindahl indices whereas the accommodative equilibria that are associated with lower expected long-run Herfindahl indices survive these conduct restrictions. By contrast, some of the more aggressive equilibria survive Definitions 3 and 4, along with all the more accommodative ones. Nevertheless, Definitions 3 and 4 eliminate at least some of the aggressive equilibria.

To illustrate, for the baseline parameterization with $\rho = 0.75$ all three equilibria (including the aggressive and accommodative equilibria at the beginning of Section 4) survive Definitions 3 and 4. For $\rho = 0.8$ one of the three equilibria survives these conduct restrictions; the two most aggressive equilibria with $HHI^{\infty} = 0.80$ and $HHI^{\infty} = 0.89$ are eliminated. For $\rho = 0.7$ three of the five equilibria survive; again the two most aggressive equilibria with $HHI^{\infty} = 0.99$ and $HHI^{\infty} = 1.00$ are eliminated.

These patterns are general. The first row of Table 7 shows the percentage of equilibria that are eliminated by a particular conduct restriction or survive it for the two-dimensional slices along (ρ, σ), $(\rho, \overline{X})$, and $(\sigma, \overline{X})$ through the equilibrium correspondence. We restrict attention to parameterizations with multiple equilibria because if an equilibrium is unique, then (under some regularity conditions) it necessarily survives the conduct restriction. In line with Figure 4, the more severe conduct restrictions based on Definitions 1 and 2 eliminate many more equilibria than the less severe conduct restrictions based on Definitions 3 and 4.

The remaining rows of Table 7 show how industry structure, conduct, and performance differ between eliminated and surviving equilibria. We report averages and standard deviations of the SCP metrics that equally weigh parameterizations in order to compensate for the different number of equilibria at different parameterizations. The eliminated equilibria have, on average, higher concentration, higher prices, and lower expected long-run consumer surplus than the surviving equilibria. With the relatively small exception of Definition 4 for the $(\rho, \overline{X})$-slice, the eliminated equilibria also have, on average, lower expected long-run total surplus. The equilibria that are eliminated by a particular conduct restriction thus tend to be "worse" in the long run than the equilibria that survive it.

While the eliminated equilibria tend to have less competition in the market in the long

[33] See Case B in Figure 1 in Borkovsky, Doraszelski & Kryukov (2010) for an example of such a return.

		(ρ,σ)				$(\rho,\overline{X})$				$(\sigma,\overline{X})$			
		1	2	3	4	1	2	3	4	1	2	3	4
		SRP	DCV	REI	REII	SRP	DCV	REI	REII	SRP	DCV	REI	REII
	elim.	84%	88%	53%	51%	85%	85%	39%	36%	97%	97%	69%	75%
	surv.	2%	3%	36%	36%	15%	14%	51%	61%	2%	2%	13%	18%
HHI^{∞}	elim.	0.95	0.95	0.97	0.97	0.89	0.89	0.91	0.92	0.93	0.93	0.93	0.94
		(0.10)	(0.10)	(0.08)	(0.07)	(0.14)	(0.14)	(0.11)	(0.09)	(0.10)	(0.10)	(0.09)	(0.09)
	surv.	0.85	0.78	0.89	0.89	0.55	0.55	0.77	0.78	0.82	0.81	0.87	0.87
		(0.22)	(0.24)	(0.19)	(0.19)	(0.13)	(0.13)	(0.21)	(0.21)	(0.22)	(0.22)	(0.18)	(0.18)
$\overline{p}^{\infty}$	elim.	7.96	7.98	8.14	8.22	7.05	7.03	7.00	7.01	8.23	8.24	8.30	8.30
		(1.33)	(1.31)	(1.31)	(1.16)	(1.35)	(1.37)	(1.31)	(1.19)	(0.78)	(0.78)	(0.67)	(0.66)
	surv.	7.12	6.09	7.30	7.31	3.45	3.44	5.90	6.00	7.57	7.54	7.91	7.91
		(2.52)	(3.05)	(2.26)	(2.26)	(1.92)	(1.94)	(2.34)	(2.31)	(1.50)	(1.49)	(1.21)	(1.21)
CS^{∞}	elim.	2.18	2.16	1.97	1.89	3.22	3.25	3.23	3.22	1.98	1.97	1.91	1.91
		(1.45)	(1.44)	(1.39)	(1.24)	(1.46)	(1.49)	(1.39)	(1.25)	(0.94)	(0.94)	(0.82)	(0.81)
	surv.	3.14	4.26	2.91	2.91	7.20	7.21	4.50	4.39	2.76	2.80	2.36	2.36
		(2.81)	(3.35)	(2.50)	(2.50)	(2.02)	(2.04)	(2.55)	(2.51)	(1.81)	(1.80)	(1.48)	(1.47)
TS^{∞}	elim.	8.12	8.13	8.01	7.98	8.77	8.78	8.98	9.03	6.59	6.59	6.58	6.58
		(1.83)	(1.85)	(1.92)	(1.92)	(1.35)	(1.35)	(1.34)	(1.32)	(0.41)	(0.41)	(0.40)	(0.40)
	surv.	8.15	8.59	8.33	8.33	9.53	9.56	9.03	9.01	6.84	6.83	6.72	6.72
		(2.10)	(2.20)	(1.95)	(1.95)	(1.45)	(1.45)	(1.41)	(1.40)	(0.55)	(0.55)	(0.51)	(0.51)
CS^{NPV}	elim.	149.66	150.12	148.02	147.49	151.43	151.48	159.32	160.85	105.09	105.07	104.59	104.49
		(38.96)	(39.27)	(40.37)	(40.44)	(30.92)	(30.90)	(27.88)	(27.26)	(4.97)	(4.96)	(4.86)	(4.78)
	surv.	143.34	149.64	149.87	149.86	154.88	155.50	152.40	152.28	106.25	106.08	105.59	105.64
		(40.98)	(40.92)	(38.95)	(38.95)	(30.70)	(30.66)	(30.71)	(30.64)	(4.16)	(3.96)	(4.58)	(4.59)
TS^{NPV}	elim.	155.50	155.93	153.72	153.16	167.92	167.97	173.86	175.46	119.29	119.28	119.37	119.37
		(39.14)	(39.44)	(40.61)	(40.65)	(31.29)	(31.27)	(30.41)	(29.84)	(7.76)	(7.76)	(7.80)	(7.83)
	surv.	151.28	159.56	157.44	157.43	173.01	173.75	169.63	169.44	120.14	119.89	119.63	119.66
		(42.11)	(43.42)	(40.15)	(40.15)	(32.20)	(32.18)	(31.54)	(31.44)	(7.01)	(6.81)	(7.37)	(7.34)

Table 7: Eliminated and surviving equilibria for Definitions 1–4. Industry structure, conduct, and performance. Uniformly spaced grid $(\rho,\sigma)\in\{0.05,0.10,\dots 1.0\}\times\{0.1,0.2,\dots,2.0\}$ (left panel), $(\rho,\overline{X})\in\{0.05,0.10,\dots 1.0\}\times\{-1.5,-1,\dots,7.5\}$ (middle panel), and $(\sigma,\overline{X})\in\{0.1,0.2,\dots 2.0\}\times\{-1.5,-1,\dots,7.5\}$ (right panel), limited to parameterizations with multiple equilibria. Percentages in first row do not add up if the homotopy algorithm crashed and we have been unable to deduce survival or elimination from adjacent equilibria on the solution path. Averages with standard deviations in parenthesis in remaining rows.

run than the surviving equilibria, they may have more competition for the market in the short run. The eliminated equilibria have, on average, higher expected discounted consumer and total surplus than the surviving equilibria under Definition 1 for the (ρ, σ)-slice and under Definitions 3 and 4 for the $(\rho, \overline{X})$-slice. The eliminated equilibria also have, on average, higher expected discounted consumer surplus under Definition 2 for the (ρ, σ)-slice. This is because consumers benefit—at least on the short run—from the aggressive pricing in the wells and trenches that are part and parcel of competition for the market.

In sum, forcing the firm to ignore the predatory incentives can eliminate equilibria that involve high concentration, high prices, and low expected long-run consumer and total surplus. While the stronger Definitions 1 and 2 eliminate many more such equilibria than the weaker Definitions 3 and 4, the weaker Definitions 3 and 4 tend to eliminate the "worst" equilibria. Along with the predation-like behavior, a fair amount of competition for the market is, however, eliminated.

In the presence of multiple equilibria, the underlying primitives do not suffice to tie down equilibrium behavior and industry dynamics. Which equilibrium is being played additionally depends on firms' expectations regarding the evolution of the industry (Besanko et al. 2010). Our analysis suggests that guiding these expectations toward "good" equilibria can have a similar impact as imposing a conduct restriction. Creating a business environment in which firms anticipate that predatory pricing "does not work" (by issuing general guidelines about how allegations of predation are handled, speaking out against predation, pursuing high-profile cases, etc.) can thus be a powerful tool for antitrust policy.

6.3 Impact of conduct restrictions

The elimination-survival analysis illustrates the extent to which the predatory incentives (according to a particular definition) are responsible for "bad" equilibria, but it does not directly quantify the economic significance of the predatory incentives. The economic significance is revealed by comparing counterfactuals to equilibria.

The multiplicity of counterfactuals and equilibria makes such a comparison difficult: which counterfactual should be compared to which equilibrium? To answer this question, we posit an out-of-equilibrium process by which agents adjust to a shock to the system in the form of the conduct restriction.

For a given parameterization we proceed in three steps. First, a surviving equilibrium can by construction be smoothly deformed into a counterfactual. To the extent that the out-of-equilibrium adjustment process is itself sufficiently smooth, it plausibly leads to this counterfactual (Doraszelski & Escobar 2010).[34] Thus, we directly compare (using the SCP

[34] Subsequent research by Aguirregabiria (2012) has exploited the theoretical result in Doraszelski & Escobar (2010) and used the homotopy method for counterfactual analysis along the same lines we do. Lee &

metrics) the surviving equilibrium to its counterfactual counterpart. Second, for an eliminated equilibrium, we assume that, once the conduct restriction is in place, all counterfactuals are equally likely to be played and average over the possible comparisons. Third, we assume that all equilibria are equally likely to be played and average over all comparisons from the first two steps.

Table 8 summarizes the change in SCP metrics from equilibria to counterfactuals. Similar to Table 7, Table 8 reports averages and standard deviations that equally weigh parameterizations. It also shows the percentage of parameterizations for which the change from equilibria to counterfactuals is positive ("up") or negative ("down").

The conduct restrictions associated with all definitions of predatory incentives, on average, decrease concentration and prices and increase expected long-run consumer and total surplus. These changes are substantially more pronounced for the stronger Definitions 1 and 2 that eliminate many more aggressive equilibria than for the weaker Definitions 3 and 4.

With the relatively small exception of Definition 4 for the $(\sigma, \overline{X})$-slice, all conduct restrictions, on average, decrease expected discounted consumer surplus as they restrict competition for the market. This decrease is, however, small for Definitions 2 and 3 and especially for Definition 4. Moreover, with the relatively small exception of Definition 2 for the $(\sigma, \overline{X})$-slice, the conduct restrictions associated with these definitions increase expected discounted total surplus.

The conduct restriction associated with Definition 1, in contrast, substantially decreases TS^{NPV} in addition to CS^{NPV}. The intense competition for the market in the well of an aggressive equilibrium is driven almost entirely by the baseline advantage-building and advantage-building/exit motives (see Table 6). These motives are shut down by the conduct restriction for Definition 1, thereby annihilating competition for the market. By shutting down the advantage-building motive in its entirety, Definition 1 further denies the efficiency gains from pricing aggressively in order to move down the learning curve. Definition 1 thus tends to "throw the baby" (pricing aggressively to pursue efficiency) "out with the bath water" (predation-like behavior in aggressive equilibria).

Definitions 2 and 4 permit the firm to take the advantage-building motive into account but force it to ignore all or part of the advantage-denying motive. The intense competition for the market in the trench of an aggressive equilibrium is driven almost entirely by the baseline advantage-denying motive and the advantage-denying/exit motive (see again Table 6). Like Definition 1, Definitions 2 and 4 restrict competition for the market. While Definitions 2 and 4 disallow a trench and thus the mobility barrier that is likely to lead to an entrenched monopoly over time, they, unlike Definition 1, allow a well. Because they preserve a fair

Pakes (2009) explore the alternative of fully specifying a learning process to compute a distribution over counterfactuals that may be reached from a given equilibrium.

			(ρ,σ)				$(\rho,\overline{X})$				$(\sigma,\overline{X})$			
			1	2	3	4	1	2	3	4	1	2	3	4
	avg.		SRP	DCV	REI	REII	SRP	DCV	REI	REII	SRP	DCV	REI	REII
HHI^{∞}	0.70	change	-0.11	-0.11	-0.02	-0.02	-0.20	-0.20	-0.03	-0.03	-0.14	-0.12	-0.02	-0.02
	(0.22)		(0.20)	(0.19)	(0.08)	(0.08)	(0.22)	(0.22)	(0.09)	(0.08)	(0.19)	(0.18)	(0.07)	(0.07)
		up	6%	2%	10%	11%	0%	0%	8%	9%	1%	2%	3%	3%
		down	40%	40%	21%	19%	63%	62%	39%	37%	44%	40%	23%	22%
$\overline{p}^{\infty}$	6.71	change	-1.17	-1.23	-0.23	-0.18	-2.08	-2.05	-0.27	-0.22	-1.06	-0.89	-0.14	-0.13
	(2.25)		(2.27)	(2.18)	(0.92)	(0.87)	(2.35)	(2.35)	(0.95)	(0.89)	(1.51)	(1.40)	(0.47)	(0.47)
		up	6%	2%	12%	13%	0%	0%	9%	11%	1%	2%	4%	4%
		down	39%	40%	22%	20%	63%	62%	38%	32%	44%	39%	23%	22%
CS^{∞}	3.97	change	1.27	1.33	0.24	0.20	2.29	2.27	0.30	0.24	1.17	0.99	0.16	0.15
	(2.40)		(2.45)	(2.35)	(0.99)	(0.95)	(2.59)	(2.58)	(1.04)	(0.97)	(1.66)	(1.55)	(0.54)	(0.53)
		up	41%	41%	28%	26%	63%	62%	43%	40%	45%	41%	31%	30%
		down	6%	4%	14%	15%	0%	0%	9%	11%	1%	4%	5%	5%
TS^{∞}	7.73	change	0.32	0.30	0.05	0.05	0.45	0.45	0.07	0.06	0.25	0.22	0.04	0.04
	(2.35)		(0.52)	(0.51)	(0.24)	(0.24)	(0.58)	(0.58)	(0.25)	(0.23)	(0.41)	(0.40)	(0.17)	(0.17)
		up	40%	38%	9%	10%	60%	59%	22%	17%	38%	34%	11%	11%
		down	0%	0%	1%	0%	0%	0%	1%	2%	1%	1%	0%	0%
CS^{NPV}	119.88	change	-64.94	-1.80	-1.38	-0.09	-61.92	-1.92	-1.94	-0.02	-46.65	-3.27	-0.61	0.05
	(44.57)		(41.14)	(3.59)	(2.96)	(1.69)	(29.50)	(3.80)	(2.77)	(1.31)	(16.69)	(2.74)	(1.62)	(1.17)
		up	0%	14%	0%	5%	0%	8%	1%	7%	0%	7%	3%	8%
		down	95%	60%	40%	7%	95%	51%	56%	1%	100%	77%	27%	4%
TS^{NPV}	139.16	change	-12.72	2.19	0.32	0.40	-14.05	1.22	0.47	0.33	-14.12	-0.34	0.09	0.08
	(45.96)		(7.47)	(4.43)	(2.65)	(2.55)	(7.61)	(6.89)	(2.15)	(2.08)	(4.16)	(3.17)	(1.40)	(1.38)
		up	1%	35%	8%	9%	0%	37%	14%	12%	0%	16%	6%	5%
		down	93%	0%	4%	2%	95%	22%	1%	1%	100%	16%	4%	4%

Table 8: Impact of conduct restriction for Definitions 1–4. Industry structure, conduct, and performance. Uniformly spaced grid $(\rho,\sigma) \in \{0.05, 0.10, \ldots 1.0\} \times \{0.1, 0.2, \ldots, 2.0\}$ (left panel), $(\rho,\overline{X}) \in \{0.05, 0.10, \ldots 1.0\} \times \{-1.5, -1, \ldots, 7.5\}$ (middle panel), and $(\sigma,\overline{X}) \in \{0.1, 0.2, \ldots 2.0\} \times \{-1.5, -1, \ldots, 7.5\}$ (right panel). Averages with standard deviations in parenthesis. Up means that the increase exceeds 1% of the value of the metric in equilibrium, down that the decrease exceeds 1%.

amount of competition for the market, the conduct restrictions associated with Definitions 2 and 4 tend to very modestly decrease expected discounted consumer surplus and increase expected discounted total surplus.

Definition 3 finally forces the firm to ignore the advantage-building/exit motive—thereby limiting the competition for the market in the well of an aggressive equilibrium—and the advantage-denying/exit motive—thereby limiting the competition for the market in the trench. Imposing the associated conduct restriction brings about a long-run benefit comparable to that of the weaker Definition 4, but it does so at a short-run cost comparable to that of the stronger Definition 2.

While the averages in Table 8 provide a "broad brush" view of the impact of a conduct restriction, the standard deviations as well as the percentages up and down indicate that this impact can differ depending on the parameterization. Especially for Definitions 3 and 4, the averages encompass positive changes for some parameterizations and negative changes for others. For example, the conduct restrictions associated with Definitions 3 and 4 worsen the SCP metrics for the baseline parameterization with $\rho = 0.75$ and they improve them for $\rho = 0.7$. In this respect, our analysis echoes the point made by Cabral & Riordan (1997) and Farrell & Katz (2005) that, depending on the details, predatory pricing can either harm or benefit consumers. Hence, a more "scalpel-like" approach to identifying predatory incentives may be warranted that, ideally, starts with tailoring the model to the institutional realities of the industry under study and then estimates the underlying primitives.

Summing up, our impact analysis resonates with the "bird-in-hand" view of predatory pricing (Edlin 2010). Judge (now U.S. Supreme Court Justice) Stephen Breyer expressed skepticism about declaring an above-cost price cut illegal: "[T]he antitrust laws rarely reject such beneficial 'birds in hand' [an immediate price cut] for the sake of more speculative 'birds in the bush' [preventing exit and thus preventing increases in price in the future]."[35] Our impact analysis supports this view because for all definitions of predatory incentives, the price of making future consumers better off is making current consumers worse off.

Our impact analysis further affords some broad conclusions regarding the different definitions. First, by forcing a static model of profit maximization onto a dynamic world, Definition 1 annihilates competition for the market and is thus very costly for consumers and society in the short run. As it is closely related to Definition 1, this likely carries over to the classic Areeda & Turner (1975) test that equates predatory pricing with below-cost pricing. Second, Definition 3 is dominated by Definition 2 in terms of preserving competition in the market in the long run and by Definition 4 in terms of preserving competition for the market in the short run. Third, Definition 2 brings about a larger benefit to society and to consumers in the long run at a larger cost to consumers in the short run than Defi-

[35] *Barry Wright Corp. v. ITT Grinnell Corp.*, 724 F.2d 227, 234 (1st Cir. 1983).

nition 4. While none of the conduct restrictions is unambiguously beneficial for consumers and society at large in both the short run and the long run, the conduct restrictions associated with Definitions 2 and 4 nevertheless come closest. For the overwhelming majority of parameterizations, both definitions increase CS^∞, TS^∞, and TS^{NPV} or leave them unchanged. Definition 4 moreover increases CS^{NPV} or leaves it unchanged in a majority of parameterizations.

What unifies Definitions 2 and 4 is their emphasis on advantage denying as the basis for predation. This suggests that a sensible line between predatory pricing and mere competition for efficiency on a learning curve is the *exclusion of opportunity*: If a firm's aggressive pricing behavior is primarily driven by the benefits from acquiring competitive advantage, the behavior should be considered benign and should—arguably—not be restricted. If, by contrast, the behavior is primarily driven by the benefits from preventing the rival from acquiring competitive advantage or overcoming competitive disadvantage, the behavior should be considered predatory and should (arguably) be restricted. Of course, because Definition 2 is stronger than Definition 4, there is some latitude in where exactly to draw the line; the choice depends on whether antitrust policy is obligated to consumers—thus preferring the smaller cost to consumers in the short run of Definition 4—or society at large—thus preferring the larger benefit to society in both the short run and the long run of Definition 2. Our analysis nevertheless highlights that the distinction between efficiency-enhancing and predatory motives in pricing is closely related to the distinction between advantage-building and advantage-denying motives. Advantage-building and advantage-denying motives, in turn, can be isolated and measured using our decomposition (10).

7 Conclusions

In this paper we formally characterize predatory pricing in a modern industry-dynamics framework. Our dynamic pricing model endogenizes competitive advantage and industry structure. It gives rise to an advantage-building motive and an advantage-denying motive under fairly general conditions that encompass learning-by-doing, network effects, switching costs, and much more. We separate a firm's incentives for pricing aggressively to eliminate competitors from the pursuit of efficiency by decomposing the equilibrium pricing condition.

We depart from the existing literature on predation in two key aspects. First, rather than aiming for an ironclad definition of predation, we use the decomposed advantage-building and advantage-denying motives to define a firm's predatory pricing incentives in a variety of ways. Our definitions of predatory incentives correspond to alternative implementations of the sacrifice test that is widely used in practice. Second, rather than argue for (or against) the merits of a particular definition of predation on conceptual grounds, we directly measure the impact of the predatory incentives on industry structure, conduct, and performance.

Our numerical analysis of a model of learning-by-doing shows that behavior resembling conventional notions of predatory pricing—aggressive pricing followed by reduced competition—arises routinely, thus casting doubt on the notion that predatory pricing is a myth and does not have to be taken seriously by antitrust authorities.

Aggressive equilibria involving predation-like behavior typically coexist with accommodative equilibria involving much less aggressive pricing. Multiple equilibria arise in our model if, for given demand and cost fundamentals, there is more than one set of firms' expectations regarding the value of continued play that is consistent with rational expectations about equilibrium behavior and industry dynamics. A conduct restriction that forces a firm to ignore the predatory incentives in setting its price can short-circuit the expectation that predatory pricing "works" and in this way eliminate some—or even all—of the aggressive equilibria.

The conduct restrictions associated with the stronger Definitions 1 and 2 eliminate many more equilibria than the conduct restrictions associated with the weaker Definitions 3 and 4. Along with the predation-like behavior in the aggressive equilibria, a fair amount of competition for the market is eliminated. Antitrust authorities may thus face a tension between making future consumers better off and making current consumers worse off.

There may nevertheless be sensible ways of disentangling efficiency-enhancing motives from predatory motives in pricing. The conduct restrictions associated with Definitions 2 and 4 come closest to being unambiguously beneficial for consumers and society at large in both the short run and the long run. These definitions emphasize advantage denying as the basis for predation: In contrast to aggressive pricing behavior that is primarily driven by the benefits from acquiring competitive advantage, aggressive pricing behavior that is primarily driven by the benefits from preventing the rival from acquiring competitive advantage or overcoming competitive disadvantage is predatory. Overall, the distinction between mere competition for efficiency on a learning curve and predatory pricing is closely related to the distinction between the advantage-building and advantage-denying motives that our decomposition isolates and measures.

References

Aguirregabiria, V. (2012), 'A method for implementing counterfactual experiments in models with multiple equilibria', *Economics Letters* **114**, 190–194.

Areeda, P. & Turner, F. (1975), 'Predatory pricing and related practices under Section 2 of the Sherman Act', *Harvard Law Review* **88**, 697–733.

Argote, L., Beckman, S. & Epple, D. (1990), 'The persistence and transfer of learning in an industrial setting', *Management Science* **36**(2), 140–154.

Baker, J. (1994), 'Predatory pricing after Brooke Group: An economic perspective', *Antitrust Law Journal* **62**, 585–603.

Basar, T. & Olsder, J. (1999), *Dynamic noncooperative game theory*, 2nd edn, Society for Industrial and Applied Mathematics, Philadelphia.

Benkard, L. (2000), 'Learning and forgetting: The dynamics of aircraft production', *American Economic Review* **90**(4), 1034–1054.

Bergemann, D. & Välimäki, J. (1996), 'Learning and strategic pricing', *Econometrica* **64**(5), 1125–1149.

Bergemann, D. & Välimäki, J. (2006), 'Dynamic price competition', *Journal of Economic Theory* **127**, 232–263.

Besanko, D., Doraszelski, U., Kryukov, Y. & Satterthwaite, M. (2010), 'Learning-by-doing, organizational forgetting, and industry dynamics', *Econometrica* **78**(2), 453–508.

Bolton, P., Brodley, J. & Riordan, M. (2000), 'Predatory pricing: Strategic theory and legal policy', *Georgetown Law Journal* **88**(8), 2239–2330.

Bolton, P. & Sharfstein, D. (1990), 'A theory of predation based on agency problems in financial contracting', *American Economic Review* **80**(1), 93–106.

Bork, R. (1978), *The antitrust paradox*, Free Press, New York.

Borkovsky, R., Doraszelski, U. & Kryukov, Y. (2010), 'A user's guide to solving dynamic stochastic games using the homotopy method', *Operations Research* **58**(4), 1116–1132.

Borkovsky, R., Doraszelski, U. & Kryukov, Y. (2012), 'A dynamic quality ladder model with entry and exit: Exploring the equilibrium correspondence using the homotopy method', *Quantitative Marketing and Economics* **10**(2), 197–229.

Cabral, L. (2011), 'Dynamic price competition with network effects', *Review of Economic Studies* **78**, 83–111.

Cabral, L. & Riordan, M. (1994), 'The learning curve, market dominance, and predatory pricing', *Econometrica* **62**(5), 1115–1140.

Cabral, L. & Riordan, M. (1997), 'The learning curve, predation, antitrust, and welfare', *Journal of Industrial Economics* **45**(2), 155–169.

Caves, R. & Porter, M. (1977), 'From entry barriers to mobility barriers: Conjectural decisions and contrived deterrence to new competition', *Quarterly Journal of Economics* **91**(2), 241–262.

Chen, J. (2011), How do switching costs affect market concentration and prices in network industries?, Working paper, UC Irvine, Irvine.

Chen, J., Doraszelski, U. & Harrington, J. (2009), 'Avoiding market dominance: Product compatibility in markets with network effects', *Rand Journal of Economics* **49**(3), 455–485.

Ching, A. (2010), 'A dynamic oligopoly structural model for the prescription drug market after patent expiration', *International Economic Review* **51**(4), 1175–1207.

Darr, E., Argote, L. & Epple, D. (1995), 'The acquisition, transfer, and depreciation of knowledge in service organizations: Productivity in franchises', *Management Science* **41**(11), 1750–1762.

Dasgupta, P. & Stiglitz, J. (1988), 'Learning-by-doing, market structure and industrial and trade policies', *Oxford Economics Papers* **40**(2), 246–268.

Developing World Industry and Technology, Inc. (1978), 'Sources of competitiveness in the Japanese color television and video tape recorder industry', Department of Labor, Washington.

Dick, A. (1991), 'Learning by doing and dumping in the semiconductor industry', *Journal of Law and Economics* **34**(1), 133–159.

Doraszelski, U. & Escobar, J. (2010), 'A theory of regular Markov perfect equilibria in dynamic stochastic games: Genericity, stability, and purification', *Theoretical Economics* **5**, 369–402.

Doraszelski, U. & Satterthwaite, M. (2010), 'Computable Markov-perfect industry dynamics', *Rand Journal of Economics* **41**(2), 215–243.

Dube, J., Hitsch, G. & Chintagunta, P. (2010), 'Tipping and concentration in markets with indirect network effects', *Journal of Marketing Research* **29**(2), 216–249.

Dube, J., Hitsch, G. & Rossi, P. (2009), 'Do switching costs make markets less competitive?', *Journal of Marketing Research* **46**, 435–445.

Dutton, J. & Thomas, A. (1984), 'Treating progress functions as a managerial opportunity', *Academy of Management Review* **9**(2), 235–247.

Edlin, A. (2002), 'Stopping above-cost predatory pricing', *Yale Law Journal* **111**, 235–257.

Edlin, A. (2010), Predatory pricing, Working paper, UC Berkeley, Berkeley.

Edlin, A. & Farrell, J. (2004), The American Airlines case: A chance to clarify predatory policy, *in* J. Kwoka & L. White, eds, 'The antitrust revolution: Economics, competition, and policy', Oxford University Press, New York, pp. 502–527.

Erdem, T., Imai, S. & Keane, M. (2003), 'Brand and quantity choice dynamics under price uncertainty', *Quantitative Marketing and Economics* **1**, 5–64.

Ericson, R. & Pakes, A. (1995), 'Markov-perfect industry dynamics: A framework for empirical work', *Review of Economic Studies* **62**, 53–82.

Farrell, J. & Katz, M. (2005), ‘Competition or predation? Consumer coordination, strategic pricing and price floors in network markets’, *Journal of Industrial Economics* **53**(2), 203–231.

Filar, J. & Vrieze, K. (1997), *Competitive Markov decision processes*, Springer, New York.

Flamm, K. (1993), ‘Semiconductor dependency and strategic trade policy’, *Brookings Papers on Economic Activity: Microeconomics* pp. 249–333.

Flamm, K. (1996), *Mismanaged trade: Strategic policy in the semiconductor industry*, Brookings Institution, Washington.

Fudenberg, D. & Tirole, J. (1983), ‘Learning-by-doing and market performance’, *Bell Journal of Economics* **14**(2), 522–530.

Fudenberg, D. & Tirole, J. (1986), ‘A signal jamming theory of predation’, *Rand Journal of Economics* **17**(4), 366–377.

Ghemawat, P. & Spence, M. (1985), ‘Learning curve spillovers and market performance’, *Quarterly Journal of Economics* **100**(Supplement), 839–852.

Goettler, R. & Gordon, B. (2011), ‘Does AMD spur Intel to innovate more?’, *Journal of Political Economy* **119**(6), 1141–1200.

Gowrisankaran, G. & Rysman, M. (2012), Dynamics of consumer demand for new durable goods, Working paper, University of Arizona, Tucson.

Habermeier, K. (1992), ‘The learning curve and competition’, *International Journal of Industrial Organization* **10**, 369–392.

Hendel, I. & Nevo, A. (2006), ‘Measuring the implications of sales and consumer inventory behavior’, *Econometrica* **74**(6), 1637–1674.

Jacobson, J. & Sher, S. (2006), ‘“No economic sense” makes no sense for exclusive dealing’, *Antitrust Law Journal* **73**, 779–801.

Jorgensen, S. & Zaccour, G. (2004), *Differential games in marketing*, Kluwer Academic Publishers, Dordrecht.

Jun, B. & Vives, X. (2004), ‘Strategic incentives in dynamic duopoly’, *Journal of Economic Theory* **116**, 249–281.

Kreps, D., Milgrom, P., Roberts, J. & Wilson, R. (1982), ‘Reputation and imperfect information’, *Journal of Economic Theory* **27**, 253–279.

Lapham, B. & Ware, R. (1994), ‘Markov puppy dogs and related animals’, *International Journal of Industrial Organization* **12**, 569–593.

Lee, R. & Pakes, A. (2009), ‘Multiple equilibria and selection by learning in an applied setting’, *Economics Letters* **104**, 13–16.

Melamed, D. (2006), 'Exclusive dealing agreements and other exclusionary conduct—Are there unifying principles?', *Antitrust Law Journal* **73**, 375–412.

Mitchell, M. & Skrzypacz, A. (2006), 'Network effects and long-run market shares', *Economic Theory* **29**(3), 621–648.

Newhouse, J. (1982), *The sporty game*, Alfred A. Knopf, New York.

Newhouse, J. (2002), *Boeing versus Airbus*, Alfred A. Knopf, New York.

Ordover, J. & Saloner, G. (1989), Predation, monopolization, and antitrust, *in* R. Schmalensee & R. Willig, eds, 'Handbook of Industrial Organization', Vol. 1, North-Holland, Amsterdam, pp. 537–596.

Ordover, J. & Willig, R. (1981), 'An economic definition of predation: Pricing and product innovation', *Yale Law Journal* **91**, 8–53.

Ross, D. (1986), 'Learning to dominate', *Journal of Industrial Economics* **34**(4), 337–353.

Salop, S. (2006), 'Exclusionary conduct, effect on consumers, and the flawed profit-sacrifice standard', *Antitrust Law Journal* **73**, 311–374.

Shafer, S., Nembhard, D. & Uzumeri, M. (2001), 'The effects of worker learning, forgetting, and heterogeneity on assembly line productivity', *Management Science* **47**(12), 1639–1653.

Shalem, R., Spiegel, Y. & Stahl, K. (2011), A dynamic model of predation, Working paper, Tel Aviv University, Tel Aviv.

Snider, C. (2008), Predatory incentives and predation policy: The American Airlines case, Working paper, University of Minnesota, Minneapolis.

Spence, M. (1981), 'The learning curve and competition', *Bell Journal of Economics* **12**(1), 49–70.

Stigler, G. (1950), 'Monopoly and oligopoly by merger', *American Economic Review* **40**, 23–34.

Thompson, P. (2007), 'How much did the Liberty shipbuilders forget?', *Management Science* **53**(6), 908–918.

Werden, G. (2006), 'Identifying exclusionary conduct under Section 2: The "no economic sense" test', *Antitrust Law Journal* **73**, 413–433.

Willig, R., Orszag, J. & Levin, G. (2009), An economic perspective on the antitrust case against Intel, Technical report, Compass Lexecon.

Yamamura, K. & Vandenberg, J. (1986), Japan's rapid-growth policy on trial: The television case, *in* G. Saxonhouse & K. Yamamura, eds, 'Law and trade issues of the Japanese economy: American and Japanese perspectives', University of Washington Press, Seattle, pp. 238–283.