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

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September 10, 2011
—WORKING DRAFT: SUBJECT TO REVISION—

Abstract

Predatory pricing—a deliberate strategy of pricing aggressively in order to eliminate competitors—is one of the more contentious areas of antitrust policy and its existence and efficacy are widely debated. The purpose of this paper is to formally characterizes predatory pricing in a modern industry dynamics framework. We endogenize competitive advantage and industry structure through learning-by-doing. We show that we can isolate and measure a firm's predatory incentives by decomposing the equilibrium pricing condition. Our decomposition maps into existing economic definitions of predation and provides us with a coherent and flexible way to develop alternative characterizations of a firm's predatory incentives. We ask three interrelated questions. First, when does predation-like behavior arise? Second, what drives pricing and, in particular, how can we separate predatory incentives for pricing aggressively from efficiency-enhancing incentives for pricing aggressively in order to move further down the learning curve? Third, what is the impact of predatory incentives on industry structure, conduct, and performance? In answer to the first question, we find widespread existence of Markov perfect equilibria involving behavior that resembles conventional notions of predatory pricing in the sense that possibility of rival's exit is associated with aggressive pricing. We answer the second question by presenting an analytical decomposition of the Markov equilibrium pricing condition that allows us to isolate predatory incentives in a vareity of plausible ways. To answer the third question, we show how conduct restrictions corresponding to a variety of different definitions of predatory incentives affects equilibrium behavior. Based on our numerical analysis, conduct restrictions based on definitions of predatory incentives that isolate advantage-denying motives in pricing — i.e., the marginal benefit to a firm from denying a rival the opportunity to develop a competitive advantage or overcome a competitive disadvantage—appear to provide the best balance of short-run and long-run welfare improvements.

*We thank Lanier Benkard, Chiara Fumagalli, Mike Riordan, Mark Satterthwaite, and Connan Snider for helpful discussions and comments. We also thank participants at the 2010 Searle Center Conference on Antitrust Economics and Competition Policy and the Ninth Annual International Industrial Organization Conference for their useful questions and comments. Besanko and Doraszelski gratefully acknowledge financial support from the National Science Foundation under Grant 0615615.

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1 Introduction

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

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

Characterizing predatory pricing is especially complicated because aggressive pricing with subsequent recoupment can also arise when firms face other intertemporal trade-offs such as learning-by-doing, network effects, or switching costs. 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 preda-

[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), DeJong (1957), Alchian (1963), Levy (1965), Kilbridge (1962), Hirschmann (1964), Preston & Keachie (1964), Baloff (1971), Dudley (1972), Zimmerman (1982), Lieberman (1984), Argote, Beckman & Epple (1990), Gruber (1992), Irwin & Klenow (1994), Jarmin (1994), Pisano (1994), Bohn (1995), Darr, Argote & Epple (1995), Hatch & Mowery (1998), Benkard (2000), Shafer, Nembhard & Uzumeri (2001), Thompson (2001), Thornton & Thompson (2001), and Thompson (2003).

[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).

tion. Moreover, if one entertains the possibility that predatory pricing is a viable business strategy, then a characterization of predatory pricing is required to allow economists, legal scholars, and antitrust practitioners to detect its presence and measure its extent.

The purpose of this paper is to formally characterize predatory pricing in a modern industry dynamics framework along the lines of Ericson & Pakes (1995). Unlike much of the previous literature, we do not attempt to deliver an ironclad definition of predatory pricing. 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 possibility of rival's exit is associated with aggressive pricing. 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. Our paper goes beyond establishing possibility by way of an example or a case study by showing just how common predation-like behavior is.

Our paper moreover reinforces and formalizes 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 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 incremental benefit from an 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 incremental benefit from preventing a 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). Our decomposition therefore allows us to clarify the relationship between the existing economic definitions of predation. Most important, however, 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

[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).

firm sacrifices current profit in exchange for the expectation of higher future profit following the exit of its rival. One way to test for sacrifice is to determine whether the derivative of a profit function that "incorporate[s] everything except effects on competition" is positive at the price the firm has chosen (Edlin & Farrell 2004, p. 510). Our alternative characterizations of predatory incentives 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 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 predatory pricing on conceptual grounds, we instead directly measure the impact of firms' predatory incentives on industry structure, conduct, and performance. To do this, we note that our alternative definitions of predatory incentives correspond to conduct restrictions of different severity. These conduct restrictions can be enforced by requiring firms to ignore the predatory pricing incentive in setting their prices. We compute counterfactual equilibria that arise when firms are subject to conduct restrictions corresponding to each of our definitions of predatory incentives. We then compare these counterfactuals to the actual equilibria over a wide range of parameterizations.

We present these comparisons in two ways. First, we show that a conduct restriction typically eliminates equilibria for those parameterizations for which there are multiple equilibria, so for each definition, we compare structure, conduct, and performance metrics of the eliminated and surviving equilibria. Second, we directly compare structure, conduct, and performance metrics in the actual equilibria and the counterfactual equilibria for each definition.

We find that more severe conduct restrictions typically eliminate more equilibria than less severe restrictions. We also find that more severe conduct restrictions have, on average, a greater impact on industry structure, conduct, and performance than less severe conduct restrictions, including those inspired by Ordover & Willig (1981) and Cabral & Riordan (1997). This occurs because the less severe restrictions tend to preserve some of the equilibria with predation-like behavior, while the more severe restrictions tend to eliminate most or all of the equilibria with predation-like behavior and, at the same time, cause little change in equilibria involving less aggressive pricing. A risk of a severe restriction, however, is that it may "throw the baby out with the bath water" in the sense that it can eliminate equilibria with intense competition for the market and high levels of consumer surplus in the short run. In other words, a severe restriction runs the risk of eliminating what Cabral & Riordan (1997) call welfare-improving predation.

Overall, our numerical analysis shows that there may be sensible ways of disentangling predatory incentives from efficiency-enhancing incentives in pricing. In particular, a conduct restriction based on either the advantage-denying motive or the advantage-denying/exit motive appears to minimize the likelihood of prohibiting welfare-improving predation. Since advantage-denying motives are principally about the returns to a firm from preventing a rival from improving its competitive position, our analysis suggests that the line separating efficiency-enhancing pricing behavior from predation should be based on *exclusion of opportunity*: is a firm's pricing behavior primarily driven by the benefits from building its own competitive advantage, or is it based on the benefits from excluding a rival the opportunity to build its own advantage or overcome an existing disadvantage?

The organization of the remainder of this paper is as follows. In Section 2, we describe the model and state the conditions that describe equilibrium entry and exit decisions and equilibrium pricing behavior. In Section 3, we describe our computational approach and present representative numerical results that illustrate equilibrium behavior and industry dynamics. We also summarize how equilibrium outcomes vary with the progress ratio, product differentiation, and expected salvage value. In Section 4, we decompose the equilibrium pricing condition and interpret the terms in the decomposition. We then relate the decomposition to economic definitions of predatory behavior that have been offered in the literature, and we use the decomposition to formulate alternative definitions of predatory pricing incentives. In Section 5, we analyze the economic impact of these predatory pricing incentives. Section 6 summarizes and concludes. Appendix A contains derivations of selected expressions, while Appendix B contains proofs of propositions. All figures are at the end of the paper. A separate Online Appendix contains additional figures and tables.

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 ($\mathbf{e}''$) 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 $\rho \in [0, 1]$:

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

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*.

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

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 the policy function $p_n(\mathbf{e})$; the exit-entry phase determines the value function $U_n(\mathbf{e}')$ along with the policy function $\phi_n(\mathbf{e}')$.

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

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

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

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

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

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

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

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

$$\begin{aligned} V_1(\mathbf{e}) &= \max_{p_1}\,(p_1 - c(e_1))D_1(p_1, p_2(\mathbf{e})) + D_0(p_1, p_2(\mathbf{e}))U_1(\mathbf{e}) \\ &\quad +D_1(p_1, p_2(\mathbf{e}))U_1(e_1+1, e_2) + D_2(p_1, p_2(\mathbf{e}))U_1(e_1, e_2+1). \end{aligned} \tag{3}$$

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

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

$$\Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e}) = (p_1 - c(e_1))D_1(p_1, p_2(\mathbf{e})) + U_1(\mathbf{e})$$
$$+D_1(p_1, p_2(\mathbf{e}))\left[U_1(e_1+1, e_2) - U_1(\mathbf{e})\right] - D_2(p_1, p_2(\mathbf{e}))\left[U_1(\mathbf{e}) - U_1(e_1, e_2+1)\right] \quad (4)$$

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

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

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] The pricing decision in our model is thus akin to an investment decision in that it encompasses the short run and the long run.

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

[7] See Appendix A.2 for an explanation.

[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 hence capacity) makes it less attractive for its rival to produce in the future (for fear of lower prices), thereby crimping its opportunity to achieve a competitive advantage through learning-by-doing.

[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.

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 (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 equilibrium correspondence mapping parameters into values and policies is

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

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

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

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.[11] 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.[12]

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.

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).[13]

[11] The discount factor can be thought of as $\beta = \frac{\zeta}{1+r}$, where $r > 0$ is the per-period discount rate and $\zeta \in (0, 1]$ is the exogenous probability that the industry survives from one period to the next. Consequently, our baseline value of β corresponds to a variety of scenarios that differ in the length of a period. For example, it corresponds to a period length of one year, a yearly discount rate of 5.26%, and certain survival. But it also corresponds to a period length of one month, a monthly discount rate of 1% (corresponding to a yearly discount rate of 12.7%), and a monthly survival probability of about 0.96. To put this in perspective, technology companies such as IBM and Microsoft had costs of capital in the range of 11 to 15% per annum in the late 1990s. Further, an industry with a monthly survival probability of 0.96 has an expected lifetime of 26.25 months. This scenario is therefore consistent with a pace of innovative activity that is expected to make an industry's current generation of products obsolete within two to three years.

[12] Any predatory incentives vanish as $\Delta_X \to \infty$ because the probability that the rival exits the industry approaches 0.5 irrespective of the behavior of the firm.

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

The upper panels of Figure 2 exemplify what we call a *trenchy equilibrium*.[14] 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 $e_1 \in \{2,\dots,30\}$.[15] 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 $e_2 \in \{2,\dots,30\}$ as the upper middle panel shows. The follower remains in 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.[16] 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 $\mathbf{p}$ and $\boldsymbol{\phi}$ to construct the matrix of state-to-state transition probabilities that characterizes the Markov process of industry dynamics. From this, we compute the transient distribution over states in period T, $\boldsymbol{\mu}^T$, starting from state $(1,1)$ in period 0. This tells us how likely each possible industry structure is in period T given that the game began as an emerging duopoly. Depending on T, the transient distributions can capture short-run or long-run (steady-state) dynamics. We think of period 1000 as the long run and, with a slight abuse of notation, denote $\boldsymbol{\mu}^{1000}$ by $\boldsymbol{\mu}^{\infty}$. Finally, we use the transient distributions to compute six metrics of industry structure, conduct, and performance.

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[14] Our terminology is similar, but not identical, to that of Besanko et al. (2010).

[15] 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 $e_2 \in \{2,\dots,30\}$.

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

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

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

is the Herfindahl index in state $\mathbf{e}$ and $D_k(\mathbf{e}) = D_k(p_1(\mathbf{e}), p_2(\mathbf{e}))$ is the probability that the buyer purchases good $k \in \{0, 1, 2\}$ in state $\mathbf{e}$. The expected long-run Herfindahl index is a summary measure of industry concentration. If $HHI^{\infty} > 0.5$, then an asymmetric industry structure arises and persists.

Conduct. *Expected long-run average price:*

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

where

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

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

Performance. *Expected long-run consumer surplus:*

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

where

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

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

Expected long-run total surplus:

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

where $PS_n(\mathbf{e})$ is the producer surplus of firm n in state $\mathbf{e}$.[17]

[17] See Appendix A.3 for a derivation.

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.

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 $\boldsymbol{\mu}^0, \boldsymbol{\mu}^1, \ldots$). 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.[18] If $\rho = 1$ there is no learning-by-doing, while if $\rho = 0$ the learning economies become infinitely strong in the sense that the marginal cost of production jumps from κ for the first unit to 0 for any further unit. The progress ratio ρ therefore determines the possible extent of efficiency gains from pricing aggressively in order to move down the learning curve.

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

The equilibria on MP are 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 $HHI^{\infty} \approx 1.0$.[19]

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 $\sigma = 3$.[20]

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.

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,

[18] The remaining metrics are presented in the Online Appendix.

[19] Trenchy equilibria can arise even if there is practically no learning-by-doing, e.g., if $\rho = 0.99$ and $\sigma = 0.10$ or $\rho = 0.98$, $\sigma = 0.35$, and $p_0 = 20$.

[20] 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.

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.[21]

There are multiple equilibria for $\overline{X}$ from 0.7 to 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. 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 $\sum_{k=1}^{4} \Theta_1^k(\mathbf{e})$ decomposes 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.[22]

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:

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

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.

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

[22] 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.

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. 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

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.

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:

$$\Theta_1^1(\mathbf{e}) = (1 - \phi_1(\mathbf{e}))(1 - \phi_2(e_1, e_2 + 1))\beta \left[V_1(\mathbf{e}) - V_1(e_1, e_2 + 1)\right]. \tag{7}$$

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 preventing 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 $\Gamma_2^1(1,1)$. 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 $\Theta_2^1(e_1,1)$. 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 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:

			advantage building					advantage denying				definitions						
$\mathbf{e}$	$p_1(\mathbf{e})$	$c(e_1)$	$\Gamma_1^1(\mathbf{e})$	$\Gamma_1^2(\mathbf{e})$	$\Gamma_1^3(\mathbf{e})$	$\Gamma_1^4(\mathbf{e})$	$\Gamma_1^5(\mathbf{e})$	$\Theta_1^1(\mathbf{e})$	$\Theta_1^2(\mathbf{e})$	$\Theta_1^3(\mathbf{e})$	$\Theta_1^4(\mathbf{e})$	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 pricing 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.

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*

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

$\Gamma_1^2(\mathbf{e}) \geq 0$*, and* $\Theta_1^2(\mathbf{e}) \geq 0$*, with at least one of the last two inequalities being strict, then the firm's equilibrium price* $p_1(\mathbf{e})$ *in state* $\mathbf{e}$ *is predatory according to the Cabral & Riordan (1997) definition.*[23] *(b) If* $p_1(\mathbf{e})$ *is predatory according to the Cabral & Riordan definition, then inequality (8) holds and* $\Gamma_1^2(\mathbf{e}) > 0$ *or* $\Theta_1^2(\mathbf{e}) > 0$*.*

Proof. See Appendix B. ■

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.[24] 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*

$$\begin{aligned} &\Gamma_1^2(\mathbf{e}) + \left[\Gamma_1^3(\mathbf{e}) - \Gamma_1^3(\mathbf{e})\big|_{\phi_2=0}\right] + \Gamma_1^5(\mathbf{e}) \\ &+\Upsilon(p_2(\mathbf{e}))\left[\left[\Theta_1^1(\mathbf{e}) - \Theta_1^1(\mathbf{e})\big|_{\phi_2=0}\right] + \Theta_1^2(\mathbf{e}) + \left[\Theta_1^3(\mathbf{e}) - \Theta_1^3(\mathbf{e})\big|_{\phi_2=0}\right]\right] > 0, \end{aligned} \tag{9}$$

$\Gamma_1^2(\mathbf{e}) \geq 0$*, and* $\Theta_1^2(\mathbf{e}) \geq 0$*, with at least one of the last two inequalities being strict, 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 inequality (9) holds and* $\Gamma_1^2(\mathbf{e}) > 0$ *or* $\Theta_1^2(\mathbf{e}) > 0$*.*

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

[23] The notation $\cdot|_{\phi_2=\phi_2(\mathbf{e})}$ signifies 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 $\phi_2(\mathbf{e})$.

[24] 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).

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).[25]

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 in this spirit 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 $\Omega_1^0(p_1, p_2(\mathbf{e}), \mathbf{e}) = \Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e}) - \Pi_1^0(p_1, p_2(\mathbf{e}), \mathbf{e})$ 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

$$-\frac{\partial \Omega_1^0(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})}{\partial p_1} = \frac{\partial \Omega_1^0(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})}{\partial(-p_1)} > 0. \tag{10}$$

$\frac{\partial \Omega_1^0(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})}{\partial(-p_1)}$ 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 (10) tells us that these changes in the competitive environment are to the firm's advantage. In this sense, $\frac{\partial \Omega_1^0(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})}{\partial(-p_1)}$ 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 $\frac{\partial \Omega_1^0(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})}{\partial(-p_1)}$ 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 prac-*

[25] 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).

tice 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 (10) that $\frac{\partial\Omega_1^0(p_1(\mathbf{e}),p_2(\mathbf{e}),\mathbf{e})}{\partial(-p_1)} > 0$ 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 $c(e_1)$.[26] 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.[27]

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, $\Pi_1^0(p_1, p_2(\mathbf{e}), \mathbf{e}) = (p_1 - c(e_1))D_1(p_1, p_2(\mathbf{e})) + U_1(\mathbf{e}) + D_1(p_1, p_2(\mathbf{e}))\left[U_1(e_1+1, e_2) - U_1(\mathbf{e})\right]$, 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 (10) that $\frac{\partial\Omega_1^0(p_1(\mathbf{e}),p_2(\mathbf{e}),\mathbf{e})}{\partial(-p_1)}) > 0$ 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* $\sum_{k=1}^4 \Theta_1^k(\mathbf{e})$.

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

[26] 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 a sacrifice test based the comparison of inclusive price and marginal cost. Edlin & Farrell (2004) and Snider (2008) provide detailed analyses of this case.

[27] Below-cost pricing underpins the current *Brooke Group* standard for predatory pricing in the U.S.

the learning curve $c(m)$ (see 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 embody 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	predatory incentives	
1. short-run profit	all decomposed advantage-building and advantage-denying motives	$\Gamma_1^k(\mathbf{e})$, $k=1,\ldots,5$, $\Theta_1^k(\mathbf{e})$, $k=1,\ldots,5$
2. dynamic competitive vacuum	all decomposed advantage-denying motives	$\Theta_1^k(\mathbf{e})$, $k=1,\ldots,4$
3. Ordover & Willig	marginal benefit from nonzero probability of rival exit in current period	$\Gamma_1^2(\mathbf{e})$, $\Theta^2(\mathbf{e})$, $\Gamma_1^5(\mathbf{e})$, $\left[\Gamma_1^3(\mathbf{e}) - \Gamma_1^3(\mathbf{e})\big\|_{\phi_2=0}\right]$, $\left[\Theta_1^1(\mathbf{e}) - \Theta_1^1(\mathbf{e})\big\|_{\phi_2=0}\right]$, $\left[\Theta_1^3(\mathbf{e}) - \Theta_1^3(\mathbf{e})\big\|_{\phi_2=0}\right]$
4. Cabral & Riordan	marginal benefit from nonconstant probability of rival exit in current period	$\Gamma_1^2(\mathbf{e})$, $\Theta^2(\mathbf{e})$, $\left[\Gamma_1^3(\mathbf{e}) - \Gamma_1^3(\mathbf{e})\big\|_{\phi_2=\phi_2(\mathbf{e})}\right]$, $\left[\Theta_1^1(\mathbf{e}) - \Theta_1^1(\mathbf{e})\big\|_{\phi_2=\phi_2(\mathbf{e})}\right]$, $\left[\Theta_1^3(\mathbf{e}) - \Theta_1^3(\mathbf{e})\big\|_{\phi_2=\phi_2(\mathbf{e})}\right]$
5. modified Cabral & Riordan I	advantage-building/exit and advantage-denying/exit motives	$\Gamma_1^2(\mathbf{e})$, $\Theta_1^2(\mathbf{e})$
6. modified Cabral & Riordan II	advantage-denying/exit motive	$\Theta_1^2(\mathbf{e})$
7. Snider	advantage-building/exit motive	$\Gamma_1^2(\mathbf{e})$

Table 6: Definitions of predatory incentives.

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.

Table 6 summarizes our definitions of predatory incentives 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 greater 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 for each of the definitions in Section 4.2. Imagine an omniscient regulator that can instantly flag a predatory profit sacrifice and can prevent a firm from pricing to achieve that sacrifice by forcing it to ignore its predatory pricing incentive. Each definition in Section 4.2 would then imply a conduct restriction that constrains the range of each firm's price. For example, Definition 1 would prevent the inclusive price from being less than marginal cost.[28]

We can formalize a conduct restriction by rewriting our decomposition (6) as[29]

$$
\begin{aligned}
mr_1(p_1, p_2(\mathbf{e})) - c(e_1) + \left[\sum_{k=1}^{5} \Gamma_1^k(\mathbf{e}) \pm \Gamma_1^3(\mathbf{e})\big|_{\phi_2=0} \pm \Gamma_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} \right] \\
+\Upsilon(p_2(\mathbf{e})) \left[\sum_{k=1}^{4} \Theta_1^k(\mathbf{e}) \pm \Theta_1^1(\mathbf{e})\big|_{\phi_2=0} \pm \Theta_1^1(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} \pm \Theta_1^3(\mathbf{e})\big|_{\phi_2=0} \pm \Theta_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} \right] = 0.
\end{aligned}
\tag{11}
$$

For each definition, a constraint $\Xi_1(p_1, p_2(\mathbf{e}), \mathbf{e}) = 0$ is formed by "switching off" the predatory incentives corresponding to that definition. For example, for Definition 2, the conduct restriction would force firm 1 to ignore the term $\sum_{k=1}^{4} \Theta_1^k(\mathbf{e}) = 0$, so the constraint on firm 1's maximization problem would be $\Xi_1(p_1, p_2(\mathbf{e}), \mathbf{e}) = mr_1(p_1, p_2(\mathbf{e})) - c(e_1) + \sum_{k=1}^{5} \Gamma_1^k(\mathbf{e}) = 0$. Firm 1's profit-maximization problem in the price-setting phase is then:

$$
\max_{p_1 \in \{\widehat{p}_1 : \Xi(\widehat{p}_1, p_2(\mathbf{e}), \mathbf{e}) = 0\}} \Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})
$$

For each definition of the predatory pricing incentive, we compute the Markov perfect equilibria of a counterfactual game in which each firm faces the conduct restriction implied by the definition. The pricing constraint facing each firm depends on equilibrium behavior and is thus endogenous to the equilibrium. As in our analysis above, we use homotopy methods to compute the counterfactual equilibria, and we characterize the counterfactual equilibrium correspondence using the same industry structure, conduct, and performance metrics used to characterize the actual equilibrium correspondence.

5.1 Counterfactual and equilibrium correspondences

We characterize the impact of these conduct restrictions in three steps. First, to build intuition, we illustrate graphically how the equilibrium correspondence with a conduct restriction compares to the actual equilibrium correspondence. Those graphs show how the conduct restrictions can "eliminate" certain equilibria. Second, over a wide set of parameterizations, we contrast the equilibria that are eliminated with those that survive. This sheds light on the extent to which predatory incentives, defined in various ways, are re-

[28]And since price exceeds marginal revenue, it thus rules out price less than marginal cost.

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

sponsible for “bad equilibria.” Third, we compare actual equilibria to the counterfactual equilibria that arise under the conduct restrictions corresponding to each definition. This sheds light on the impact of predatory incentives on industry structure, prices, and welfare. If a conduct restriction associated with a particular definition of predatory pricing incentives is beneficial, the predatory incentives can be inferred to be harmful; if not, the predatory incentives are arguably beneficial.

Figures 4–6 illustrate the counterfactual correspondence for Definitions 1–7 by plotting HHI^{∞} against ρ.[30] We superimpose the equilibrium correspondence $\mathbf{H}^{-1}(\rho)$ from Figure 3.

For Definitions 1 and 2, the counterfactual correspondence consists of a single main path represented by a flat line that is identical to the main path for the actual equilibrium. Thus, for values of ρ for which there are multiple equilibria ($\rho \in [0, 0.8)$), the conduct restrictions associated with Definitions 1 and 2 eliminated all of the equilibria except those resulting in a symmetric long-run industry structure. For example, for the showcase example of $\rho = 0.75$, the conduct restrictions under Definitions 1 and 2 eliminate two of three equilibria, including the trenchy equilibrium that gives rise to behavior that resembles conventional notions of predatory pricing.

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 two (Definition 7) loops. The counterfactual equilibria span the same range of industry structures as the actual equilibria. For these definitions, many of the actual equilibria appear to have a counterfactual counterpart “nearby.”

5.2 Eliminated and surviving equilibria

Figures 4–6 intuitively suggest that some equilibria are eliminated by a particular conduct restriction while other equilibria survive it. To make this intuition more precise, we perform a homotopy analysis that matches actual equilibria with counterfactual equilibria. Instead of abruptly “switching off” the predatory pricing incentive in equation (11), we gradually drive it to zero. For Definition 2, for example, we put a weight λ on the terms $\Theta_1^k(\mathbf{e}), k = 1, \ldots, 4$, 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 the actual equilibrium, and at $\lambda = 0$ we have the counterfactual equilibrium with the conduct restriction. We say that an equilibrium *survives the conduct restriction* if, starting from $\lambda = 1$, the homotopy reaches the counterfactual equilibrium correspondence. A surviving equilibrium smoothly deforms into a counterfactual equilibrium by gradually tightening the conduct restriction. We say

[30]The remaining slices along σ and $\overline{X}$ are presented in the Online Appendix.

metric		definition						
		1	2	3	4	5	6	7
	surv.	19%	19%	64%	56%	64%	65%	86%
	elim.	80%	77%	34%	44%	33%	35%	0%
HHI^{∞}	surv.	0.50	0.50	0.74	0.70	0.74	0.74	0.81
	elim.	0.90	0.91	0.99	0.99	0.99	0.99	NaN
EP^{∞}	surv.	2.99	2.99	5.45	5.05	5.45	5.50	6.24
	elim.	7.17	7.21	8.10	8.11	8.09	8.10	NaN
CS^{∞}	surv.	7.71	7.71	4.98	5.42	4.98	4.93	4.12
	elim.	3.09	3.05	2.07	2.05	2.07	2.07	NaN
TS^{∞}	surv.	9.70	9.70	9.07	9.21	9.07	9.05	8.76
	elim.	8.63	8.57	8.34	8.29	8.38	8.34	NaN
CS^{NPV}	surv.	158.28	158.28	158.96	160.54	158.96	158.64	154.66
	elim.	157.55	156.24	154.52	153.04	155.14	154.58	NaN
TS^{NPV}	surv.	172.48	172.48	167.86	169.85	167.86	167.49	162.83
	elim.	164.01	162.70	160.64	159.15	161.26	160.70	NaN

Table 7: Industry structure, conduct, and performance for eliminated and surviving equilibria for various definitions of predatory incentives, for a uniformly spaced grid $\rho \in \{0.05.0.10, \dots 1.0\}$ (limited to paramterizations with multiple equilibria).

that an equilibrium is *eliminated by the conduct restriction* if the homotopy algorithm returns to the actual equilibrium correspondence.[31]

Figure B, which plots HHI^{∞} against ρ, distinguishes between eliminated and surviving equilibria for Definitions 2 and 5. Definition 2 (which has similar effects to Definition 1) eliminates the trenchy equilibria that are associated with higher expected long-run Herfindahl indices whereas the flatter equilibria that are associated with lower expected long-run Herfindahl indices survive the conduct restriction. By contrast, Definition 5 (which is broadly representative of Definitions 3–7) allows some of the trenchier equilibria to survive, along with all of the flat ones. Still, with the exception of Definition 7, at least some of trenchy equilibria are eliminated.

Table 7 compares the surviving and eliminated equilibria for a uniformly spaced grid of parameter values $\rho \in \{0.05.0.10, \dots 1.0\}$.[32] The first row shows, for each definition of predatory incentives, the percentage of equilibria that survive the conduct restriction.[33] The more severe conduct restrictions based on Definitions 1 and 2 eliminate many more

[31]For an example of such return, see Figure 1, case B in Borkovsky et al. (2010). In cases in which a homotopy crashes, we deduce survival or elimination from adjacent equilibria along the solution path.

[32]The data reported in the table pertain only to those parameterization for which multiple equilibria occurred, and they represent averages across these parameterizations.

[33]The percentages in the table may not add to 100%. This is because in some cases, the homotopy crashed, and we were unable to deduce survival or elimination from adjacent equilibria along the solution path.

equilibria than the weaker conduct restrictions based on Definitions 3–7.

The remaining rows of Table 7 contrast the metrics of industry structure, conduct, and performance for eliminated and surviving equilibria. For all definitions, surviving equilibria involve less concentration, lower average long-run prices, higher long-run consumer and total surplus welfare, and higher discounted consumer and total surplus than the eliminated equilibria. Definitions 1 and 2 tend to have surviving equilibria with higher long-run consumer and total surplus and higher discounted total surplus than the surviving equilibria under (the weaker) Definitions 3–7. However, the weaker definitions tend to have surviving equilibria with slightly higher levels of discounted consumer surplus. This is because some trenchy equilibria that involve moderately strong competition for the market survive the conduct restrictions for the weaker definitions, but are eliminated by the conduct restrictions for the stronger definitions.

These results indicate that under any definition, removing the predatory pricing incentive can eliminate "bad equilibria," with Definitions 1 and 2 eliminating a much larger set of "bad equilibria" than Definitions 3–7. Defining unlawful predation according to Definitions 3–7 would thus be compatible with some trenchy equilibria in which the market can evolve into a monopoly. By contrast, using Definition 1 or 2 to identify unlawful predation would generally be incompatible with equilibria that give rise to long-run asymmetries among firms.

5.3 Impact of predatory incentives

The survival-elimination analysis indicates the extent to which predatory incentives are responsible for "bad equilibria," but it does not directly illustrate the economic impact of the predatory pricing incentives. This economic impact is revealed by the impact of the associated conduct restriction on equilibrium outcomes, and this involves comparing counterfactual equilibria to actual equilibria.

But the multiplicity of equilibria complicates such a comparison: for a given parameterization, which counterfactual equilibria should be compared to which actual equilibria? To answer this question, we need to posit an out-of-equilibrium process by which agents adjust to the shock to the system implied by the imposition of the conduct restriction.

To deal with this, we proceed as follows. 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 is plausible that it would lead to this counterfactual (Doraszelski & Escobar 2010). Thus, for a given parameterization, we compare each surviving equilibrium to its counterfactual counterpart. For an eliminated equilibrium, in contrast, we assume that all counterfactuals (at the same parameterization) are equally likely. Thus, we compare the structure, conduct, and performance metrics for each eliminated equilibrium to the value of these metrics averaged across all counterfactual equilibria for that parameterization. To be precise, imagine that for a given parameterization, we have I equilibria with measures $x_1^s, ..., x_I^s$ for a particular structure, conduct, performance metric s. Assume that for Definition d, the first $J < I$ equilibria survive the associated conduct restriction, and the measures for the corresponding counterfactual equilibria with the conduct restriction are $y_1^{ds}, ..., y_J^{ds}$. In addition, there are $K - J$ counterfactuals that have no corresponding equilibrium and measures $y_{J+1}^{ds}, ..., y_K^{ds}$. The impact Z_{ds} of conduct restriction d on metric s is then:[34]

$$Z_{ds} = \frac{1}{I}\left[\sum\nolimits_{i=1}^{J}\left(y_i^{ds} - x_i^s\right) + \sum\nolimits_{i=J+1}^{I}\left(\frac{1}{K}\sum\nolimits_{j=1}^{K} y_j^{ds} - x_i^s\right)\right].$$

Table 8 summarizes conduct restriction impacts $Z_{ds}(\rho)$ for the grid $\rho \in \{0.05.0.10, \ldots 1.0\}$.[35] Each cell pertains to a particular (d, s) combination and reports the percentage of parameterizations for which $Z_{ds}(\rho) > 0$ and $Z_{ds}(\rho) < 0$. It also shows the average impact across all parameterizations, i.e., $\overline{Z}_{ds} = \sum_{\rho \in \{0.05.0.10,\ldots 1.0\}} \frac{Z_{ds}(\rho)}{20}$.

For all definitions, the associated conduct restrictions tend to improve long-run outcomes, i.e., they tend to decrease long-run price and market concentration and increase long-run per-period consumer and total surplus. The long-run impact of the conduct restrictions for Definitions 1 and 2 is both more pronounced and more unambiguously beneficial than for Definitions 3–7. For example, the conduct restrictions for Definitions 1 and 2 increase CS^∞ in 80% of the parameterizations in the grid and never decrease it. On average, CS^∞ goes up by 2.8 for each definition, an increase of about 75% over the average value in the actual equilibria. By contrast, the conduct restrictions for Definitions 3-6 increase long-run consumer surplus in 50 to 55% of the parameterizations and (except for Definition 7) decrease it in 25% of them. On average these conduct restrictions increase CS^∞ by 8 to 24% depending on the definition. The generally large impact of the predatory incentives under Definitions 1 and 2 arise because they are, in effect, necessary for the trenchy equilibria. The conduct restrictions for these definitions preserve the flat equilibria along

[34]For example, for the baseline parameterization recall from Section 3.1 there were three equilibria. HHI^∞ for these equilibria was 0.50, 0.58, and 0.96, respectively. Imposing the conduct restriction associated with Definition 1 eliminates the latter two equilibria, while the first equilibrium survives. The counterfactual equilibrium with the conduct restriction has $HHI^\infty = 0.5$. The three actual equilibria are then compared to this sole counterfactual, and thus

$$\begin{aligned} Z_{1,HHI^\infty} &= \frac{[(0.50 - 0.50) + (0.50 - 0.58) - (0.50 - 0.96)]}{3} \\ &= -0.18. \end{aligned}$$

[35]The Online Appendix presents analogous tables for σ and $\overline{X}$.

		definitions						
metric		1	2	3	4	5	6	7
$\overline{p}^{\infty}$	Up	-	-	25%	25%	25%	25%	-
Avg=	Down	80%	80%	50%	55%	50%	50%	55%
6.7653	Change	-2.5435	-2.5435	-0.5411	-0.8043	-0.5425	-0.5185	-0.2766
HHI^{∞}	Up	-	-	25%	25%	25%	25%	-
Avg=	Down	80%	80%	50%	55%	50%	50%	40%
0.7406	Change	-0.2406	-0.2406	-0.0558	-0.0816	-0.0560	-0.0536	-0.0234
CS^{∞}	Up	80%	80%	50%	55%	50%	50%	55%
Avg=	Down	-	-	25%	25%	25%	25%	-
3.7407	Change	+2.8046	+2.8046	+0.6001	+0.8913	+0.6017	+0.5752	+0.3027
TS^{∞}	Up	80%	80%	50%	55%	50%	50%	35%
Avg=	Down	-	-	-	-	-	5%	-
7.6554	Change	+0.7411	+0.7411	+0.1701	+0.2496	+0.1706	+0.1633	+0.0728
CS^{NPV}	Up	-	-	-	10%	-	45%	-
Avg=	Down	95%	75%	60%	45%	60%	-	75%
132.26	Change	-62.8235	-2.9228	-2.7762	-2.3527	-2.7690	+0.7673	-2.2480
TS^{NPV}	Up	-	80%	50%	55%	50%	50%	20%
Avg=	Down	95%	-	-	-	-	-	-
142.04	Change	-9.6971	+5.9320	+1.4464	+2.0791	+1.4466	+1.3928	+0.6780

Table 8: Impact of conduct restriction for $\rho \in \{0.05, 0.10, \ldots, 1.0\}$.

MP but eliminate all of the trenchy equilibria that arise for ρ less than about 0.8. On the other hand, the conduct restriction for a definition such as Definition 3 not only does not eliminate some of moderately trenchy equilibria on the lower fold of the semi-loop SL, but it actually causes these equilibria to morph into equilibria with a greater degree of long-run concentration.

In contrast to the long-run impacts, the impact of the conduct restrictions on discounted consumer and total surplus is mixed. For Definitions 1-5 and 7, the corresponding conduct restrictions generally reduce discounted consumer surplus CS^{NPV}. This is due to the elimination of the trenchiest equilibria that involve very intense competition for the market. This effect is particularly large for Definition 1. The exception to this pattern is Definition 6. The conduct restriction associated with this definition (which identified the predatory pricing incentive with the advantage-denying/exit motive) increases CS^{NPV} in 45% of the parameterizations in the grid and never decreases it. This is because the intense competition for the market in an emerging industry is not due to the advantage-denying/exit motive (recall Table 5), and so a conduct restriction based on Definition 6 does not restrict the aggressive price competition between two firms who are on equal footing at the top of the learning curve.

The conduct restrictions associated with Definitions 2-7 tend to increase discounted total surplus TS^{NPV}, while TS^{NPV} decreases for the conduct restriction associated with Definition 1. The decrease in total surplus from the Definition 1-conduct restriction is due to slower learning in the industry as a whole that occurs when firms are constrained from charging a price for which marginal revenue is less than marginal cost.[36]

Summing up, our impact analysis has several implications: First, our various definitions can be thought of offering different "takes" on what Edlin (2010) calls Stephen Breyer's "bird-in-hand" view of predatory pricing. In *Barry Wright Corp. v. ITT Grinnell Corp.*, then-Judge (and now U.S. Supreme Court Justice) 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]."[37] Breyer's

[36]Because it covers a large grid of possible values of ρ, the data in Table 8 provides a "broad brush" view of the impact of the conduct restrictions associated each definition of predatory incentives. Since it seems possible that a conduct restriction could have a different impact depending on parameter values, one might prefer a more "scalpel-like" approach to examining economic impact of conduct restrictions.

To address this concern, the Online Appendix presents a table with the same data as in Table 8 except it confines attention to a smaller grid of progress ratios, $\rho \in \{0.70.0.75, \ldots 0.90\}$ that coincides with the empirically relevant range. Though the impact of the conduct restrictions are muted (since there are fewer trenchy equilibria to eliminate in this range), the pattern of impacts is broadly similar to that shown in Table 8. Except for Definition 7, there was no conduct restriction whose impact was qualitatively different from that shown on Table 8. Over the empirically relevant range, Definition 7 had a negligible impact on all of structure, conduct, and performance.

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

"bird in hand" view might be thought of one that gives more weight to the immediate benefits of short-run *competition for the market* as opposed to the future benefits of long-run *competition in the market*. Our impact analysis indicates that to the extent that antitrust policy inclines toward Breyer's "bird in hand" view, our weaker definitions (Definitions 3-7) of predatory incentives would be appealing; conduct restrictions based on these definitions tend to "reject" fewer "birds in hand." On the other hand, to the extent that antitrust policy inclines away from Breyer's "bird in hand" view—thus placing greater weight on preserving competition in the market—the stronger definitions (Definitions 1 and 2) would be a more compelling basis for defining predatory incentives.[38]

Second, defining the predatory pricing incentive according to Definition 1 is impactful, but very restrictive. Though this restriction eliminates all trenchy equilibria and thus improves long-run outcomes, it also stifles aggressive price competition to attain a competitive advantage based on lower cost. This hurts consumers in the early stages of industry evolution, and it reduces total surplus by slowing the rate at which firms move down their learning curves. In an industry in which learning-based cost advantages are potentially important, Definition 1 tends to "throw the baby" (aggressive price competition to attain a cost advantage) "out with the bath water" (trenchy equilibria that involve predation-like behavior).

Third, there is no definition of predatory incentives that is unambiguously harmful in the sense that the associated conduct restriction increases long-run per-period consumers and total surplus and, at the same time, also increases discounted consumer and total surplus. In this respect, our analysis echoes a point made by Cabral & Riordan (1997): predatory pricing (however defined) can sometimes be welfare improving. That said, two definitions come close to the implication that predatory incentives are unambiguously harmful: Definitions 2 and 6. The conduct restriction based on Definition 2 causes fairly small decreases in CS^{NPV} (only about 2.2% of actual equilibrium values when averaged over all parameterizations in the grid) but otherwise unambiguously increases CS^{∞}, TS^{∞}, and TS^{NPV}.[39] The conduct restriction based on Definition 6 may slightly decrease CS^{∞} and TS^{∞} for some parameterizations, but more often than not it increases CS^{∞} and TS^{∞}, and it unambiguously increases CS^{NPV} and TS^{NPV}.

What unifies Definitions 2 and 6 is their emphasis on the advantage-denying motive as

[38] Edlin (2010) argues that Breyer's "bird-in-hand" view is actually fallacious because it presumes entry, but in equilibrium entry may not occur. Our analysis provides some support for this view because in a trenchy equilibria, once one firm exits the market, future entry does not occur even though it is theoretically possible and the incumbent firm is still close to the top of its learning curve.

[39] A relatively small increase in the discount factor used to compute CS^{NPV} (holding the firms' discount factors fixed) would make the average impact of conduct restriction associated with Definition 2 on CS^{NPV} switch from negative to positive. Thus, if the social rate of time preference was sufficiently less than the firms' cost of capital, the conduct restriction associated with Definition 2 would unambiguously increase consumer and total welfare in the long run and the short run.

the basis of predation. This suggests that a sensible way to draw the line that separates efficiency-enhancing pricing behavior from predatory pricing behavior is based on the extent to which the behavior is driven by *exclusion of opportunity.* If a firm's aggressive pricing behavior is primarily driven by the benefits from building its own competitive advantage, the behavior should be considered to be benign and (arguably) should not be restricted. If, by contrast, the behavior is primarily driven by the benefits from excluding a rival from the opportunity to build its own advantage or overcome an existing disadvantage, the behavior should be considered predatory and (arguably) should be restricted. Of course, because Definitions 2 and 6 are different (the former embodying a stronger notion of predation than the latter), there is some latitude for how to draw this line. In particular, the choice between these two definitions would depend, as just discussed, on whether antitrust policy seeks to emphasize competition in the market or competition for the market. Still, broadly speaking, our analysis highlights that the distinction between efficiency motives in pricing from predatory motives is closely related to the distinction between advantage-building motives and advantage-denying motives.

6 Conclusions

Our analysis shows how predatory pricing can be analyzed in a modern industry dynamics framework. We have analyzed and computed equilibria for a dynamic stochastic game with learning-by-doing, and by decomposing the equilibrium pricing condition, we proposed a variety of ways to describe a firm's predatory pricing incentives. Some of these definitions map into definitions of predation that have been offered in the economics literature. Moreover, these definitions correspond to alternative implementations of sacrifice standards to test for the presence of predatory pricing. Based on computations of equilibria using a baseline set of parameterizations, we show the economic impact of these incentives on long-run and transitory industry dynamics for (virtually) full ranges of values of the progress ratio of the learning curve, the degree of product differentiation, and the scrap value.

Because our results are based on computations and not formal proofs, they are, of course, necessarily tentative. We nevertheless believe that our results are suggestive and can enrich policy discussions of predatory pricing. Here, we emphasize three implications.

First, our analysis confirms the analytical finding of Cabral & Riordan (1994) that behavior that resembles conventional notions of predatory pricing can arise as a Markov perfect equilibrium in a dynamic pricing game with learning-by-doing. This equilibrium behavior is rooted in the fundamentals of demand and cost, rather than asymmetric information or capital market imperfections. And going beyond the "possibility" result in Cabral & Riordan (1994), we show that the equilibria that spawn predatory behavior are not special cases or the results of extreme parameterizations. Rather, they arise for empirically plausible parameter values and occur over rather wide ranges of certain parameter values. For example, the trenchy equilibria that give rise to predation-like behavior arise for all progress ratios less than about 0.80. Overall, our analysis, at the very least, calls into question the claim that economic theory implies that predatory pricing is a myth and need not taken seriously by antitrust authorities.

Second, the multiplicity of equilibria in our model confirms an important point about predatory pricing made by Edlin (2010) who writes: "Whether predation is a successful strategy depends very much on whether predator and prey believe it is successful strategy." 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. As we have shown, conduct restrictions that force firms to ignore these incentives can short-circuit some of these expectations and eliminate some or all (depending on the definition of predatory incentives) of the trenchy equilibria that spawn predation-like behavior.

Third, our analysis has implications for defining predatory pricing incentives in situations in which a firm's aggressive pricing may reflect both efficiency and predatory considerations, and this in turn can provide insight into how a sacrifice test might be framed under such circumstances. We find that definitions of predatory pricing incentives based on EEEC profit functions that emphasize the direct impact of pricing on rival exit—in particular Definitions 3–7—seem, on average to have a relatively modest impact on long-run equilibrium outcomes. By contrast, when predatory incentives are defined by Definition 1—a definition that equates any departure from short-run profit maximization with predation—the predatory incentives have a significant impact on long-run outcomes. This is because removing these incentives tends to eliminate all the trenchy equilibria which give rise to long-run monopolization of the industry. But as firms move toward the long run, these incentives also tend to lead to lower prices. In particular, the advantage-building motives that are included within them are responsible for intense competition for the market in an emerging duopoly. Our analysis suggests that in markets with learning curves, equating predation with Definition 1 incentives may involve giving up considerable consumer surplus (and modest amounts of total surplus) as the industry transitions to an eventual state of maturity. An advantage of sacrifice standards based on the "less strict" definitions of predation-like Definitions 3-7 is that they could achieve *some* improvements in long-run outcomes, without the large costs to consumers in the short run that would come from a standard based on Definition 1. Put another way, if one believes that a good policy is one that bends over backwards to avoid labeling aggressive pricing as predatory in situations where firms are competing for efficiency-based advantages, then one might prefer standards based on Definitions 3–7.

Overall, our analysis suggests that the definitions of predatory incentives that reflect the best balance of long-run and short-run welfare effects are Definitions 2 and 6. Both definitions emphasize advantage-denying motives — Definition 2 equates predatory incentives with the entire advantage-denying motive, while Definition 6 equates predatory incentives with the advantage-denying/exit motive — and thus they are both squarely focused on exclusion of opportunity as the basis of predation. While conduct restrictions based on each definition do not unambiguously increase long-run and short-run consumer and total surplus for all of the parameterizations we studied, they come close to achieving this welfare dominance. Thus, by defining predatory incentives according to either of these definitions, a policy maker would minimize the likelihood of proscribing predatory behavior that enhances consumer or total welfare in the long run or short run. The choice between these definitions would rest on whether one is more concerned about making policy errors that tend to reduce competition in the market or competition for the market.

A Appendix: Omitted expressions

A.1 Expectations and probabilities

Given the assumed distribution for scrap values, the probability of incumbent firm 1 exiting the industry in state $\mathbf{e}'$ is

$$\begin{aligned}
\phi_1(\mathbf{e}') &= E_X\left[\phi_1(\mathbf{e}', X_1)\right] \\
&= \int \phi_1(\mathbf{e}', X_1)dF_X(X_1) = 1 - F_X(\widehat{X}_1(\mathbf{e}')) \\
&= \begin{cases} 1 & \text{if} \quad \widehat{X}_1(\mathbf{e}') < \overline{X} - \Delta_X, \\ \frac{1}{2} - \frac{\left[\widehat{X}_1(\mathbf{e}') - \overline{X}\right]}{2\Delta_X} & \text{if} \quad \widehat{X}_1(\mathbf{e}') \in [\overline{X} - \Delta_X, \overline{X} + \Delta_X], \\ 0 & \text{if} \quad \widehat{X}_1(\mathbf{e}') > \overline{X} + \Delta_X. \end{cases}
\end{aligned}$$

and the expectation of the scrap value conditional on exiting the industry is

$$\begin{aligned}
E_X\left[X_1 | X_1 \geq \widehat{X}_1(\mathbf{e}')\right] &= \frac{\int_{F_X^{-1}(1-\phi_1(\mathbf{e}'))}^{\overline{X}+\Delta_X} X_1 dF_X(X_1)}{\phi_1(\mathbf{e}')} \\
&= \frac{1}{\phi_1(\mathbf{e}')}\left[Z_X(0) - Z_X\left(1 - \phi_1(\mathbf{e}')\right)\right],
\end{aligned}$$

where

$$Z_X\left(1-\phi\right)=\frac{1}{\Delta_X^2}\begin{cases} -\frac{1}{6}\left(\overline{X}-\Delta_X\right)^3 & \text{if} \quad 1-\phi\leq 0, \\ \frac{1}{2}\left(\Delta_X-\overline{X}\right)\left(F_X^{-1}(1-\phi)\right)^2+\frac{1}{3}\left(F_X^{-1}(1-\phi)\right)^3 & \text{if} \quad 1-\phi\in\left[0,\frac{1}{2}\right], \\ \frac{1}{2}\left(\Delta_X+\overline{X}\right)\left(F_X^{-1}(1-\phi)\right)^2-\frac{1}{3}\left(F_X^{-1}(1-\phi)\right)^3-\frac{1}{3}\overline{X}^3 & \text{if} \quad 1-\phi\in\left[\frac{1}{2},1\right], \\ \frac{1}{6}\left(\overline{X}+\Delta_X\right)^3-\frac{1}{3}\overline{X}^3 & \text{if} \quad 1-\phi\geq 1 \end{cases}$$

and

$$F_X^{-1}(1-\phi)=\overline{X}+\Delta_X\begin{cases} -1 & \text{if} \quad 1-\phi\leq 0, \\ -1+\sqrt{2\left(1-\phi\right)} & \text{if} \quad 1-\phi\in\left[0,\frac{1}{2}\right], \\ 1-\sqrt{2\phi} & \text{if} \quad 1-\phi\in\left[\frac{1}{2},1\right], \\ 1 & \text{if} \quad 1-\phi\geq 1. \end{cases}$$

Given the assumed distribution for setup costs, the probability of potential entrant 1 not entering the industry in state $\mathbf{e}'$ is

$$\begin{aligned} \phi_1(\mathbf{e}') &= E_S\left[\phi_1(\mathbf{e}',S_1)\right] \\ &= \int \phi_1(\mathbf{e}',S_1)dF_S(S_1)=1-F_S(\widehat{S}_1(\mathbf{e}')) \\ &= \begin{cases} 1 & \text{if} \quad \widehat{S}_1(\mathbf{e}')<\overline{S}-\Delta_S, \\ \frac{1}{2}-\frac{\left[\widehat{S}_1(\mathbf{e}')-\overline{S}\right]}{2\Delta_S} & \text{if} \quad \widehat{S}_1(\mathbf{e}')\in[\overline{S}-\Delta_S,\overline{S}+\Delta_S], \\ 0 & \text{if} \quad \widehat{S}_1(\mathbf{e}')>\overline{S}+\Delta_S \end{cases} \end{aligned}$$

and the expectation of the setup cost conditional on entering the industry is

$$\begin{aligned} E_S\left[S_1|S_1\leq\widehat{S}_1(\mathbf{e}')\right] &= \frac{\int_{\overline{S}-\Delta_S}^{F_S^{-1}(1-\phi_1(\mathbf{e}'))}S_1dF_S(S_1)}{(1-\phi_1(\mathbf{e}'))} \\ &= \frac{1}{\phi_1(\mathbf{e}')}\left[Z_S\left(1-\phi_1(\mathbf{e}')\right)-Z_S\left(1\right)\right], \end{aligned}$$

where

$$Z_S\left(1-\phi\right)=\frac{1}{\Delta_S^2}\begin{cases} -\frac{1}{6}\left(\overline{S}-\Delta_S\right)^3 & \text{if} \quad 1-\phi\leq 0, \\ \frac{1}{2}\left(\Delta_S-\overline{S}\right)\left(F_S^{-1}(1-\phi)\right)^2+\frac{1}{3}\left(F_S^{-1}(1-\phi)\right)^3 & \text{if} \quad 1-\phi\in\left[0,\frac{1}{2}\right], \\ \frac{1}{2}\left(\Delta_S+\overline{S}\right)\left(F_S^{-1}(1-\phi)\right)^2-\frac{1}{3}\left(F_S^{-1}(1-\phi)\right)^3-\frac{1}{3}\overline{S}^3 & \text{if} \quad 1-\phi\in\left[\frac{1}{2},1\right], \\ \frac{1}{6}\left(\overline{S}+\Delta_S\right)^3-\frac{1}{3}\overline{S}^3 & \text{if} \quad 1-\phi\geq 1 \end{cases}$$

and

$$F_S^{-1}(1-\phi)=\overline{S}+\Delta_S\begin{cases} -1 & \text{if} \quad 1-\phi\leq 0, \\ -1+\sqrt{2\left(1-\phi\right)} & \text{if} \quad 1-\phi\in\left[0,\frac{1}{2}\right], \\ 1-\sqrt{2\phi} & \text{if} \quad 1-\phi\in\left[\frac{1}{2},1\right], \\ 1 & \text{if} \quad 1-\phi\geq 1. \end{cases}$$

A.2 Marginal revenue and inclusive price

$mr_1(p_1, p_2(\mathbf{e}))$ is the marginal revenue of incumbent firm 1 with respect to quantity and therefore analogous to the traditional textbook concept. To see this, let $q_1 = D_1(p_1, p_2(\mathbf{e}))$ be demand and $p_1 = P_1(q_1, p_2(\mathbf{e}))$ inverse demand as implicitly defined by $q_1 = D_1(P_1(q_1, p_2(\mathbf{e})), p_2(\mathbf{e}))$. The marginal revenue of incumbent firm 1 is

$$MR_1(q_1, p_2(\mathbf{e})) = \frac{\partial \left[q_1 P_1(q_1, p_2(\mathbf{e}))\right]}{\partial q_1} = q_1 \frac{\partial P_1(q_1, p_2(\mathbf{e}))}{\partial q_1} + P_1(q_1, p_2(\mathbf{e})). \tag{12}$$

Define $mr_1(p_1, p_2(\mathbf{e})) = MR_1(D_1(p_1, p_2(\mathbf{e})), p_2(\mathbf{e}))$ to be the marginal revenue of incumbent firm 1 evaluated at the quantity $q_1 = D_1(p_1, p_2(\mathbf{e}))$ corresponding to prices p_1 and $p_2(\mathbf{e})$. Then we have

$$\frac{\partial P_1(D_1(p_1, p_2(\mathbf{e})), p_2(\mathbf{e}))}{\partial q_1} = \left[\frac{\partial D_1(p_1, p_2(\mathbf{e}))}{\partial p_1}\right]^{-1} = -\frac{\sigma}{\left[1 - D_1(p_1, p_2(\mathbf{e}))\right] D_1(p_1, p_2(\mathbf{e}))}. \tag{13}$$

Substituting equation (13) into equation (12), it follows that $mr_1(p_1, p_2(\mathbf{e})) = p_1 - \frac{\sigma}{1 - D_1(p_1, p_2(\mathbf{e}))}$.

A.3 Producer surplus

The producer surplus of firm 1 in state $\mathbf{e}$ is

$$\begin{aligned} PS_1(\mathbf{e}) = 1\left[e_1 > 0\right] \Big\{ & D_0(\mathbf{e})\phi_1(\mathbf{e}) E_X \left[X_1 | X_1 \geq \widehat{X}_1(\mathbf{e})\right] \\ & + D_1(\mathbf{e}) \left\{ p_1(\mathbf{e}) - c(e_1) + \phi_1(e_1+1, e_2) E_X \left[X_1 | X_1 \geq \widehat{X}_1(e_1+1, e_2)\right] \right\} \\ & + D_2(\mathbf{e})\phi_1(e_1, e_2+1) E_X \left[X_1 | X_1 \geq \widehat{X}_1(e_1, e_2+1)\right] \Big\} \\ -1\left[e_1 = 0\right] \Big\{ & D_0(\mathbf{e}) \left(1 - \phi_1(\mathbf{e})\right) E_S \left[S_1 | S_1 \leq \widehat{S}_1(\mathbf{e})\right] \\ & + D_1(\mathbf{e}) \left(1 - \phi_1(e_1+1, e_2)\right) E_S \left[S_1 | S_1 \leq \widehat{S}_1(e_1+1, e_2)\right] \\ & + D_2(\mathbf{e}) \left(1 - \phi_1(e_1, e_2+1)\right) E_S \left[S_1 | S_1 \leq \widehat{S}_1(e_1, e_2+1)\right] \Big\}. \end{aligned}$$

The first set of terms represents the contingency that firm 1 is an incumbent that participates in the product market and receives a scrap value upon exit; the second set the contingency that firm 1 is an entrant that incurs a setup cost upon entry.

B Appendix: Proofs

Proof of Proposition 2. 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

$$\begin{aligned} mr_1(\widetilde{p}_1, p_2(\mathbf{e})) - c(e_1) + \left[\Gamma_1^1(\mathbf{e}) + \Gamma_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} + \Gamma_1^4(\mathbf{e}) + \Gamma_1^5(\mathbf{e})\right] \\ + \Upsilon(p_2(\mathbf{e})) \left[\Theta_1^1(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} + \Theta_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} + \Theta_1^4(\mathbf{e})\right] = 0. \end{aligned} \tag{14}$$

Subtracting equation (6) from equation (14), we have

$$\begin{aligned} mr_1(\widetilde{p}_1, p_2(\mathbf{e})) - mr_1(p_1(\mathbf{e}), p_2(\mathbf{e})) = \left[\Gamma_1^2(\mathbf{e}) + \left[\Gamma_1^3(\mathbf{e}) - \Gamma_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})}\right]\right] \\ + \Upsilon(p_2(\mathbf{e})) \left[\left[\Theta_1^1(\mathbf{e}) - \Theta_1^1(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})}\right] + \Theta_1^2(\mathbf{e}) + \left[\Theta_1^3(\mathbf{e}) - \Theta_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})}\right]\right] > 0 \end{aligned}$$

per inequality (8). 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

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

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

$$\begin{aligned} &\Phi_2(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e}) - \Phi_2(\widetilde{p}_1, p_2(\mathbf{e}), \mathbf{e}) \\ &= \left[D_1(p_1(\mathbf{e}), p_2(\mathbf{e})) - D_1(\widetilde{p}_1, p_2(\mathbf{e}))\right] \left[\phi_2(e_1+1, e_2) - \phi_2(\mathbf{e})\right] \\ &- \left[D_2(p_1(\mathbf{e}), p_2(\mathbf{e})) - D_2(\widetilde{p}_1, p_2(\mathbf{e}))\right] \left[\phi_2(\mathbf{e}) - \phi_2(e_1, e_2+1)\right] > 0. \end{aligned} \tag{15}$$

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 (15) 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

$$\begin{aligned}\frac{\partial\, \Pi_1(p_1(\mathbf{e}),p_2(\mathbf{e}),\mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})}}{\partial p_1} &= mr_1(p_1(\mathbf{e}),p_2(\mathbf{e})) - c(e_1)\\ &+ \left[\Gamma_1^1(\mathbf{e}) + \Gamma_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} + \Gamma_1^4(\mathbf{e}) + \Gamma_1^5(\mathbf{e})\right]\\ &+\Upsilon(p_2(\mathbf{e}))\left[\Theta_1^1(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} + \Theta_1^3(\mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})} + \Theta_1^4(\mathbf{e})\right] < 0. \end{aligned} \tag{16}$$

Subtracting inequality (16) from equation (6) then yields

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

■

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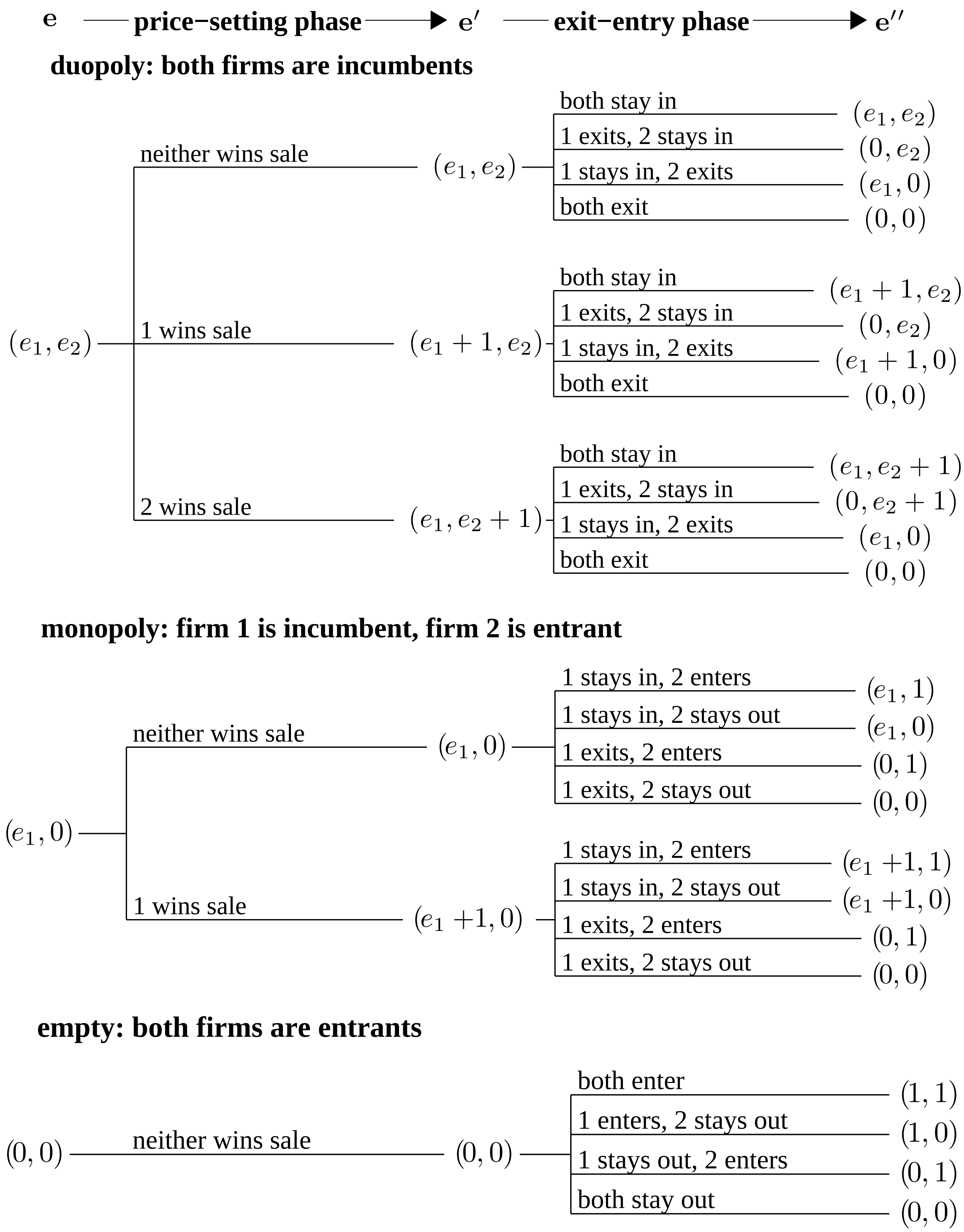

Figure 1: Possible state-to-state transitions.

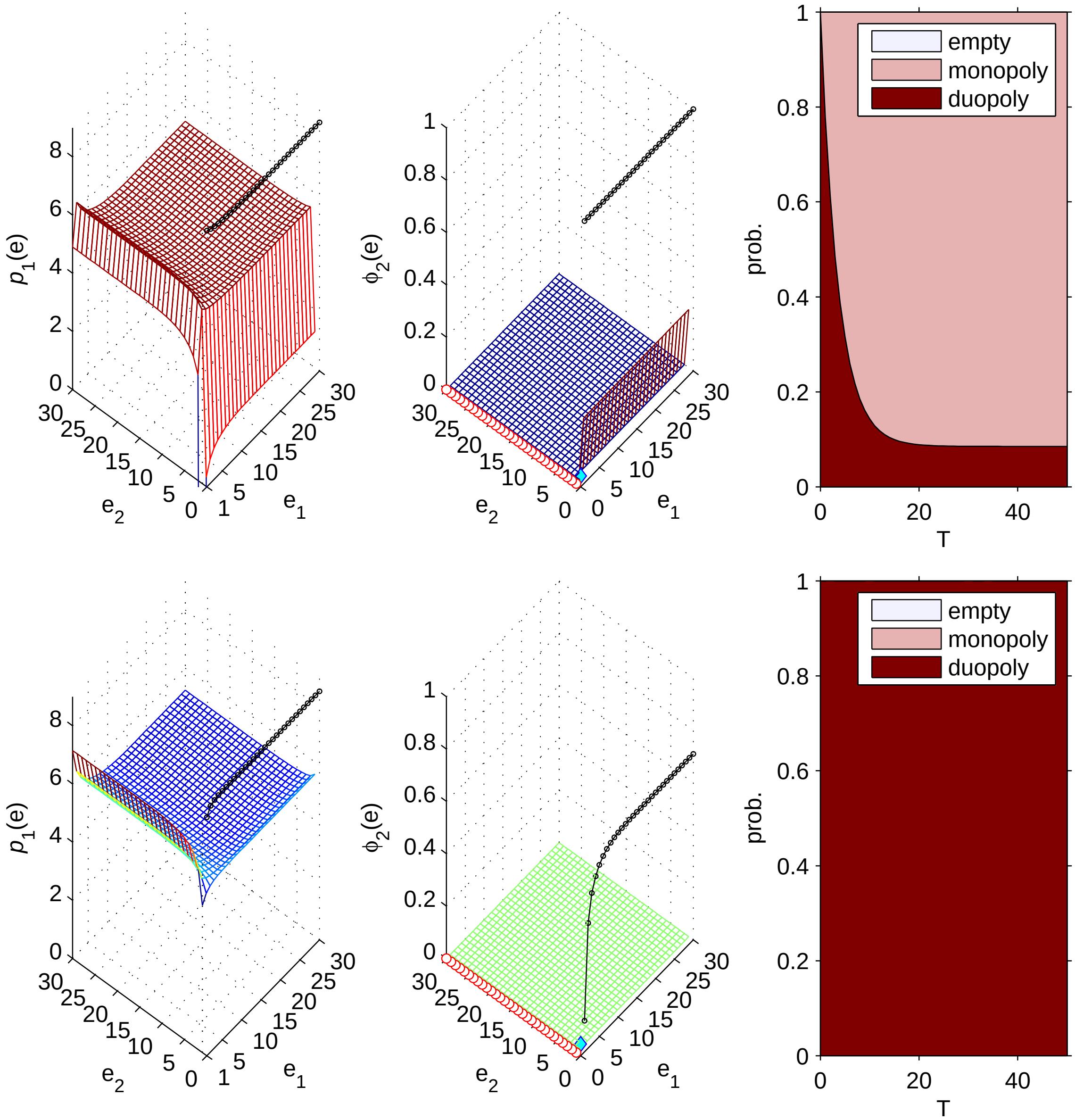

Figure 2: Pricing decision of firm 1 (left panels), non-operating probability of firm 2 (middle panels), and time path of probability distribution over industry structures, starting from $\mathbf{e} = (1, 1)$ at $T = 0$ (right panels). Trenchy (upper panels) and flat (lower panels) equilibria.

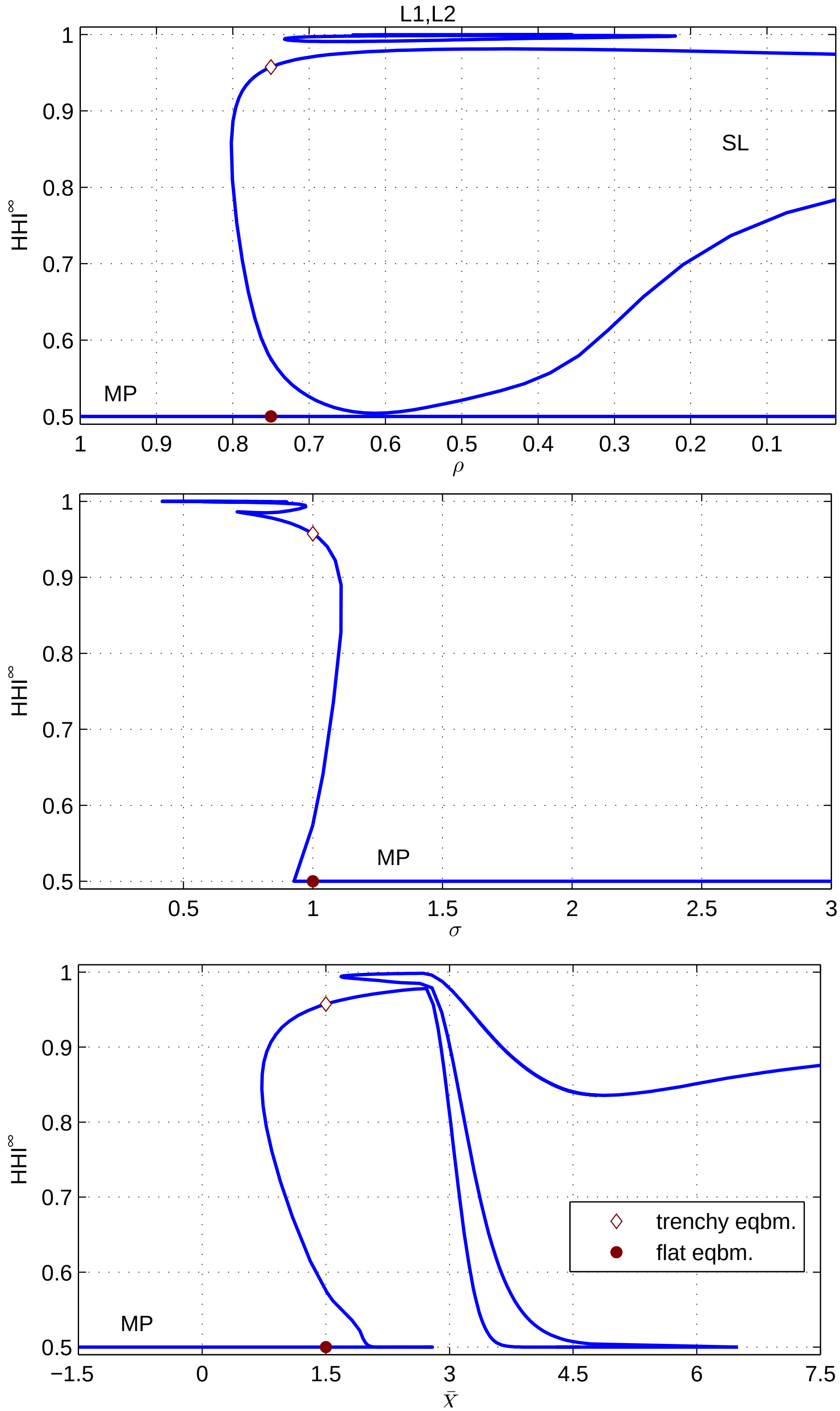

Figure 3: Expected long-run Herfindahl index. Equilibrium correspondence: slice along $\rho \in [0, 1]$ (upper panel), $\sigma \in [0.3, 3]$ (middle panel), and $\overline{X} \in [-1.5, 7.5]$ (lower panel).

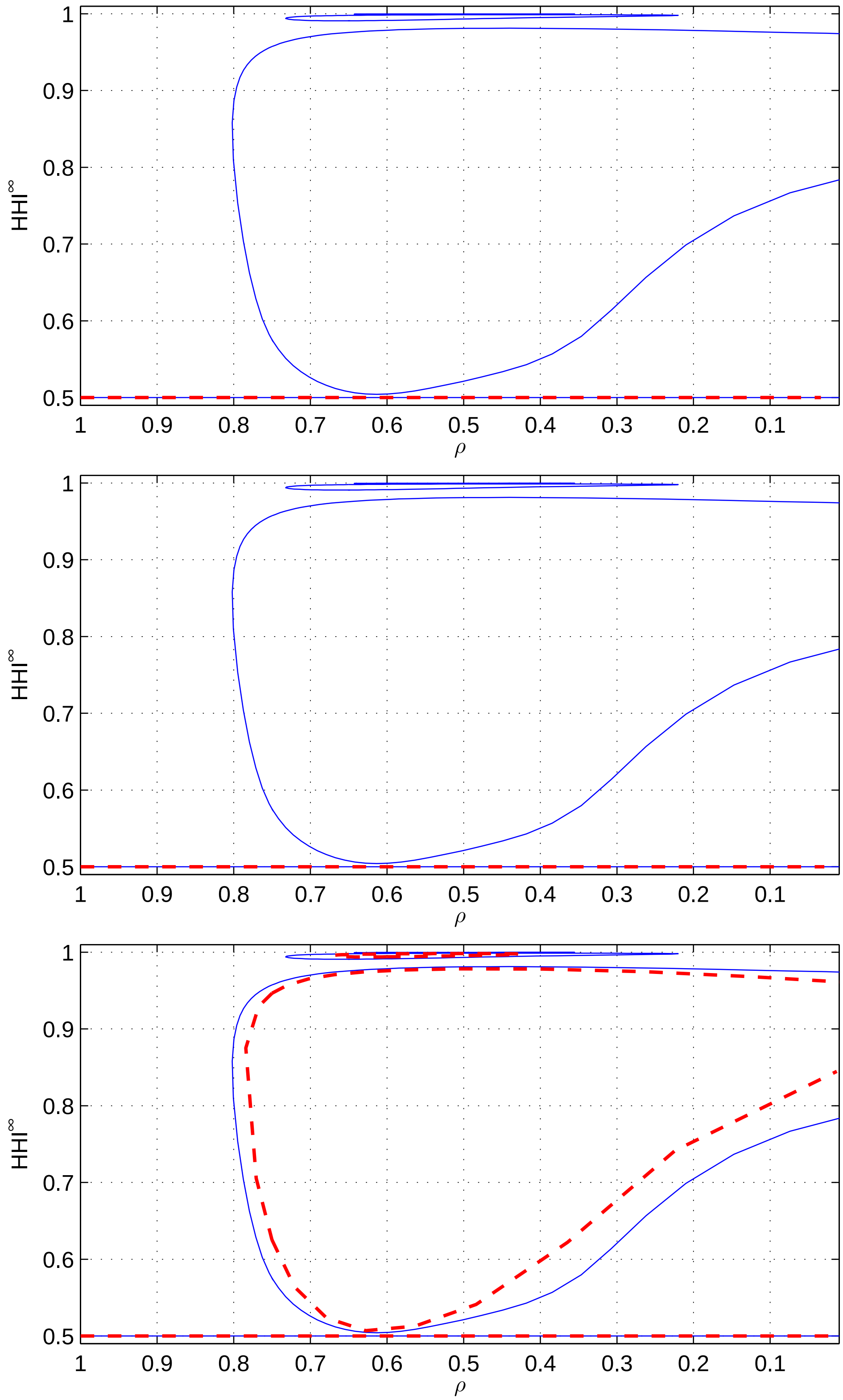

Figure 4: Expected long-run Herfindahl index. Equilibrium and counterfactual correspondences for Definitions 1–3 (upper, middle, and lower panels). Slice along $\rho \in [0, 1]$.

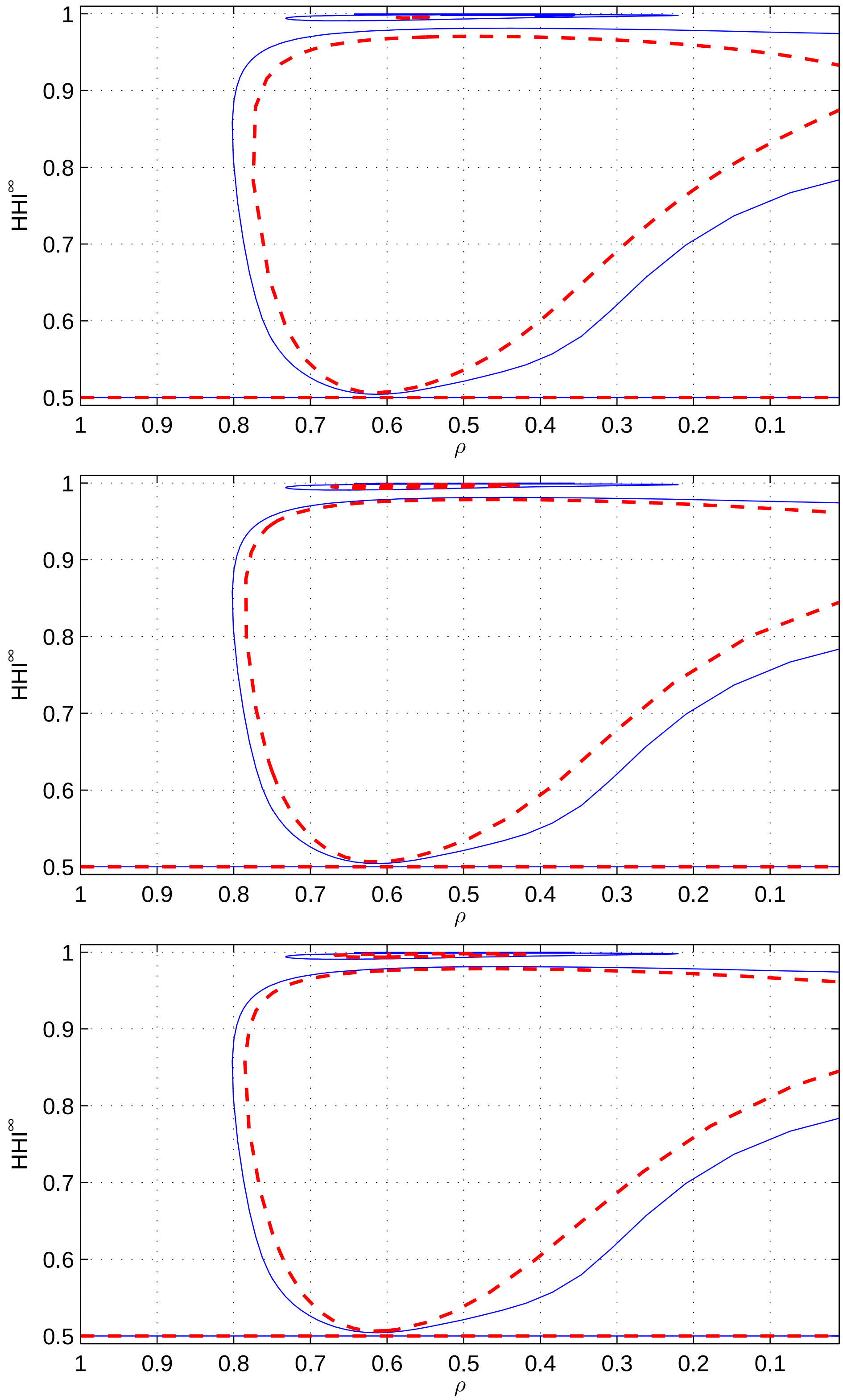

Figure 5: Expected long-run Herfindahl index. Equilibrium and counterfactual correspondences for Definitions 4–6 (upper, middle, and lower panels). Slice along $\rho \in [0, 1]$.

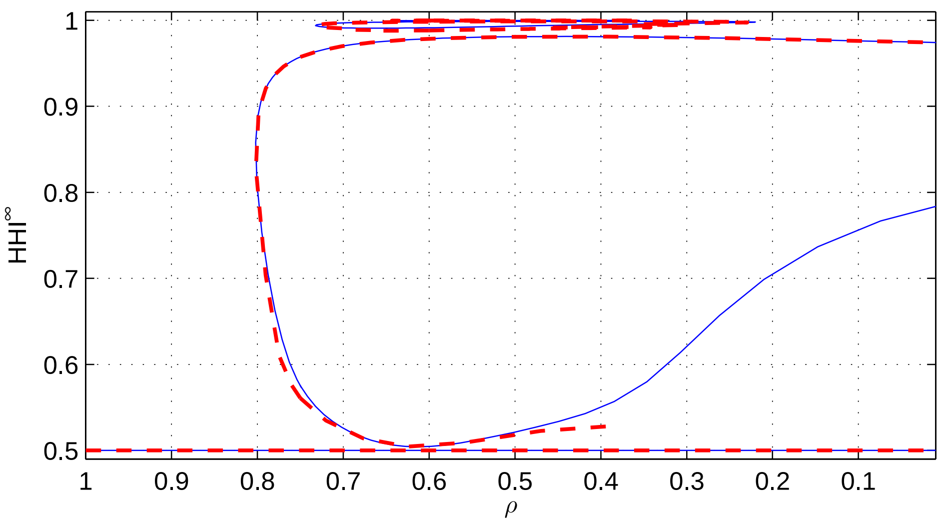

Figure 6: Expected long-run Herfindahl index. Equilibrium and counterfactual correspondences for Definition 7. Slice along $\rho \in [0, 1]$.

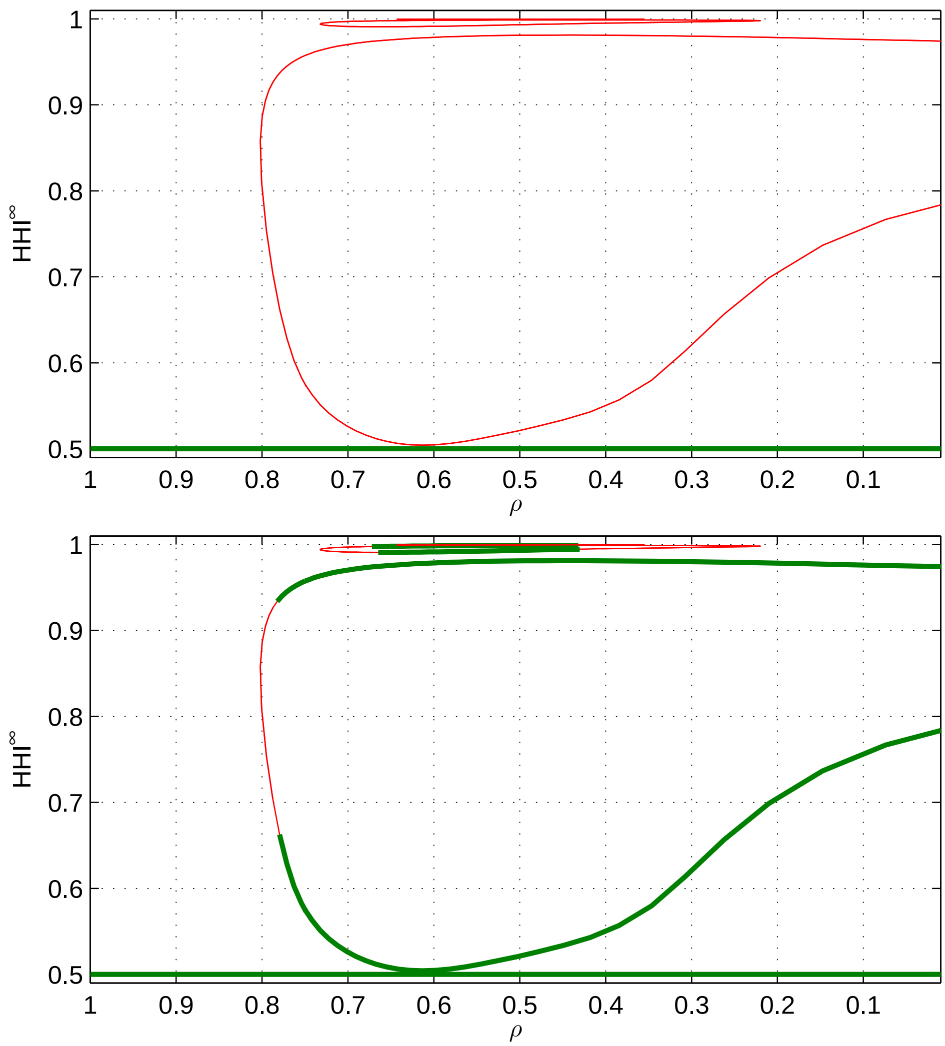

Figure 7: Expected long-run Herfindahl index. Eliminated and surviving equilibria for Definitions 2 and 5. Slice along $\rho \in [0, 1]$.