DISCUSSION PAPER SERIES

No. 8708

THE ECONOMICS OF PREDATION: WHAT DRIVES PRICING WHEN THERE IS LEARNING-BY-DOING?

David Besanko, Ulrich Doraszelski and Yaroslav Kryukov

INDUSTRIAL ORGANIZATION

Centre for Economic Policy Research

www.cepr.org

THE ECONOMICS OF PREDATION: WHAT DRIVES PRICING WHEN THERE IS LEARNING-BY-DOING?

David Besanko, Northwestern University
Ulrich Doraszelski, University of Pennsylvania and CEPR
Yaroslav Kryukov, Carnegie Mellon University

ABSTRACT

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

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. We endogenize competitive advantage and industry structure through learning-by-doing.

We first show that predation-like behavior arises routinely in our 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. 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. We finally measure the impact of the predatory pricing incentives on industry structure, conduct, and performance. We show that forcing a firm to ignore these 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. Overall, the distinction between predatory pricing and pricing aggressively to pursue efficiency is closely related to the distinction between the advantage-building and advantage-denying motives that our decomposition of the equilibrium pricing condition isolates and measures.

David Besanko
Kellogg Graduate School of
Management
Northwestern University
2001 Sheridan Road
Evanston IL 60208
USA

Email: d-besanko
@kellogg.northwestern.edu

For further Discussion Papers by this author see:
www.cepr.org/pubs/new-dps/dplist.asp?authorid=116444

Ulrich Doraszelski
Wharton School
University of Pennsylvania
1405 Steinberg Hall-Dietrich Hall
3620 Locust Walk
Philadelphia, PA 19104-6372
USA

Email: ulrichd@wharton.upenn.edu

For further Discussion Papers by this author see:
www.cepr.org/pubs/new-dps/dplist.asp?authorid=162558

Yaroslav Kryukov
Tepper School of Business
Carnegie Mellon University
Pittsburgh, PA 15213
USA

Email: kryukov@cmu.edu

For further Discussion Papers by this author see:
www.cepr.org/pubs/new-dps/dplist.asp?authorid=166133

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. The empirical literature provides ample evidence that the marginal cost of production decreases with cumulative experience in a variety of industrial settings.[2] The resulting tension between predatory pricing and mere competition for efficiency on a learning curve was 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). 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).[3] More generally, contractual arrangements such as nonlinear pricing 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 obviously 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,

---

[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]See Wright (1936), Hirsch (1952), Alchian (1963), Dudley (1972), Zimmerman (1982), Lieberman (1984), Argote, Beckman & Epple (1990), Irwin & Klenow (1994), Jarmin (1994), Darr, Argote & Epple (1995), Benkard (2000), Thompson (2001), Thornton & Thompson (2001), Thompson (2007), and many others.

[3]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 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). 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 usefully isolate and measure a firm's predatory incentives by decomposing the equilibrium pricing condition. We ask three interrelated questions. First, when does predation-like behavior arise in a dynamic pricing model with endogenous competitive advantage and industry structure? Second, what drives pricing and, in particular, how can we separate predatory incentives for pricing aggressively from efficiency-enhancing incentives? 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.

When does predation-like behavior arise?   We develop a dynamic pricing model with endogenous competitive advantage and industry structure similar to the models of learning-by-doing in Cabral & Riordan (1994) and Besanko, Doraszelski, Kryukov & Satterthwaite (2010). 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 model forgoes these features and thus "stacks the deck" against predatory pricing. Our numerical analysis nevertheless reveals the widespread existence of Markov perfect 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 folks think so." 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

3

expectations about equilibrium behavior and industry dynamics.[4] Which of these equilibria is realized therefore depends on firms' expectations. Loosely speaking, if firms anticipate that predatory pricing may work, then they have an incentive to choose the extremely aggressive prices that, in turn, ensure that predatory pricing does work.

What drives pricing? We isolate a firm's predatory pricing incentive 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 equilibrium of a dynamic stochastic game. The cornerstone of our decomposition is the insight that the price that a firm sets 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, by pricing aggressively 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.*

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 motives. For example, one component of the advantage-building motive is 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.

Certain terms of our decomposition map into the existing economic definitions of predation including those due to Ordover & Willig (1981) and Cabral & Riordan (1997). Most important, 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

---

[4]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).

the price the firm has chosen (Edlin & Farrell 2004, p. 510). Our alternative characterizations correspond to different operationalizations of the everything-except-effects-on-competition profit function and identify clusters of terms in our decomposition as the firm's predatory pricing incentives.

What is the impact of firms' 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 the 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 a firm to ignore the predatory pricing 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 the less severe conduct restrictions, including those inspired by Ordover & Willig (1981) and Cabral & Riordan (1997), have on average a small impact on industry structure, conduct, and performance. The more severe conduct restrictions have a large impact. This large impact stems from the fact that these restrictions eliminate equilibria with predation-like behavior, thereby paving the way for lower concentration, lower prices, and higher consumer and total surplus in the long run. Even the more severe conduct restrictions, in contrast, 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 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 the ones 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 the distinction is closely related to the distinction 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 that compete in an industry characterized by learning-by-doing. At any point in time, firm $n \in \{1, 2\}$ is described by its state $e_n \in \{0, 1, \ldots, M\}$. A firm can be either an incumbent firm that actively produces or a potential entrant. State $e_n = 0$ indicates a potential entrant. States $e_n \in \{1, \ldots, M\}$ indicate the cumulative experience or stock of know-how of an incumbent firm. By making a sale in the current period, an incumbent firm can add to its stock of know-how and, through learning-by-doing, lower its production cost in the subsequent period. Thus, competitive advantage is determined endogenously in our model. At any point in time, 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. As illustrated in Figure 1, during the price-setting phase the industry's state changes from $\mathbf{e}$ to $\mathbf{e}'$ depending on the outcome of pricing game between the incumbent firms. During the exit-entry phase, the state then changes from $\mathbf{e}'$ to $\mathbf{e}''$ depending on the exit decisions of the incumbent firm(s) and the entry decisions of the potential entrant(s). The state at the end of the current period finally becomes the state at the beginning of the subsequent period. 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 potential entrant to enter the industry.

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

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 $\mathbf{p} = (p_1, p_2)$ or an "outside good" at an exogenously given price p_0. The probability that firm n makes the sale is given by the logit specification

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

where $\sigma > 0$ is a scale parameter that governs the degree of product differentiation. As $\sigma \to 0$, goods become homogeneous. If firm n is a potential entrant, then we set its price to infinity so that $D_n(\mathbf{p}) = 0$.

Learning-by-doing and production cost. Incumbent firm n's marginal cost of production $c(e_n)$ depends on its stock of know-how through a learning curve with a progress ratio
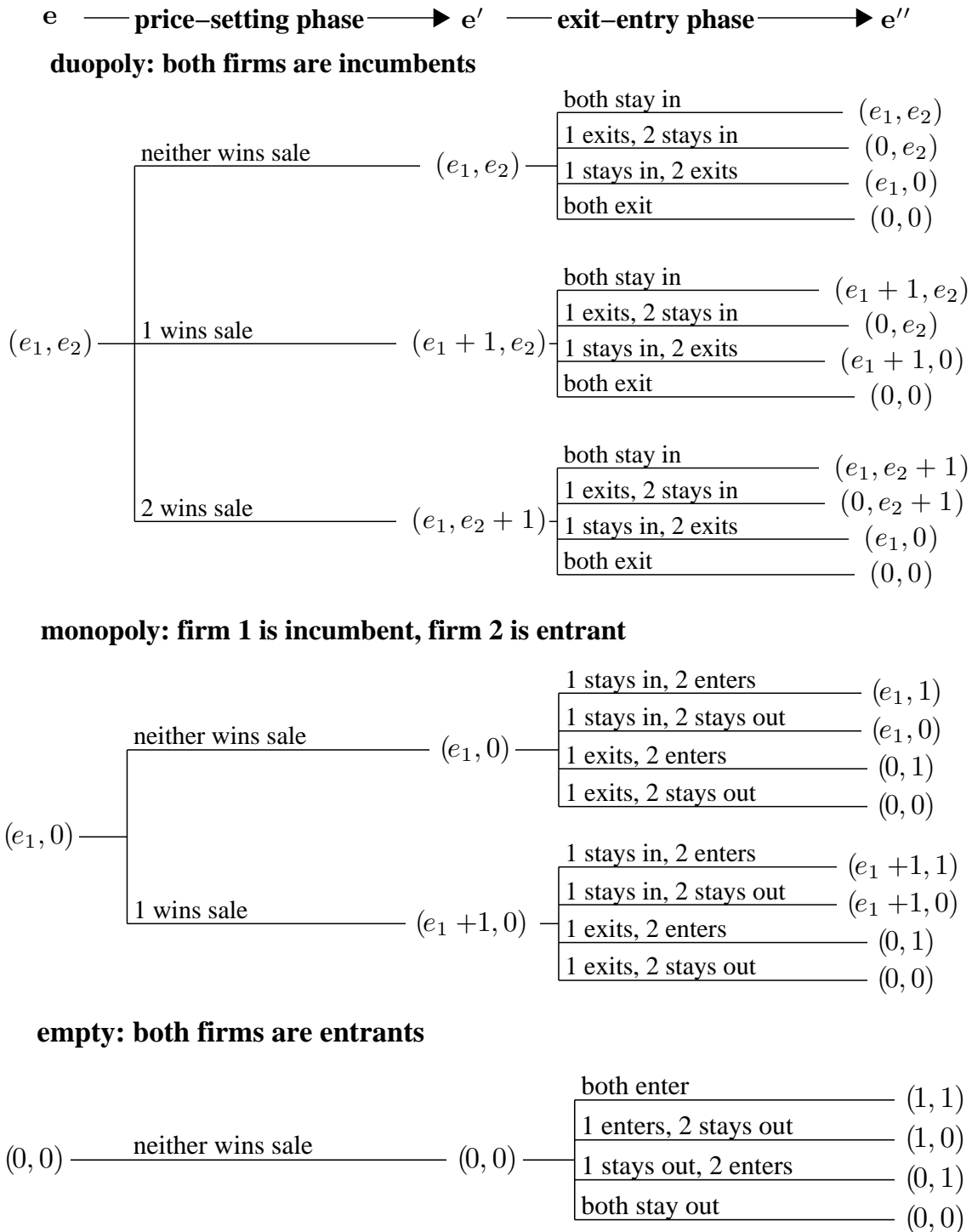
Figure 1: Possible state-to-state transitions.

$\rho \in [0, 1]$:

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

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. The marginal cost for a firm without prior experience, $c(1)$, is $\kappa > 0$. The firm can add to its stock of know-how by making a sale.[5] Once the firm reaches state m, the learning curve "bottoms out" and there are no further experience-based cost reductions. Following Cabral & Riordan (1994), we refer to an incumbent firm in state $e_n \geq m$ as a *mature firm* and an industry in state $\mathbf{e} \geq (m, m)$ as a *mature duopoly*. In the same spirit, we refer to an incumbent firm in state $e_n = 1$ as an *emerging firm* and an industry in state $(1, 1)$ as an *emerging duopoly*.

Scrap value and setup cost. 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.

2.1 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 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 $\phi_n(\mathbf{e}') = E_X[\phi_n(\mathbf{e}', X_n)]$ is the probability of exiting; if $e_n' = 0$ so that firm n is an entrant, then $\phi_n(\mathbf{e}') = E_S[\phi_n(\mathbf{e}', S_n)]$ 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

---

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

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

$$U_1(\mathbf{e}') = E_X \left[\max \left\{ \widehat{X}_1(\mathbf{e}'), X_1 \right\} \right]$$
$$= (1 - \phi_1(\mathbf{e}'))\beta \left[V_1(\mathbf{e}')(1 - \phi_2(\mathbf{e}')) + V_1(e_1', 0)\phi_2(\mathbf{e}') \right] + \phi_1(\mathbf{e}')E_X \left[X_1 | X_1 \geq \widehat{X}_1(\mathbf{e}') \right], \quad (1)$$

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 (without prior experience) 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

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

9

where $E_S\left[S_1 | S_1 \le \widehat{S}_1(\mathbf{e}')\right]$ is the expectation of the setup cost conditional on entering the industry.[6]

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

$$V_1(\mathbf{e}) = \max_{p_1} (p_1 - c(e_1))D_1(p_1, p_2(\mathbf{e})) + D_0(p_1, p_2(\mathbf{e}))U_1(\mathbf{e})$$

$$+ D_1(p_1, p_2(\mathbf{e}))U_1(e_1 + 1, e_2) + D_2(p_1, p_2(\mathbf{e}))U_1(e_1, e_2 + 1). \tag{3}$$

Because $D_0(\mathbf{p}) = 1 - D_1(\mathbf{p}) - D_2(\mathbf{p})$, 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

$$\Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e}) = (p_1 - c(e_1))D_1(p_1, p_2(\mathbf{e})) + U_1(\mathbf{e})$$

$$+ D_1(p_1, p_2(\mathbf{e})) \left[U_1(e_1 + 1, e_2) - U_1(\mathbf{e})\right] - D_2(p_1, p_2(\mathbf{e})) \left[U_1(\mathbf{e}) - U_1(e_1, e_2 + 1)\right] \tag{4}$$

is the long-run profit of incumbent firm 1. 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 the first-order condition

$$mr_1(p_1, p_2(\mathbf{e})) - c(e_1) + \left[U_1(e_1 + 1, e_2) - U_1(\mathbf{e})\right] + \Upsilon(p_2(\mathbf{e})) \left[U_1(\mathbf{e}) - U_1(e_1, e_2 + 1)\right] = 0, \tag{5}$$

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*,[7] and $\Upsilon(p_2(\mathbf{e})) = \frac{D_2(p_1, p_2(\mathbf{e}))}{1 - D_1(p_1, p_2(\mathbf{e}))} = \frac{\exp\left(-\frac{p_2(\mathbf{e})}{\sigma}\right)}{\exp\left(-\frac{p_0}{\sigma}\right) + \exp\left(-\frac{p_2(\mathbf{e})}{\sigma}\right)}$ is the probability of firm 2 making a sale conditional on firm 1 not making a sale.

Equations (4) and (5) show that, besides short-run profit $(p_1 - c(e_1))D_1(p_1, p_2(\mathbf{e}))$, the price that an incumbent firm sets reflects two distinct goals. 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 $[U_1(e_1 + 1, e_2) - U_1(\mathbf{e})]$, which we call the *advantage-building motive*. 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 $[U_1(\mathbf{e}) - U_1(e_1, e_2 + 1)]$, which we call the *advantage-denying motive*.[8] Because it encompasses the short run and the

---

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

[7] See the Online Appendix for details.

[8] With quantity instead of price setting an advantage-denying motive does not arise because the firm's quantity has no direct effect on its rival's quantity. However, if producing additional quantity requires installing additional durable capacity, then an advantage-denying motive may arise if the firm's quantity and

long run, the pricing decision in our model is akin to an investment decision.

Because $mr_1(p_1, p_2(\mathbf{e}))$ is strictly increasing in p_1, equation (5) 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.[9] If these motives are sufficiently large, price may be below marginal cost.

2.2 Equilibrium

Because our demand and cost specification is symmetric, we restrict ourselves to symmetric Markov perfect equilibria. 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.

Existence of a symmetric Markov perfect equilibrium in pure strategies 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.

3 Equilibrium behavior and industry dynamics

We use the homotopy method in Besanko et al. (2010) to compute the Markov perfect equilibria of our dynamic stochastic game. Although it cannot be guaranteed to find all equilibria, the advantage of this method is its ability to search for multiple equilibria in a systematic fashion.[10]

Let $(\mathbf{V}_1, \mathbf{U}_1, \mathbf{p}_1, \boldsymbol{\phi}_1)$ denote the vector of values and policies that are determined by the model, $\boldsymbol{\Omega}$ the vector of parameters of the model, and $\mathbf{H}(\mathbf{V}_1, \mathbf{U}_1, \mathbf{p}_1, \boldsymbol{\phi}_1; \boldsymbol{\Omega}) = \mathbf{0}$ the system of equations (Bellman equations and optimality conditions) that defines an equilibrium. The

---

[9] hence capacity makes it less attractive for its rival to produce in the future, thereby delaying its movement down the learning curve.

[9] 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.

[10] See Borkovsky, Doraszelski & Kryukov (2010) 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.

equilibrium correspondence mapping parameters into values and policies is

$$\mathbf{H}^{-1}(\mathbf{\Omega}) = \{(\mathbf{V}_1, \mathbf{U}_1, \mathbf{p}_1, \boldsymbol{\phi}_1) | \mathbf{H}(\mathbf{V}_1, \mathbf{U}_1, \mathbf{p}_1, \boldsymbol{\phi}_1; \mathbf{\Omega}) = \mathbf{0}\}.$$

The equilibrium correspondence is a potentially complicated set of multidimensional surfaces. To explore the equilibrium correspondence, we compute slices of it by varying one parameter of the model, such as the progress ratio ρ. A slice of the equilibrium correspondence along ρ, denoted as $\mathbf{H}^{-1}(\rho)$ in what follows, consists of a finite number of differentiable paths through $(\mathbf{V}_1, \mathbf{U}_1, \mathbf{p}_1, \boldsymbol{\phi}_1, \rho)$ space. The homotopy algorithm traces out a path by numerically solving the differential equation that describes it.

Baseline parameterization. To compute a slice of the equilibrium correspondence, we hold all but one parameter 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 has a reasonable shot at gaining traction and a mature firm enjoys a modest degree of market power. Profit opportunities are reasonably good: in a mature duopoly the annual rate of return on the investment of setup costs is about 22% at static Nash equilibrium prices.

12

3.1 Predation-like behavior

To illustrate the types of behavior that can emerge in our 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).[11]

The upper panels of Figure 2 exemplify what we call a *trenchy 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 in order to gain a competitive advantage. 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 $e_1 \in \{2, \ldots, 30\}$.[12] 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 $\phi_2(1, e_2) = 0.22$ for $e_2 \in \{2, \ldots, 30\}$ 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.[13] This sequence of events resembles conventional 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 a *flat equilibrium*. There is a shallow well in state $(1,1)$ with $p_1(1,1) = 5.05$ as the lower left panel shows. Absent 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.

3.2 Industry structure, conduct, and performance

We succinctly describe an equilibrium by the industry structure, conduct, and performance that it implies. First, we use the policy functions $\mathbf{p}_1$ and $\boldsymbol{\phi}_1$ 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

---

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

[12]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 $e_2 \in \{2, \ldots, 30\}$.

[13]In this particular equilibrium, $\phi_2(e_1, 0) = 1.00$ for $e_1 \in \{2, \ldots, 30\}$, so that a potential entrant does not enter if the incumbent firm has moved down from the top of its learning curve.
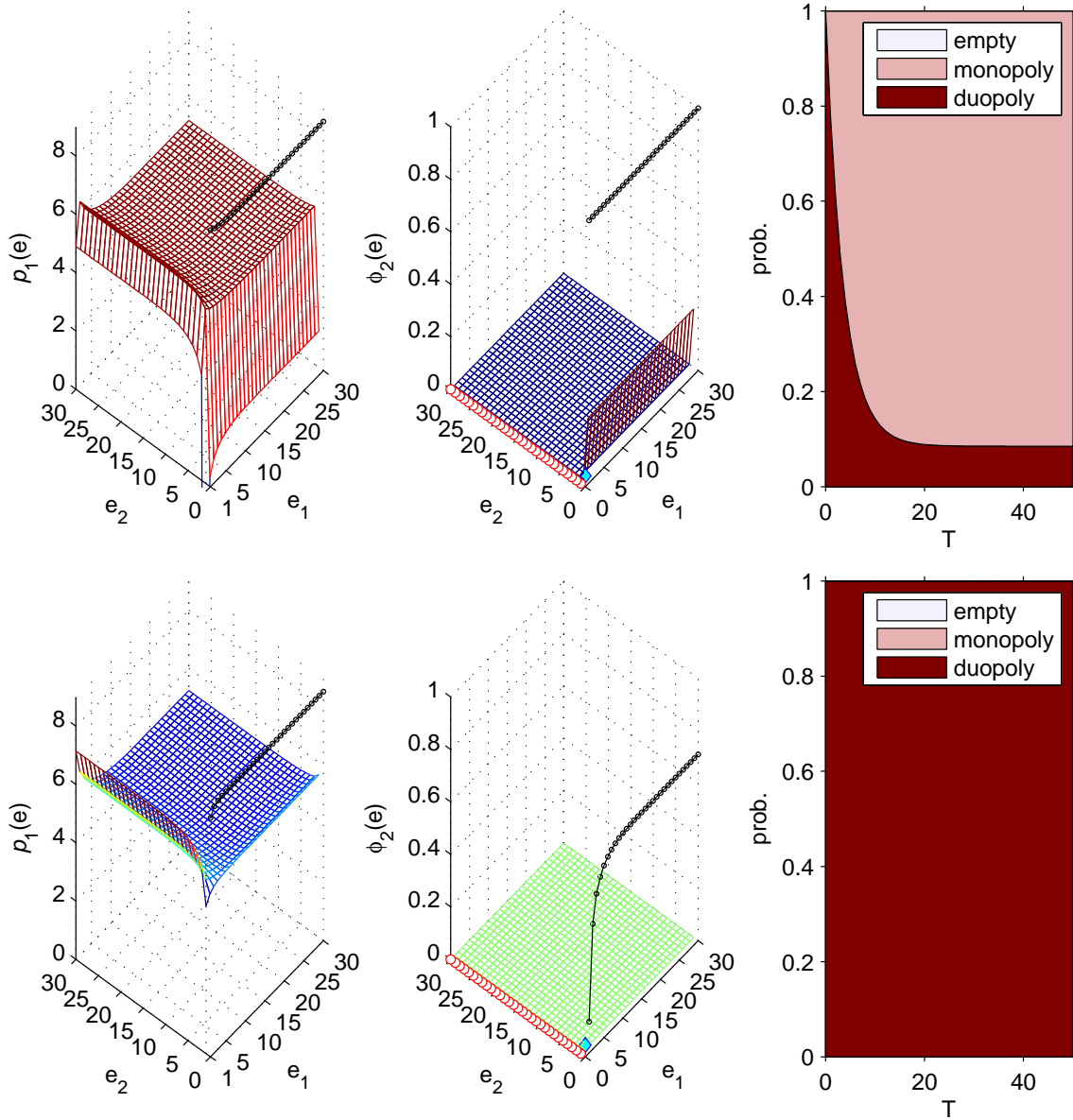
Figure 2: Pricing decision of firm 1 (left panels), non-operating probability of firm 2 (middle panels), and time path of probability distribution over industry structures, starting from $\mathbf{e} = (1, 1)$ at $T = 0$ (right panels). Trenchy (upper panels) and flat (lower panels) equilibria.

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 $\boldsymbol{\mu}^\infty$.[14] Finally, we use the transient distributions to compute six metrics of industry structure, conduct, and performance.

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:*

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

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

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

Performance. *Expected long-run consumer surplus:*

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

where consumer surplus in state $\mathbf{e}$ is

$$CS(\mathbf{e}) = \sigma \log \left\{ \exp\left(\frac{-p_0}{\sigma}\right) + \sum_{n=1}^2 \exp\left(\frac{-p_n(\mathbf{e})}{\sigma}\right) \right\}.$$

---

[14]We use the transient distribution in period 1000 rather than the limiting (or ergodic) distribution to capture long-run dynamics because there may be several closed communicating classes. The transient distribution accounts for the probability of reaching any one of them, starting from state $(1, 1)$ in period 0.

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 $\mathbf{e}$.[15]

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 2 illustrates industry structure, conduct, and performance for the equilibria in Section 3.1. The Herfindahl index reflects that the industry is substantially more likely to be monopolized under the trenchy equilibrium than under the flat equilibrium. In the entrenched monopoly prices are higher. Finally, consumer and total surplus are lower under the trenchy equilibrium than under the flat equilibrium. The difference between the equilibria is smaller for CS^{NPV} than for CS^{∞} because the former metric accounts for the competition for the market in the short run that manifests itself in the deep well and trench of the trenchy equilibrium and mitigates the lack of competition in the market in the long run.

3.3   Equilibrium correspondence

Progress ratio.   The upper panel of Figure 3 illustrates the equilibrium correspondence by plotting HHI^{∞} against ρ.[16] 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

---

[15]See the Online Appendix for details.
[16]See the Online Appendix for additional figures and tables.

metric	trenchy equilibrium	flat 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 2: Industry structure, conduct, and performance. Trenchy and flat equilibria.

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 flat. The industry evolves into a mature duopoly with $HHI^\infty = 0.5$ as in the flat equilibrium in Section 3.1. 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 trenchy. As in the trenchy equilibrium in Section 3.1, the industry evolves into an entrenched monopoly with $HHI^\infty \approx 1.0$.[17]

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 $\sigma = 3$.[18]

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 flat and the industry evolves into a mature duopoly. The equilibria on the upper fold of MP are trenchy and the industry evolves into an entrenched monopoly.

---

[17]Trenchy 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.

[18]Our 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.
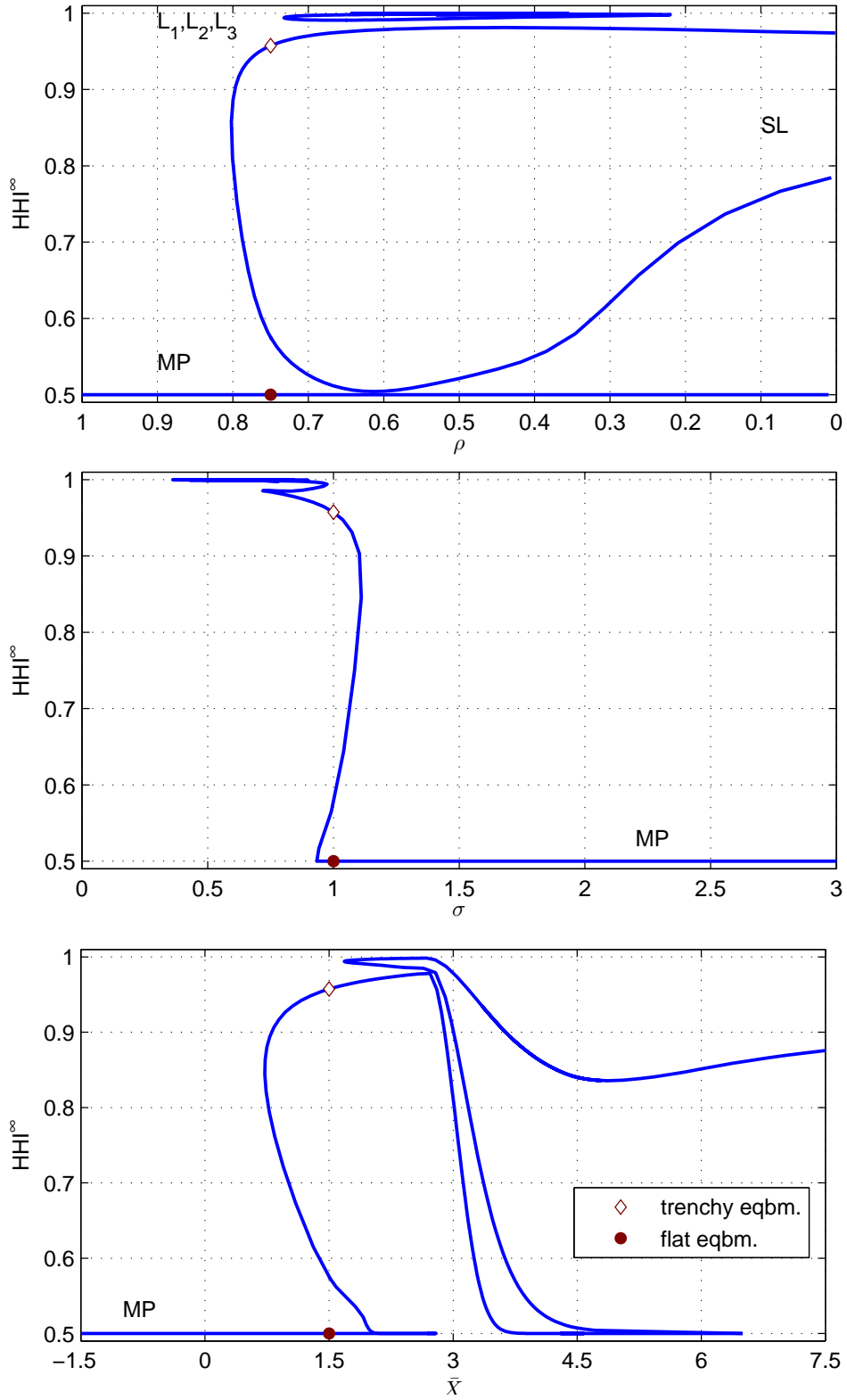
Figure 3: Expected long-run Herfindahl index. Equilibrium correspondence: slice along $\rho \in [0,1]$ (upper panel), $\sigma \in [0.3, 3]$ (middle panel), and $\overline{X} \in [-1.5, 7.5]$ (lower panel).

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.[19]

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 flat and the industry evolves into a mature duopoly. The equilibria on the upper fold of MP are trenchy and the industry evolves into an entrenched monopoly.

Overall, many equilibria are trenchy. In these equilibria predation-like behavior arises. Generally speaking, trenchy equilibria are associated with a lower progress ratio ρ, a lower degree of product differentiation σ, and a higher expected scrap value $\overline{X}$. Multiplicity of equilibria is the norm rather than the exception, and trenchy equilibria typically coexist with flat equilibria.

4 Isolating predatory incentives

To isolate a firm's predatory pricing incentives, we write the equilibrium pricing condition (5) as

$$mr_1(p_1(\mathbf{e}), p_2(\mathbf{e})) - c(e_1) + \left[\sum_{k=1}^{5} \Gamma_1^k(\mathbf{e})\right] + \Upsilon(p_2(\mathbf{e})) \left[\sum_{k=1}^{4} \Theta_1^k(\mathbf{e})\right] = 0. \tag{6}$$

$\sum_{k=1}^{5} \Gamma_1^k(\mathbf{e})$ decomposes the advantage-building motive $[U_1(e_1 + 1, e_2) - U_1(\mathbf{e})]$ and $\sum_{k=1}^{4} \Theta_1^k(\mathbf{e})$ the advantage-denying motive $[U_1(\mathbf{e}) - U_1(e_1, e_2 + 1)]$. Each term in this decomposition has a distinct economic interpretation that we describe below.[20]

Advantage building. The decomposed advantage-building motives summarized in Table 3 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.

Baseline advantage-building motive:

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

---

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

[20] The decomposition applies to an industry with two incumbent firms in state $\mathbf{e} \geq (1, 1)$ and we focus on firm 1. We use equation (1) to express $U_1(\mathbf{e})$ in terms of $V_1(\mathbf{e})$. Because the terms $\Gamma_1^k(\mathbf{e})$ 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 motives	if the firm wins the sale and moves further down its learning curve, then the firm...
$\Gamma_1^1(\mathbf{e})$ baseline	...improves its competitive position within the duopoly
$\Gamma_1^2(\mathbf{e})$ exit	...increases its rival's exit probability
$\Gamma_1^3(\mathbf{e})$ survival	...decreases its exit probability
$\Gamma_1^4(\mathbf{e})$ scrap value	...increases its expected scrap value
$\Gamma_1^5(\mathbf{e})$ market structure	...gains from an improved competitive position as a monopolist versus as a duopolist

Table 3: Decomposed advantage-building motives.

The baseline advantage-building motive is the marginal benefit to the firm from an improvement in its competitive position, assuming that its rival does not exit in the current period. It captures both the lower marginal cost and any future advantages (winning the sale, exit of rival, etc.) that stem from this lower cost.

Advantage-building/exit motive:

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

The advantage-building/exit motive is the marginal benefit to the firm from increasing its rival's exit probability from $\phi_2(\mathbf{e})$ to $\phi_2(e_1 + 1, e_2)$.

Advantage-building/survival motive:

$$\Gamma_1^3(\mathbf{e}) = [\phi_1(\mathbf{e}) - \phi_1(e_1 + 1, e_2)] \beta \left[\phi_2(e_1 + 1, e_2)V_1(e_1 + 1, 0) + (1 - \phi_2(e_1 + 1, e_2))V_1(e_1 + 1, e_2)\right].$$

The advantage-building/survival motive is the marginal benefit to the firm from decreasing its exit probability from $\phi_1(\mathbf{e})$ to $\phi_1(e_1 + 1, e_2)$.

Advantage-building/scrap value motive:

$$\Gamma_1^4(\mathbf{e}) = \phi_1(e_1 + 1, e_2)E_X \left[X_1|X_1 \geq \widehat{X}_1(e_1 + 1, e_2)\right] - \phi_1(\mathbf{e})E_X \left[X_1|X_1 \geq \widehat{X}_1(\mathbf{e})\right].$$

The advantage-building/scrap value motive is the marginal benefit to the firm from increasing its scrap value in expectation from $\phi_1(\mathbf{e})E_X \left[X_1|X_1 \geq \widehat{X}_1(\mathbf{e})\right]$ to $\phi_1(e_1+1, e_2)E_X \left[X_1|X_1 \geq \widehat{X}_1(e_1 + 1, e_2)\right]$.

Advantage-building/market structure motive:

$$\Gamma_1^5(\mathbf{e}) = (1 - \phi_1(\mathbf{e}))\phi_2(\mathbf{e})\beta \left\{[V_1(e_1 + 1, 0) - V_1(e_1, 0)] - [V_1(e_1 + 1, e_2) - V_1(\mathbf{e})]\right\}.$$

The advantage-building/market structure motive is the marginal benefit to the firm from an improvement in its competitive position as a monopolist versus as a duopolist.

advantage-denying motives	if the firm wins the sale and prevents its rival from moving further down its learning curve, then the firm ...
$\Theta_1^1(\mathbf{e})$ baseline	...prevents its rival from improving its competitive position within the duopoly
$\Theta_1^2(\mathbf{e})$ exit	...prevents its rival's exit probability from decreasing
$\Theta_1^3(\mathbf{e})$ survival	...prevents its exit probability from increasing
$\Theta_1^4(\mathbf{e})$ scrap value	...prevents its expected scrap value from decreasing

Table 4: Decomposed advantage-denying motives.

Advantage denying.   The decomposed advantage-denying motives summarized in Table 3 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.

Baseline advantage-denying motive:

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

The baseline advantage-denying motive is the marginal benefit to the firm from preventing an improvement in its rival's competitive position, assuming its rival does not exit in the current period.

Advantage-denying/exit motive:

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

The advantage-denying/exit motive is the marginal benefit to the firm from preventing its rival's exit probability from decreasing from $\phi_2(\mathbf{e})$ to $\phi_2(e_1, e_2 + 1)$.

Advantage-denying/survival motive:

$$\Theta_1^3(\mathbf{e}) = [\phi_1(e_1, e_2 + 1) - \phi_1(\mathbf{e})]\beta\left[\phi_2(e_1, e_2 + 1)V_1(e_1, 0) + (1 - \phi_2(e_1, e_2 + 1))V_1(e_1, e_2 + 1)\right].$$

The advantage-denying/survival motive is the marginal benefit to the firm from preventing its exit probability from increasing from $\phi_1(\mathbf{e})$ to $\phi_1(e_1, e_2 + 1)$.

Advantage-denying/scrap value motive:

$$\Theta_1^4(\mathbf{e}) = \phi_1(\mathbf{e})E_X\left[X_1|X_1 \geq \widehat{X}_1(\mathbf{e})\right] - \phi_1(e_1, e_2 + 1)E_X\left[X_1|X_1 \geq \widehat{X}_1(e_1, e_2 + 1)\right].$$

The advantage-denying/scrap value motive is the marginal benefit to the firm from pre-

venting its scrap value from decreasing in expectation from $\phi_1(\mathbf{e})E_X\left[X_1|X_1 \geq \widehat{X}_1(\mathbf{e})\right]$ to $\phi_1(e_1, e_2+1)E_X\left[X_1|X_1 \geq \widehat{X}_1(e_1, e_2+1)\right]$.

The upper panels of Table 5 illustrate the decomposition (6) for the trenchy equilibrium in Section 3.1 for a set of states where firm 2 is emerging. The competition for the market in state $(1,1)$ is driven mostly by the baseline advantage-building motive $\Gamma_1^1(1,1)$ and the advantage-building/exit motive $\Gamma_1^2(1,1)$. In contrast, the competition for the market in the trench in states $(e_1, 1)$ for $e_1 \in \{2, \ldots, 30\}$ 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 arises not because by becoming more efficient the leader increases the probability that the follower exits the industry but 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. The decomposed advantage-denying motives remain in effect in states $(e_1, 1)$ for $e_1 \in \{16, \ldots, 30\}$ where the leader has exhausted all learning economies.

As can be seen in lower panels of Table 5 for a set of states where firm 2 has already gained some traction neither the advantage-building nor the advantage-denying motives are very large. To the extent that the price is below the static optimum this is due mostly to the baseline advantage-building motive $\Gamma_1^1(e_1, 4)$ for $e_1 \in \{1, \ldots, 30\}$.

4.1 Definitions of predation in the literature

To serve as a point of departure for defining predatory incentives, we show how our decomposition (6) relates to economic definitions of predation formulated in the existing literature.

Cabral & Riordan (1997). Cabral & Riordan (1997) 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). In the context of predatory pricing, it is natural to interpret "a different action" as a higher price $\widetilde{p}_1 > p_1(\mathbf{e})$. To port the Cabral & Riordan definition from their two-period model 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. Finally, we interpret "the different action would be more profitable" in the spirit of Markov perfection to mean that by a setting a higher price in the current period but returning to equilibrium play from the subsequent period onward, the firm can affect the evolution of the

Table 5 (rotated):

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

Table 5: Decomposed advantage-building and advantage-denying motives and definitions of predatory incentives. √√ means that the weighted sum of the predatory incentives is larger than 0.5, √ that the weighted sum is between 0 and 0.5, and a blank that the weighted sum smaller or equal to 0. Trenchy equilibrium.

state to increase its expected NPV if it believed, counterfactually, that the probability that the rival exits the industry in the current period is fixed at $\phi_2(\mathbf{e})$.

With these interpretations, Proposition 1 formalizes the relationship between the Cabral & Riordan definition of predation and our decomposition:

Proposition 1 *Consider an industry with two incumbent firms in state $\mathbf{e} \geq (1,1)$. Assume $\phi_1(\mathbf{e}) < 1$, $V_1(e_1, 0) > V_1(\mathbf{e})$, and $V_1(e_1 + 1, 0) > V_1(e_1 + 1, e_2)$, i.e., exit by the firm is less than certain and the expected NPV of a monopolist exceeds that of a duopolist. (a) If $\Gamma_1^2(\mathbf{e}) \geq 0$ and $\Theta_1^2(\mathbf{e}) \geq 0$, with at least one of these inequalities being strict, and*

$$\Gamma_1^2(\mathbf{e}) + \left[\Gamma_1^3(\mathbf{e}) - \Gamma_1^3(\mathbf{e}) \big|_{\phi_2 = \phi_2(\mathbf{e})} \right]$$
$$+ \Upsilon(p_2(\mathbf{e})) \left[\left[\Theta_1^1(\mathbf{e}) - \Theta_1^1(\mathbf{e}) \big|_{\phi_2 = \phi_2(\mathbf{e})} \right] + \Theta_1^2(\mathbf{e}) + \left[\Theta_1^3(\mathbf{e}) - \Theta_1^3(\mathbf{e}) \big|_{\phi_2 = \phi_2(\mathbf{e})} \right] \right] > 0, \quad (7)$$

then the firm's equilibrium price $p_1(\mathbf{e})$ in state $\mathbf{e}$ is predatory according to the Cabral & Riordan (1997) definition.[21] *(b) If $p_1(\mathbf{e})$ is predatory according to the Cabral & Riordan definition, then $\Gamma_1^2(\mathbf{e}) > 0$ or $\Theta_1^2(\mathbf{e}) > 0$ and inequality (7) holds.*

Proof. See the Appendix. ■

Ordover & Willig (1981). 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). As Cabral & Riordan (1997) observe, the premise in the Ordover & Willig definition is that the rival is viable with certainty.[22] We have:

Proposition 2 *Consider an industry with two incumbent firms in state $\mathbf{e} \geq (1,1)$. Assume $\phi_1(\mathbf{e}) < 1$, $V_1(e_1, 0) > V_1(\mathbf{e})$, and $V_1(e_1 + 1, 0) > V_1(e_1 + 1, e_2)$, i.e., exit by the firm is less than certain and the expected NPV of a monopolist exceeds that of a duopolist. (a) If $\Gamma_1^2(\mathbf{e}) \geq 0$ and $\Theta_1^2(\mathbf{e}) \geq 0$, with at least one of these inequalities being strict, and*

$$\Gamma_1^2(\mathbf{e}) + \left[\Gamma_1^3(\mathbf{e}) - \Gamma_1^3(\mathbf{e}) \big|_{\phi_2 = 0} \right] + \Gamma_1^5(\mathbf{e})$$
$$+ \Upsilon(p_2(\mathbf{e})) \left[\left[\Theta_1^1(\mathbf{e}) - \Theta_1^1(\mathbf{e}) \big|_{\phi_2 = 0} \right] + \Theta_1^2(\mathbf{e}) + \left[\Theta_1^3(\mathbf{e}) - \Theta_1^3(\mathbf{e}) \big|_{\phi_2 = 0} \right] \right] > 0, \quad (8)$$

---

[21]The notation $\cdot|_{\phi_2 = \phi_2(\mathbf{e})}$ means that we evaluate the relevant term under the assumption that $\phi_2(\mathbf{e}) = \phi_2(e_1 + 1, e_2) = \phi_2(e_1, e_2 + 1)$ so that the probability that the rival exits the industry in the current period is indeed fixed at $\phi_2(\mathbf{e})$.

[22]This observation indeed motivates Cabral & Riordan (1997) to propose their own definition: "Is the appropriate counterfactual hypothesis that firm B remain viable with probability one? We don't think so. Taking into account that firm B exits for exogenous reasons (i.e. a high realization of [the scrap value]) hardly means that firm A intends to drive firm B from the market" (p. 160).

then the firm's equilibrium price $p_1(\mathbf{e})$ in state $\mathbf{e}$ is predatory according to the Ordover & Willig (1981) definition. (b) If $p_1(\mathbf{e})$ is predatory according to the Ordover & Willig definition, then $\Gamma_1^2(\mathbf{e}) > 0$ or $\Theta_1^2(\mathbf{e}) > 0$ and inequality (8) holds.

Proof. Omitted as it follows the same logic as the proof of Proposition 1. ∎

4.2   Definitions of predatory incentives

Propositions 1 and 2 hint at how our decomposition can be used to isolate a firm's predatory pricing 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).[23]

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). The Ordover & Willig (1981) and Cabral & Riordan (1997) definitions of predation can be thought of as a sacrifice test as the underlying counterfactuals are particular operationalizations of "everything except effects on competition."

To formalize the sacrifice test and relate it to our model, we partition the profit function $\Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})$ 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. For a variety of plausible specifications of the EEEC profit function, the associated predatory incentives $\frac{\partial \Omega_1(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})}{\partial(-p_1)}$

---

[23]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).

can be characterized using our decomposition (6).

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 $\Pi_1^0(p_1, p_2(\mathbf{e}), \mathbf{e}) = (p_1 - c_1(e_1))D_1(p_1, p_2(\mathbf{e}))$ to be short-run profit, it follows from our decomposition (6) and 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 $\sum_{k=1}^{5} \Gamma_1^k(\mathbf{e}) + \Upsilon(p_2(\mathbf{e})) \left[\sum_{k=1}^{4} \Theta_1^k(\mathbf{e})\right] > 0$. Our first definition of predatory incentives thus comprises all decomposed advantage-building and advantage-denying motives:

Definition 1 (short-run profit) *The firm's predatory pricing incentives are* $\sum_{k=1}^{5} \Gamma_1^k(\mathbf{e}) + \Upsilon(p_2(\mathbf{e})) \left[\sum_{k=1}^{4} \Theta_1^k(\mathbf{e})\right]$.

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 $c(e_1)$.[24] 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 denies the efficiency gains from pricing aggressively in order to move down the learning curve. Instead, the firm should 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. Hence, $\Pi_1^0(p_1, p_2(\mathbf{e}), \mathbf{e}) = (p_1 - c(e_1))D_1(p_1, p_2(\mathbf{e})) + U_1(\mathbf{e}) + D_1(p_1, p_2(\mathbf{e})) [U_1(e_1 + 1, e_2) - U_1(\mathbf{e})]$, where 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. It follows from our decomposition (6) and 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 $\sum_{k=1}^{4} \Theta_1^k(\mathbf{e}) > 0$. Our second definition of predatory incentives thus comprises all decomposed advantage-denying motives:

Definition 2 (dynamic competitive vacuum) *The firm's predatory pricing incentives are* $\sum_{k=1}^{4} \Theta_1^k(\mathbf{e})$.

---

[24]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.

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 $c(e_1) - \left[\sum_{k=1}^{5} \Gamma_1^k(\mathbf{e})\right]$. Note that a lower bound on long-run marginal cost $c(e_1) - \left[\sum_{k=1}^{5} \Gamma_1^k(\mathbf{e})\right]$ 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 $mr_1(p_1(\mathbf{e}), p_2(\mathbf{e})) < c(e_1) - \left[\sum_{k=1}^{5} \Gamma_1^k(\mathbf{e})\right]$. This provides a one-way test for sacrifice that can be operationalized given some basic knowledge of demand and cost.

Rival exit in current period. According to Definitions 1 and 2 the marginal return to a price cut in the current period may be positive not because the rival exits the industry in the current period but because the rival exits in some future period. The predatory incentives therefore extend to the possibility that the rival exits in some future period because the firm improves its competitive position in the current period. The economic definitions of predation formulated in the existing literature instead focus more narrowly on the immediate impact of a price cut on rival exit. Our remaining definitions of the firm's predatory pricing incentives embrace this focus.

The Ordover & Willig definition of predation sets $\Pi_1^0(p_1, p_2(\mathbf{e}), \mathbf{e}) = \Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=0}$ so that the EEEC profit function is the profit function under the counterfactual presumption that the probability that the rival exits the industry in the current period is zero. In light of Proposition 2 we have:

Definition 3 (Ordover & Willig) *The firm's predatory pricing incentives are*

$$\Gamma_1^2(\mathbf{e}) + \left[\Gamma_1^3(\mathbf{e}) - \Gamma_1^3(\mathbf{e})\big|_{\phi_2=0}\right] + \Gamma_1^5(\mathbf{e})$$
$$+\Upsilon(p_2(\mathbf{e})) \left[\left[\Theta_1^1(\mathbf{e}) - \Theta_1^1(\mathbf{e})\big|_{\phi_2=0}\right] + \Theta_1^2(\mathbf{e}) + \left[\Theta_1^3(\mathbf{e}) - \Theta_1^3(\mathbf{e})\big|_{\phi_2=0}\right]\right].$$

Similarly, the Cabral & Riordan definition of predation sets $\Pi_1^0(p_1, p_2(\mathbf{e}), \mathbf{e}) = \Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})}$. In light of Proposition 1 we have:

Definition 4 (Cabral & Riordan) *The firm's predatory pricing incentives are*

$$\Gamma_1^2(\mathbf{e}) + \left[\Gamma_1^3(\mathbf{e}) - \Gamma_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})}\right]$$
$$+\Upsilon(p_2(\mathbf{e})) \left[\left[\Theta_1^1(\mathbf{e}) - \Theta_1^1(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})}\right] + \Theta_1^2(\mathbf{e}) + \left[\Theta_1^3(\mathbf{e}) - \Theta_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})}\right]\right].$$

Our remaining three definitions of the firm's predatory pricing incentives come from partitioning the predatory incentives in Definition 4 more finely by maintaining that the truly exclusionary effects on competition are the ones aimed at inducing exit by the firm winning the sale and moving further down its learning curve and/or by the firm preventing the rival from winning the sale and moving further down its learning curve:

Definition 5 (modified Cabral & Riordan I) *The firm's predatory pricing incentives are* $\Gamma_1^2(\mathbf{e}) + \Upsilon(p_2(\mathbf{e}))\Theta_1^2(\mathbf{e})$.

Definition 6 (modified Cabral & Riordan II) *The firm's predatory pricing incentives are* $\Theta_1^2(\mathbf{e})$.

Definition 7 (Snider) *The firm's predatory pricing incentives are* $\Gamma_1^2(\mathbf{e})$.

Definition 7 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.

Our definitions of predatory incentives are in what intuitively seems to be decreasing order of severity. The right panels of Table 5 illustrate this point at the example of the trenchy equilibrium in Section 3.1. A sacrifice test based on a later definition has indeed a lesser tendency to identify a price as predatory.

5 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 that 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 4.2 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. To form the constraint, we rewrite our decomposition (6) as

$$
mr_1(p_1, p_2(\mathbf{e})) - c(e_1) + \left[\sum_{k=1}^{5} \Gamma_1^k(\mathbf{e}) \pm \Gamma_1^3(\mathbf{e})\big|_{\phi_2=0} \pm \Gamma_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} \right]
$$
$$
+ \Upsilon(p_2(\mathbf{e})) \left[\sum_{k=1}^{4} \Theta_1^k(\mathbf{e}) \pm \Theta_1^1(\mathbf{e})\big|_{\phi_2=0} \pm \Theta_1^1(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} \pm \Theta_1^3(\mathbf{e})\big|_{\phi_2=0} \pm \Theta_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} \right] = 0
$$
(10)

and "switch off" the predatory incentives according to a particular definition.[25] For example, Definition 2 forces the firm to ignore $\sum_{k=1}^{4} \Theta_1^k(\mathbf{e})$ in setting its price, so the constraint is $\Xi_1(p_1, p_2(\mathbf{e}), \mathbf{e}) = mr_1(p_1, p_2(\mathbf{e})) - c(e_1) + \sum_{k=1}^{5} \Gamma_1^k(\mathbf{e}) = 0$. We use the homotopy method to

---

[25]The notation $\pm\cdot$ means that we add and subtract the relevant term.

28

compute the Markov perfect equilibria of the counterfactual game with a conduct restriction (according to a particular definition) in place. Comparing industry structure, conduct, and performance between counterfactuals and equilibria tells us how much bite the predatory incentives have.

5.1 Counterfactual and equilibrium correspondences

Figures 4 and 5 illustrate the counterfactual correspondence for Definitions 1–7 by plotting HHI^∞ against ρ. We superimpose the equilibrium correspondence $\mathbf{H}^{-1}(\rho)$ from Figure 3.

For Definitions 1 and 2, the counterfactual correspondences consist of a main path. The industry evolves into a mature duopoly with $HHI^\infty = 0.5$. Further inspection shows that the counterfactuals are flat. While the flat equilibria on MP and the lower fold of SL have a counterfactual "nearby," the trenchy equilibria on the upper fold of SL as well as those on L_1, L_2, and L_3 do not. In particular, the flat but not the trenchy equilibrium in Section 3.1 seems to have a counterfactual counterpart.

By contrast, the counterfactual correspondences for Definitions 3–7 resemble the equilibrium correspondence and consists of a main path, a semi-loop, and one (Definitions 3–6) or three (Definition 7) loops. The counterfactuals span the same range of industry structures as the equilibria. Most, but not all, equilibria have a counterfactual "nearby."

5.2 Eliminated and surviving equilibria

Figures 4 and 5 intuitively suggest that some equilibria are eliminated by a particular conduct restriction while other equilibria survive it. To make this intuition more precise, we use the homotopy method to match equilibria with counterfactuals. Instead of abruptly "switching off" the predatory pricing incentives in equation (10), we gradually drive them to zero. For Definition 2, for example, we put a weight λ on $\sum_{k=1}^{4} \Theta_1^k(\mathbf{e})$, and we then allow the homotopy method to vary λ (along with the vector of values and policies $(\mathbf{V}_1, \mathbf{U}_1, \mathbf{p}_1, \boldsymbol{\phi}_1)$). At $\lambda = 1$ 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 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.[26]

Figures 4 and 5 distinguish between eliminated and surviving equilibria for Definitions 1–7. Definitions 1 and 2 eliminate the trenchy equilibria that are associated with higher expected long-run Herfindahl indices whereas the flatter equilibria that are associated with

---

[26]See Case B in Figure 1 in Borkovsky et al. (2010) for an example of such a return.

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 $\rho \in [0, 1]$.
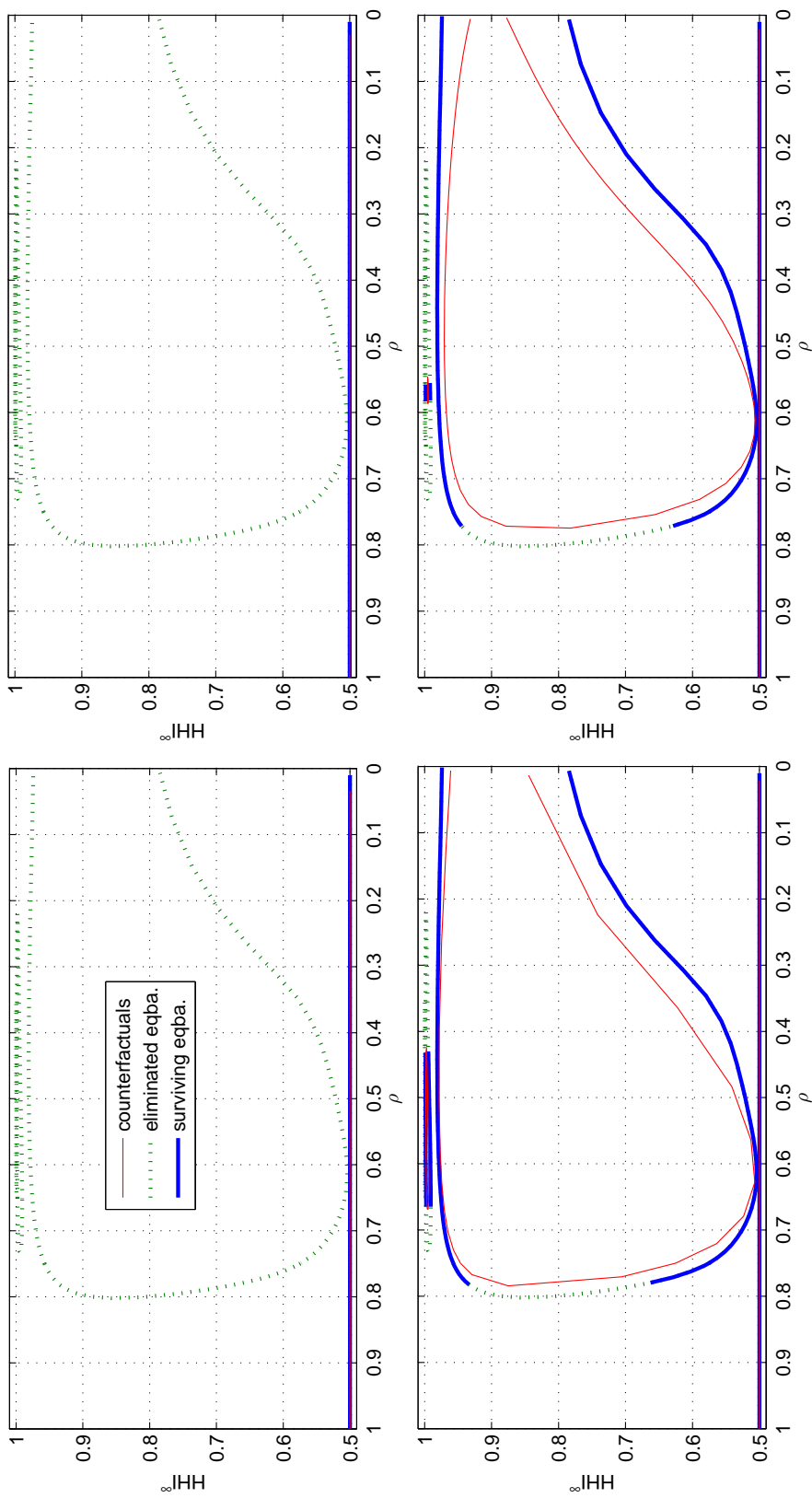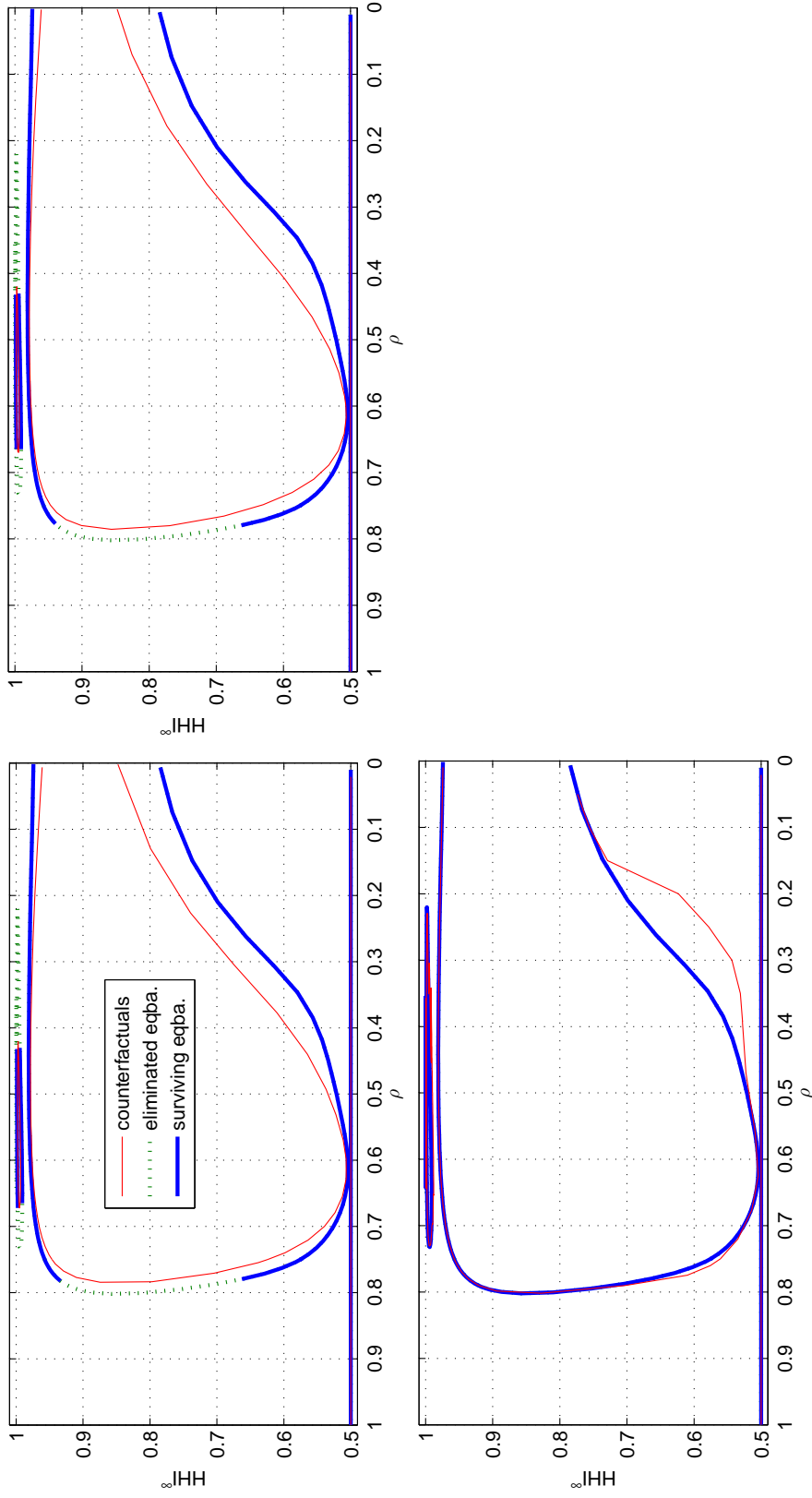
Figure 5: Expected long-run Herfindahl index. Counterfactual (solid red line) and equilibrium correspondences for Definitions 5–7 (upper left, upper right, and lower left panels) along with eliminated (dashed green line) and surviving (solid blue line) equilibria. Slice along $\rho \in [0, 1]$.

31

metric		definitions 1 SRP	2 DCV	3 OW	4 CR	5 CRI	6 CRII	7 S
	elim.	80%	77%	35%	44%	33%	35%	0%
	surv.	19%	19%	65%	56%	65%	65%	100%
HHI^∞	elim.	0.90	0.91	0.99	0.99	0.99	0.99	–
	surv.	0.50	0.50	0.74	0.70	0.74	0.74	0.83
$\overline{p}^\infty$	elim.	7.17	7.21	8.10	8.11	8.09	8.10	–
	surv.	2.99	2.99	5.50	5.05	5.50	5.50	6.40
CS^∞	elim.	3.09	3.05	2.07	2.05	2.07	2.07	–
	surv.	7.71	7.71	4.93	5.42	4.93	4.93	3.93
TS^∞	elim.	8.63	8.57	8.34	8.29	8.38	8.34	–
	surv.	9.70	9.70	9.05	9.21	9.05	9.05	8.80
CS^{NPV}	elim.	157.55	156.24	154.58	153.04	155.14	154.58	–
	surv.	158.28	158.28	158.64	160.54	158.64	158.64	157.22
TS^{NPV}	elim.	164.01	162.70	160.70	159.15	161.26	160.70	–
	surv.	172.48	172.48	167.49	169.85	167.49	167.49	165.12

Table 6: Eliminated and surviving equilibria for Definitions 1–7. Industry structure, conduct, and performance. Uniformly spaced grid $\rho \in \{0.05, 0.10, \ldots 1.0\}$ limited to parameterizations with multiple equilibria. Percentages in first row do not add up if the homotopy crashed and we have been unable to deduce survival or elimination from adjacent equilibria on the solution path.

lower expected long-run Herfindahl indices survive these conduct restrictions. By contrast, some of the trenchier equilibria survive Definitions 3–7, along with all the flatter ones. Nevertheless, with the exception of Definition 7, they eliminate at least some of the trenchy equilibria.

The first row of Table 6 shows the percentage of equilibria that are eliminated by a particular conduct restriction or survive it. 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 Figures 4 and 5, the more severe conduct restrictions based on Definitions 1 and 2 eliminate many more equilibria than the less severe conduct restrictions based on Definitions 3–7. Indeed, the conduct restriction based on Definition 7 does not eliminate any equilibria.

The remaining rows of Table 6 compare industry structure, conduct, and performance between eliminated and surviving equilibria. Across parameterizations with multiple equilibria on average, surviving equilibria involve lower concentration, lower prices, and higher consumer and total surplus. Definitions 1 and 2 have surviving equilibria with higher long-run consumer and total surplus and higher discounted total surplus than Definitions 3–7. However, they tend to have surviving equilibria with lower discounted consumer surplus.

This is because some trenchy equilibria that involve moderately intense competition for the market are eliminated by the conduct restrictions for Definitions 1 and 2 but survive the conduct restrictions for Definitions 3–7.

In sum, forcing the firm to ignore the predatory pricing incentives can eliminate "bad" equilibria, with the stronger Definitions 1 and 2 eliminating many more "bad" equilibria than the weaker Definitions 3–7. Along with the predation-like behavior in these equilibria, a fair amount of competition for the market is 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.

5.3 Impact of conduct restriction

The elimination-survival analysis illustrates the extent to which the predatory pricing 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 by construction can 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).[27] Thus, we directly compare the surviving equilibrium to its counterfactual counterpart. Second, for an eliminated equilibrium, in contrast, we assume that all counterfactuals are equally likely to be played once the conduct restriction is in place and average over the possible comparisons of the eliminated equilibrium with the counterfactuals. Third, we assume that all equilibria are equally likely to be played and average over all comparisons from the first two steps.

---

[27]Subsequent research by Aguirregabiria (2011) has exploited the theoretical result in Doraszelski & Escobar (2010) and used the homotopy method for counterfactual analysis along the same lines we do. Lee & 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.

metric	avg.		1 SRP	2 DCV	3 OW	4 CR	5 CRI	6 CRII	7 S
						definition			
HHI^∞	0.74	change	-0.24	-0.24	-0.05	-0.08	-0.05	-0.05	-0.00
		up	0%	0%	25%	25%	25%	25%	0%
		down	80%	80%	50%	55%	50%	50%	20%
$\overline{p}^\infty$	6.77	change	-2.54	-2.54	-0.53	-0.80	-0.53	-0.52	-0.05
		up	0%	0%	25%	25%	25%	25%	0%
		down	80%	80%	50%	55%	50%	50%	20%
CS^∞	3.74	change	2.80	2.80	0.59	0.89	0.59	0.58	0.05
		up	80%	80%	50%	55%	50%	50%	20%
		down	0%	0%	25%	25%	25%	25%	0%
TS^∞	7.66	change	0.74	0.74	0.17	0.25	0.17	0.16	0.01
		up	80%	80%	50%	55%	50%	50%	0%
		down	0%	0%	0%	0%	0%	5%	0%
CS^{NPV}	132.26	change	-62.82	-2.92	-2.83	-2.35	-2.82	0.77	-3.14
		up	0%	0%	0%	0%	0%	25%	0%
		down	95%	75%	45%	40%	45%	0%	80%
TS^{NPV}	142.04	change	-9.70	5.93	1.42	2.08	1.42	1.39	0.10
		up	0%	80%	40%	50%	40%	40%	0%
		down	95%	0%	0%	0%	0%	0%	0%

Table 7: Impact of conduct restriction for Definitions 1–7. Industry structure, conduct, and performance. Uniformly spaced grid $\rho \in \{0.05, 0.10, \ldots, 1.0\}$. Up means that the increase exceeds 1% of the value of the metric in equilibrium, down that the decrease exceeds 1%.

Table 7 summarizes. Across parameterizations on average, for all definitions of predatory pricing incentives the associated conduct restrictions decrease concentration and prices and increase long-run consumer and total surplus. These changes are substantially more pronounced for the stronger Definitions 1 and 2 that eliminate many more trenchy equilibria than for the weaker Definitions 3–7.

With the exception of Definition 6, the conduct restrictions decrease discounted consumer surplus because they restrict competition for the market along with the predation-like behavior in the trenchy equilibria. The change is particularly striking for Definition 1: Not only does the associated conduct restriction annihilate competition for the market, but Definition 1 also 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 trenchy equilibria).

The increase in discounted consumer surplus under Definition 6 occurs because the intense competition for the market in an emerging duopoly in state $(1, 1)$ in the form of a well is driven more by the baseline advantage-building motive $\Gamma_1^1(1, 1)$ and the advantage-

building/exit motive $\Gamma_1^2(1,1)$ than by the advantage-denying/exit motive $\Theta_1^2(1,1)$ (see again Table 5). Hence, forcing the firm to ignore the advantage-denying/exit motive allows a well—thereby preserving a fair amount of competition for the market—but disallows a trench and thus the mobility barrier that, over time, is likely to lead to an entrenched monopoly.

Finally, with the exception of Definition 1, the conduct restrictions increase discounted total surplus. The decrease in discounted total surplus under Definition 1 occurs because this definition denies the efficiency gains from pricing aggressively in order to move down the learning curve.

While the averages across parameterizations in Table 7 provide a "broad brush" view of the impact of a conduct restriction, the percentages up and down indicate that this impact can differ depending on the parameterization. In particular for Definitions 3–6, the averages encompass positive changes for some parameterizations and negative changes for others. In this respect, our analysis echoes the point made by Cabral & Riordan (1997) that, depending on the details, predatory pricing can either harm or benefit consumers. Hence, a more "scalpel-like" approach 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]."[28] Our impact analysis supports this view because, with the exception of Definition 6, the price of making future consumers better off is making current consumers worse off.

None of the conduct restrictions is unambiguously beneficial for consumers and society at large in both the short run and the long run irrespective of the underlying primitives. The conduct restrictions associated with Definitions 2 and 6 come closest to being unambiguously beneficial: The conduct restriction for Definition 2 causes fairly small decreases in CS^{NPV} but unambiguous increases in CS^∞, TS^∞, and TS^{NPV}.[29] The conduct restriction for Definition 6 may slightly decrease CS^∞ and TS^∞ for some parameterizations, but more often than not increases CS^∞ and TS^∞, and it unambiguously increases CS^{NPV} and TS^{NPV}.[30]

---

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

[29]CS^{NPV} and TS^{NPV} depend on β. In line with common practice in the evaluation of public investments and cost-benefit analysis, an antitrust authority may evaluate CS^{NPV} and TS^{NPV} at a higher discount factor than the one used by firms, thereby giving more weight to the long-run implications of equilibrium behavior for industry performance that are the focus of CS^∞ and TS^∞. A conduct restriction like Definition 2 that has a small negative effect on CS^{NPV} and a large positive effect on CS^∞ may thus have a positive effect on CS^{NPV} at a higher discount factor.

[30]A similar, although not identical, pattern arises if we vary σ or $\overline{X}$ instead of ρ; see the Online Appendix for details.

What unifies Definitions 2 and 6 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 6, there is some latitude in where exactly to draw the line: The choice depends on whether antitrust policy is obligated to consumers—thus preferring Definition 6—or society at large—thus preferring 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 (6).

6 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 through learning-by-doing, thereby giving rise to a tension between pricing aggressively to eliminate competitors and pricing aggressively to pursue efficiency.

We depart from the existing literature on predation in two key aspects. First, rather than aiming for an ironclad definition of predation, we separate predatory incentives for pricing aggressively from efficiency-enhancing incentives by decomposing the equilibrium pricing condition. The decomposed advantage-building and advantage-denying motives allow us to define a firm's predatory pricing incentives in a variety of ways, some of which are motivated by the existing literature while others are novel. 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 pricing incentives on industry structure, conduct, and performance.

Our numerical analysis 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.

Trenchy equilibria involving predation-like behavior typically coexist with flat 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 trenchy 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 3–7. Along with the predation-like behavior in the trenchy 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 6 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.

Appendix

Proof of Proposition 1. The probability that firm 2 exits the industry in the current period (given $p_2(\mathbf{e})$ and $\mathbf{e}$) is

$$\Phi_2(p_1, p_2(\mathbf{e}), \mathbf{e}) = \phi_2(\mathbf{e})D_0(p_1, p_2(\mathbf{e})) + \phi_2(e_1+1, e_2)D_1(p_1, p_2(\mathbf{e})) + \phi_2(e_1, e_2+1)D_2(p_1, p_2(\mathbf{e})).$$

We say that $p_1(\mathbf{e})$ is predatory according to the Cabral & Riordan (1997) definition if there exists a price $\widetilde{p}_1 > p_1(\mathbf{e})$ such that (1) $\Phi_2(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e}) > \Phi_2(\widetilde{p}_1, p_2(\mathbf{e}), \mathbf{e})$ and (2) $\Pi_1(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})} < \Pi_1(\widetilde{p}_1, p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})}$.

Part (a): Let $\widetilde{p}_1 = \arg\max_{p_1} \Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})}$. Then $\widetilde{p}_1$ is uniquely determined by

$$mr_1(\widetilde{p}_1, p_2(\mathbf{e})) - c(e_1) + \left[\Gamma_1^1(\mathbf{e}) + \Gamma_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} + \Gamma_1^4(\mathbf{e}) + \Gamma_1^5(\mathbf{e})\right]$$
$$+ \Upsilon(p_2(\mathbf{e})) \left[\Theta_1^1(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} + \Theta_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} + \Theta_1^4(\mathbf{e})\right] = 0. \tag{11}$$

Subtracting equation (6) from equation (11), we have

$$mr_1(\widetilde{p}_1, p_2(\mathbf{e})) - mr_1(p_1(\mathbf{e}), p_2(\mathbf{e})) = \left[\Gamma_1^2(\mathbf{e}) + \left[\Gamma_1^3(\mathbf{e}) - \Gamma_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})}\right]\right]$$

$$+\Upsilon(p_2(\mathbf{e}))\left[\left[\Theta_1^1(\mathbf{e}) - \Theta_1^1(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})}\right] + \Theta_1^2(\mathbf{e}) + \left[\Theta_1^3(\mathbf{e}) - \Theta_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})}\right]\right] > 0$$

per inequality (7). Because $mr_1(p_1, p_2(\mathbf{e}))$ is strictly increasing in p_1, it follows that $\widetilde{p}_1 > p_1(\mathbf{e})$.

Because $\Gamma_1^2(\mathbf{e}) \geq 0$ and $\Theta_1^2(\mathbf{e}) \geq 0$, with at least one of these inequalities being strict, under the maintained assumptions of Proposition 1 it follows that $\phi_2(e_1+1, e_2) - \phi_2(\mathbf{e}) \geq 0$ and $\phi_2(\mathbf{e}) - \phi_2(e_1, e_2+1) \geq 0$, with at least one of these inequalities being strict. Because $D_0(\mathbf{p}) = 1 - D_1(\mathbf{p}) - D_2(\mathbf{p})$ we thus have

$$\frac{\partial \Phi_2(p_1, p_2(\mathbf{e}), \mathbf{e})}{\partial p_1} = [\phi_2(e_1+1, e_2) - \phi_2(\mathbf{e})] \frac{\partial D_1(p_1, p_2(\mathbf{e}))}{\partial p_1} - [\phi_2(\mathbf{e}) - \phi_2(e_1, e_2+1))] \frac{\partial D_2(p_1, p_2(\mathbf{e}))}{\partial p_1} < 0$$

since $\frac{\partial D_1(p_1, p_2(\mathbf{e}))}{\partial p_1} < 0$ and $\frac{\partial D_2(p_1, p_2(\mathbf{e}))}{\partial p_1} > 0$. Thus, $\Phi_2(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e}) > \Phi_2(\widetilde{p}_1, p_2(\mathbf{e}), \mathbf{e})$. This establishes part (1) of the Cabral & Riordan definition above.

To establish part (2), recall that by construction $\Pi_1(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})} \leq \Pi_1(\widetilde{p}_1, p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})}$. Moreover, this inequality is strict because $\Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})}$ is strictly quasiconcave in p_1.

Part (b): Because $p_1(\mathbf{e})$ is predatory according to the Cabral & Riordan definition, there exists a higher price $\widetilde{p}_1 > p_1(\mathbf{e})$ such that (1) $\Phi_2(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e}) > \Phi_2(\widetilde{p}_1, p_2(\mathbf{e}), \mathbf{e})$ and (2) $\Pi_1(p_1(\mathbf{e}, p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})} < \Pi_1(\widetilde{p}_1, p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})}$. Thus we have

$$\Phi_2(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e}) - \Phi_2(\widetilde{p}_1, p_2(\mathbf{e}), \mathbf{e})$$
$$= [D_1(p_1(\mathbf{e}), p_2(\mathbf{e})) - D_1(\widetilde{p}_1, p_2(\mathbf{e}))][\phi_2(e_1+1, e_2) - \phi_2(\mathbf{e})]$$
$$- [D_2(p_1(\mathbf{e}), p_2(\mathbf{e})) - D_2(\widetilde{p}_1, p_2(\mathbf{e}))][\phi_2(\mathbf{e}) - \phi_2(e_1, e_2+1)] > 0. \tag{12}$$

Because $\frac{\partial D_1(p_1, p_2(\mathbf{e}))}{\partial p_1} < 0$ and $\frac{\partial D_2(p_1, p_2(\mathbf{e}))}{\partial p_1} > 0$, $D_1(p_1(\mathbf{e}), p_2(\mathbf{e})) - D_1(\widetilde{p}_1, p_2(\mathbf{e})) > 0$ and $D_2(p_1(\mathbf{e}), p_2(\mathbf{e})) - D_2(\widetilde{p}_1, p_2(\mathbf{e})) < 0$. The only way for inequality (12) to hold is thus that $\phi_2(e_1+1, e_2) - \phi_2(\mathbf{e}) > 0$ or $\phi_2(\mathbf{e}) - \phi_2(e_1, e_2+1) > 0$ which, in turn, implies $\Gamma_1^2(\mathbf{e}) > 0$ or $\Theta_1^2(\mathbf{e}) > 0$.

Because $\Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})}$ is strictly quasiconcave in p_1, it follows from $\widetilde{p}_1 > p_1(\mathbf{e})$ and $\Pi_1(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})} < \Pi_1(\widetilde{p}_1, p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})}$ that

$$\frac{\partial \Pi_1(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})}}{\partial p_1} = mr_1(p_1(\mathbf{e}), p_2(\mathbf{e})) - c(e_1)$$
$$+ \left[\Gamma_1^1(\mathbf{e}) + \Gamma_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} + \Gamma_1^4(\mathbf{e}) + \Gamma_1^5(\mathbf{e})\right]$$
$$+\Upsilon(p_2(\mathbf{e}))\left[\Theta_1^1(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} + \Theta_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} + \Theta_1^4(\mathbf{e})\right] < 0. \tag{13}$$

Subtracting inequality (13) from equation (6) then yields

$$\Gamma_1^2(\mathbf{e}) + \left[\Gamma_1^3(\mathbf{e}) - \Gamma_1^3(\mathbf{e})\big|_{\phi_2 = \phi_2(\mathbf{e})}\right]$$

$$+\Upsilon(p_2(\mathbf{e}))\left[\left[\Theta_1^1(\mathbf{e}) - \Theta_1^1(\mathbf{e})\big|_{\phi_2 = \phi_2(\mathbf{e})}\right] + \Theta_1^2(\mathbf{e}) + \left[\Theta_1^3(\mathbf{e}) - \Theta_1^3(\mathbf{e})\big|_{\phi_2 = \phi_2(\mathbf{e})}\right]\right] > 0.$$

∎

References

Aguirregabiria, V. (2011), 'A method for implementing counterfactual experiments in models with multiple equilibria', *Economics Letters* **forthcoming**.

Alchian, A. (1963), 'Reliability of progress curves in airframe production', *Econometrica* **31**(4), 679–693.

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.

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

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.

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.

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.

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.

Dudley, L. (1972), 'Learning and productivity changes in metal products', *American Economic Review* **62**(4), 662–669.

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.

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

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. (1986), 'A signal jamming theory of predation', *Rand Journal of Economics* **17**(4), 366–377.

Hirsch, W. (1952), 'Progress functions of machine tool manufacturing', *Econometrica* **20**(1), 81–82.

Irwin, D. & Klenow, P. (1994), 'Learning-by-doing spillovers in the seminconductor industry', *Journal of Political Economy* **102**(6), 1200–1227.

Jacobson, J. & Sher, S. (2006), '"no economic sense" makes no sense for exclusive dealing', *Antitrust Law Journal* **73**, 779–801.

Jarmin, R. (1994), 'Learning by doing and competition in the early rayon industry', *Rand Journal of Economics* **25**(3), 441–454.

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

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

Lieberman, M. (1984), 'The learning curve and pricing in the chemical processing industries', *Rand Journal of Economics* **15**(2), 213–228.

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

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.

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

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.

Thompson, P. (2001), 'How much did the Liberty shipbuilders learn? New evidence for an old case study', *Journal of Political Economy* **109**(1), 103–137.

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

Thornton, R. & Thompson, P. (2001), 'Learning from experience and learning from others: An exploration of learning and spillovers in wartime shipbuilding', *American Economic Review* **91**(5), 1350–1368.

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.

Wright, T. (1936), 'Factors affecting the cost of airplanes', *Journal of Aeronautical Sciences* **3**(4), 122–128.

Zimmerman, M. (1982), 'Learning effects and the commercialization of new energy technologies: The case of nuclear power', *Bell Journal of Economics* **13**(2), 297–310.