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Sacrifice tests for predation in a dynamic pricing model: Ordover and Willig (1981) and Cabral and Riordan (1997) meet Ericson and Pakes (1995)☆

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ABSTRACT

To detect the presence of predatory pricing, antitrust authorities and courts routinely ask whether a firm sacrifices current profit in exchange for the expectation of higher future profit following the exit of its rival. Because predatory pricing is an inherently dynamic phenomenon, we show in this paper how to construct sacrifice tests for predatory pricing in a modern industry-dynamics framework along the lines of Ericson and Pakes (1995). In particular, we adapt the definitions of predation due to Ordover and Willig (1981) and Cabral and Riordan (1997) to this setting and construct the corresponding sacrifice tests.

1. Introduction

To detect the presence of predatory pricing, antitrust authorities and courts routinely ask whether a firm sacrifices current profit in exchange for the expectation of higher future profit following the exit of its rival. Because predatory pricing is an inherently dynamic phenomenon, we show in this paper how to construct sacrifice tests for predatory pricing in a modern industry-dynamics framework that endogenizes competitive advantage and industry structure. Due to its presence in a number of high-profile predatory pricing cases, we focus on learning-by-doing.

At the core of predatory pricing is the trade-off between lower profit in the short run due to aggressive pricing and higher profit in the long run due to reduced competition. Determining what constitutes an illegitimate profit sacrifice—and thus predatory pricing—is especially difficult when firms face other intertemporal trade-offs such as learning-by-doing, network effects, or switching costs that can give rise to aggressive pricing with subsequent recoupment. As Farrell and Katz (2005) point out, "[d]istinguishing competition from predation is even harder in network markets than in others. With intertemporal increasing returns, there may innocently be intense initial competition as firms fight to make initial sales and benefit from the increasing returns" (p. 204). Yet, allegations of predation (or, in an international context, dumping) some-

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times arise in settings where learning-by-doing is a key feature of the industrial landscape. Examples include the "semiconductor wars" between the U.S. and Japan during the 1970s and 1980s (Flamm, 1993; 1996; Dick, 1991), the allegations by U.S. color television producers against Japanese producers during the 1960s and 1970s that are at the core of the *Matsushita Electric Corp.* predatory pricing case (Yamamura and Vandenberg, 1986), and more recently the debate about Chinese solar panels.

In these and many other industries, a firm has an incentive to price aggressively because its marginal cost of production decreases with its cumulative experience.[1] While this makes it difficult to disentangle predatory pricing from mere competition for efficiency on a learning curve, being able to do so is crucial when predation is alleged. In practice, antitrust authorities find a price predatory if there is evidence of an illegitimate profit sacrifice. This, in turn, requires a notion of what constitutes an illegitimate profit sacrifice in the first place. Unfortunately, antitrust authorities and courts have not yet converged on a simple, clear standard.

In this paper, we show how the definitions of predation due to Ordover and Willig (1981) and Cabral and Riordan (1997) can be used to determine what constitutes an illegitimate profit sacrifice. In contrast to antitrust authorities, the economics literature focuses more directly on the impact that a price cut has on reshaping the structure of an industry. According to the definitions of predation due to Ordover and Willig (1981) and Cabral and Riordan (1997), a price is predatory if it had not been worth charging absent its impact on the probability that the rival exits the industry. The definitions differ in that Ordover and Willig (1981) presume that the rival is viable with certainty whereas Cabral and Riordan (1997) presume that its exit probability remains unchanged. While the idea that predatory pricing can be usefully defined by a "but-for" scenario has greatly influenced economists' thinking, to our knowledge it has rarely been formalized outside simple models such as the one in Cabral and Riordan (1997).[2] In this paper, we show how to adapt the definitions of predation due to Ordover and Willig (1981) and Cabral and Riordan (1997) to a Markov-perfect industry-dynamics framework along the lines of Ericson and Pakes (1995). We then show how to construct sacrifice tests from these definitions. The economic definitions of predation in the extant literature therefore amount to particular ways of disentangling an illegitimate profit sacrifice stemming from predatory pricing from a legitimate effort to increase cost efficiency through aggressive pricing.

To construct sacrifice tests in a dynamic pricing model similar to the models of learning-by-doing in Cabral and Riordan (1994) and Besanko et al. (2010), we build on Besanko et al. (2014) and decompose the equilibrium pricing condition. The insight in that paper is that the price set by a firm reflects two goals besides short-run profit. First, by pricing aggressively, the firm may move further down its learning curve and improve its competitive position in the future, giving rise to an *advantage-building motive*. Second, the firm may prevent its rival from moving further down its learning curve and becoming a more formidable competitor, giving rise to an *advantage-denying motive*.[3]

To isolate the probability of rival exit—the linchpin of the definitions of predation due to Ordover and Willig (1981) and Cabral and Riordan (1997)—we go beyond Besanko et al. (2014) and decompose the equilibrium pricing condition with even more granularity. One component of the advantage-building motive is the *advantage-building/exit motive*. This is the marginal benefit to the firm from the increase in the probability of rival exit that results if the firm moves further down its learning curve. The *advantage-denying/exit motive* is analogously the marginal benefit from preventing the decrease in the probability of rival exit that results if the rival moves further down its learning curve. Other terms in the decomposed equilibrium pricing condition capture the impact of the firm's pricing decision on its competitive position, its rival's competitive position, and so on.

Our decomposition highlights the various incentives that a firm faces when it decides on a price. Some of these incentives may be judged to be predatory while others reflect the pursuit of efficiency. In this way, our decomposition mirrors the common practice of antitrust authorities to question the intent behind a business strategy.

We establish formally that certain terms in our decomposition map into the definitions of predation due to Ordover and Willig (1981) and Cabral and Riordan (1997). At the same time, however, our decomposition makes clear that there is much latitude in where exactly to draw the line between predatory pricing and mere competition for efficiency on a learning curve. Indeed, our decomposition lends itself to developing multiple alternative characterizations of a firm's predatory pricing incentives. Drawing on Edlin and Farrell (2004) and Farrell and Katz (2005), we compare the definitions of predation due to Ordover and Willig (1981) and Cabral and Riordan (1997) with several alternatives that Besanko et al. (2014) have previously formalized in a dynamic pricing model.

For each of these characterizations of a firm's predatory pricing incentives, we show how to construct the corresponding sacrifice test for predatory pricing. As Edlin and Farrell (2004) point out, 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 (p. 510). A different characterization of the firm's predatory pricing incentives is tantamount to a different operationalization of the everything-except-effects-on-competition profit function.

[1] See footnote 2 in Besanko et al. (2010) for references to the empirical literature on learning-by-doing.

[2] Edlin (2002) provides a comprehensive overview of the current law on predatory pricing. Bolton et al. (2000) and Edlin (2012) provide excellent reviews of the theoretical and empirical literature.

[3] As Besanko et al. (2010) discuss, the advantage-building and advantage-denying motives arise in a range of applications, including models of network effects (see their Section I for more details).

To further illustrate our decomposition and the multiple alternative sacrifice tests that follow from it, we first link the various terms in the decomposition to key features of the pricing decision. Then we gauge the consequences of applying sacrifice tests for industry structure and dynamics by way of an illustrative example. As antitrust authorities flag and prosecute an illegitimate profit sacrifice, they prevent a firm from pricing to achieve that sacrifice. This amounts to forcing firms to ignore the predatory incentives in setting their prices.

We avoid dealing with out-of-equilibrium adjustment processes and merely delineate what may happen in the counterfactual equilibria once firms are forced to ignore the predatory incentives. Because our goal is to show how to construct sacrifice tests in a modern industry-dynamics framework, and not to run a conclusive "horse race" between antitrust policies that are based on alternative characterizations of a firm's predatory pricing incentives, we content ourselves with presenting equilibria and counterfactuals for a particular parameterization of the model. At this parameterization, applying sacrifice tests limits competition for the market and thus harms consumers, at least in the short run.

In practice, the impact of forcing firms to ignore the predatory incentives may differ across parameterizations, so that an antitrust authority set to apply a sacrifice test is well advised to first tailor the model to the institutional realities of the industry under study and estimate the underlying primitives. We view our paper as a guide to how to construct sacrifice tests for predatory pricing and assess their implications for industry structure, conduct, and performance in a modern industry-dynamics framework along the lines of Ericson and Pakes (1995).

We characterize potentially predatory incentives in a dynamic pricing model in which firms jostle for competitive advantage as their cost positions evolve over time. Predatory incentives can arise for other reasons. In models of predation based on asymmetric information (Kreps and Wilson, 1982; Milgrom and Roberts, 1982; Fudenberg and Tirole, 1986), an incumbent firm's incentive to charge a low price is aimed at shaping a potential entrant's or other rival's expectations that its future profitability is likely to be low. In models based on capital market imperfections (Bolton and Sharfstein, 1990; Snyder, 1996), it is aimed at exploiting an agency problem and putting the rival in a position where it is unable to obtain financing from outside sources to continue operations. The commonality between these models and our model is that predatory incentives may reside in a firm's desire to shape future industry structure to its advantage. As in our model, the equilibrium pricing condition impounds goals that may be deemed predatory as well as non-predatory goals (e.g., short-run profit). Whether our decomposition directly generalizes is less clear. For example, models based on asymmetric information often rely on subgame perfect equilibria rather than Markov perfect equilibria.

The remainder of this paper is organized as follows. Section 2 lays out the model. Section 3 develops the decomposition of the equilibrium pricing condition and formalizes its relationship with the definitions of predation due to Ordover and Willig (1981) and Cabral and Riordan (1997). Section 4 uses the decomposition to develop multiple alternative characterizations of a firm's predatory pricing incentives and construct the corresponding sacrifice tests. Section 5 exemplifies the link between our decomposition and equilibrium behavior and the impact of forcing firms to ignore the predatory incentives in setting their prices. Section 6 concludes.

2. Model

As a special case of Besanko et al. (2014), 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 Fig. 1, during the price-setting phase, the industry's state changes from $\mathbf{e}$ to $\mathbf{e}'$ depending on the outcome of pricing game between the incumbent firms. During the exit-entry phase, the state then changes from $\mathbf{e}'$ to $\mathbf{e}''$ depending on the exit decisions of the incumbent firm(s) and the entry decisions of the potential entrant(s). The state at the end of the current period finally becomes the state at the beginning of the subsequent period. We model entry as a transition from state $e'_n = 0$ to state $e''_n = 1$ and exit as a transition from state $e'_n \geq 1$ to state $e''_n = 0$ so that the exit of an incumbent firm creates an opportunity for a potential entrant to enter the industry.

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

Demand. The industry draws customers from a large pool of potential buyers. One buyer enters the market each period 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

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

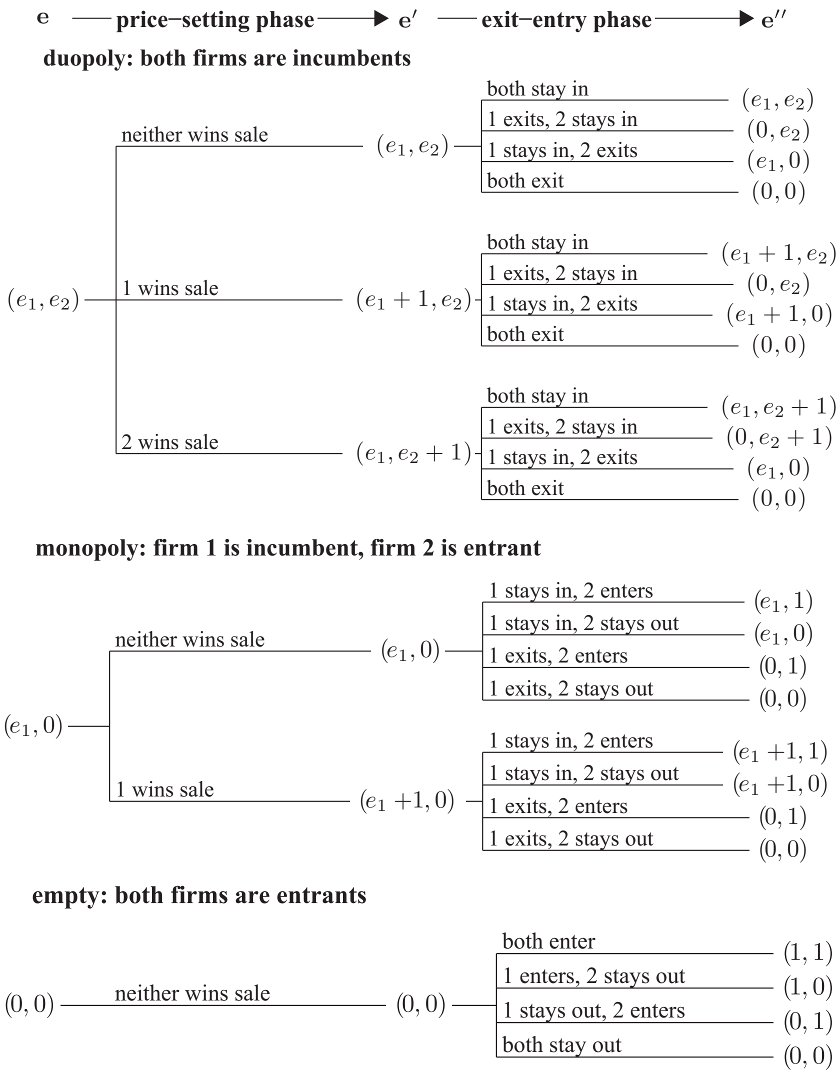

Fig. 1. Possible state-to-state transitions.

where v is gross utility and $\sigma > 0$ 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 $\rho \in [0, 1]$:

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

Because marginal cost decreases by $100(1 - \rho)\%$ as the stock of know-how doubles, 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 adds to its stock of know-how by making a sale.[4] Once the firm reaches state m, the learning curve "bottoms out," and there are no further experience-based cost reductions.

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 $F_S(\cdot)$

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

with support $[\bar{S}-\Delta_S, \bar{S}+\Delta_S]$, where $E_S(S_n)=\bar{S}$ 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 $\phi_n(\mathbf{e}')=E_X\left[\phi_n(\mathbf{e}', X_n)\right]$ is the probability of exiting; if $e'_n=0$ so that firm n is an entrant, then $\phi_n(\mathbf{e}')=E_S\left[\phi_n(\mathbf{e}', S_n)\right]$ is the probability of not entering. Note that until incumbent firm n and potential entrant n observes the realization of its scrap value, respectively, setup cost, it also assesses the probability that it does not to operate in state $\mathbf{e}'$ to be $\phi_n(\mathbf{e}')$.

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

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

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

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

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

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

$$\begin{aligned}U_1(\mathbf{e}') &= E_S\left[\max\left\{\widehat{S}_1(\mathbf{e}')-S_1,0\right\}\right]\\ &= (1-\phi_1(\mathbf{e}'))\left\{\beta[V_1(1,e'_2)(1-\phi_2(\mathbf{e}'))+V_1(1,0)\phi_2(\mathbf{e}')]-E_S\left[S_1|S_1\leq\widehat{S}_1(\mathbf{e}')\right]\right\},\end{aligned} \tag{2}$$

where $E_S\left[S_1|S_1\leq\widehat{S}_1(\mathbf{e}')\right]$ is the expectation of the setup cost conditional on entering the industry.[5]

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

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

[5] See the Online Appendix to Besanko et al. (2014) for closed-form expressions for $E_X\left[X_1|X_1\geq\widehat{X}_1(\mathbf{e}')\right]$ in Eq. (1) and $E_S\left[S_1|S_1\leq\widehat{S}_1(\mathbf{e}')\right]$ in Eq. (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 Eq. (3) as $\max_{p_1} \Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})$, where

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

is the long-run profit of incumbent firm 1. Because $\Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})$ is strictly quasiconcave in p_1 (given $p_2(\mathbf{e})$ and $\mathbf{e}$), the pricing decision $p_1(\mathbf{e})$ is uniquely determined by the first-order condition

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

where $mr_1(p_1, p_2(\mathbf{e})) = p_1 - \frac{\sigma}{1-D_1(p_1, p_2(\mathbf{e}))}$ is the marginal revenue to incumbent firm 1 or what Edlin (2012) calls *inclusive price*[6] 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.

As discussed in Besanko et al. (2014), the pricing decision impounds two distinct goals beyond short-run profit: the *advantage-building motive* $[U_1(e_1+1, e_2) - U_1(\mathbf{e})]$ and the *advantage-denying motive* $[U_1(\mathbf{e}) - U_1(e_1, e_2+1)]$. The advantage-building motive is the reward that the firm receives *by winning* a sale and moving down its learning curve. The advantage-denying motive is the penalty that the firm avoids *by preventing its rival from winning* the sale and moving down its learning curve. The advantage-building motive thus reflects the firm's marginal benefit from becoming a more formidable competitor in the future while the advantage-denying motive reflects the firm's marginal benefit from preventing its rival from becoming a more formidable competitor. Because it encompasses both the short run and the long run, the pricing decision on our model is akin to an investment decision.

2.2. Equilibrium

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

3. Decomposition

To determine what constitutes an illegitimate profit sacrifice and isolate a firm's predatory pricing incentives, we go beyond Besanko et al. (2014) and further decompose the advantage-building motive $[U_1(e_1+1, e_2) - U_1(\mathbf{e})]$ into 5 terms $\Gamma_1^1(\mathbf{e}), \ldots, \Gamma_1^5(\mathbf{e})$ and the advantage-denying motive $[U_1(\mathbf{e}) - U_1(e_1, e_2+1)]$ into 4 terms $\Theta_1^1(\mathbf{e}), \ldots, \Theta_1^4(\mathbf{e})$ and write the equilibrium pricing condition (5) as

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

The decomposed advantage-building motives $\Gamma_1^1(\mathbf{e}), \ldots, \Gamma_1^5(\mathbf{e})$ are the various sources of marginal benefit to the firm from winning the sale in the current period and moving further down its learning curve. The decomposed advantage-denying motives $\Theta_1^1(\mathbf{e}), \ldots, \Theta_1^4(\mathbf{e})$ are the various sources of marginal benefit to the firm from winning the sale in the current period and, by doing so, preventing its rival from moving further down its learning curve. The decomposed advantage-denying motives differ from the decomposed advantage-building motives in that they do not focus on the firm becoming more efficient but rather on the firm preventing its rival from becoming more efficient.

The decomposed advantage-building and advantage-denying motives have distinct economic interpretations that we describe below in detail. Because the terms $\Gamma_1^1(\mathbf{e}), \ldots, \Gamma_1^5(\mathbf{e})$ and $\Theta_1^1(\mathbf{e}), \ldots, \Theta_1^4(\mathbf{e})$ are typically positive, we refer to them as marginal benefits. To streamline the exposition, we further presume monotonicity of the value and policy functions. While this presumption simplifies the language, we do not impose it in the numerical analysis. Indeed, for some parameterizations the value and policy functions are not monotone.

Advantage building. Table 1 summarizes the decomposed advantage-building motives $\Gamma_1^1(\mathbf{e}), \ldots, \Gamma_1^5(\mathbf{e})$.[7]

Baseline advantage-building motive:

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

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[6] $mr_1(p_1, p_2(\mathbf{e}))$ is marginal revenue with respect to *quantity*, i.e., the probability of making the sale, written as a function of price. See the Online Appendix to Besanko et al. (2014) for more details.

[7] The decomposition in (6) applies to an industry with two incumbent firms in state $\mathbf{e} \geq (1, 1)$ and we focus on firm 1. We use Eq. (1) to express $U_1(\mathbf{e})$ in terms of $V_1(\mathbf{e})$.

Table 1
Decomposed advantage-building motives.

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 2
Decomposed advantage-denying motives.

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

The baseline advantage-building motive is the firm's marginal benefit from an improvement in its competitive position (state (e_1+1, e_2) versus state $\mathbf{e}$), assuming that its rival does not exit in the current period. It captures both the lower marginal cost and any future advantages (winning the sale, exit of rival, etc.) that stem from this lower cost.

Advantage-building/exit motive:

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

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

Advantage-building/survival motive:

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

The advantage-building/survival motive is the firm's marginal benefit 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 firm's marginal benefit 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:

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

The advantage-building/market structure motive is the firm's marginal benefit from an improvement in its competitive position as a monopolist (state $(e_1+1, 0)$ versus state $(e_1, 0)$) versus as a duopolist (state (e_1+1, e_2) versus state $\mathbf{e}$).

Advantage denying. Table 2 summarizes the decomposed advantage-denying motives $\Theta_1^1(\mathbf{e}), \ldots, \Theta_1^4(\mathbf{e})$.

Baseline advantage-denying motive:

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

The baseline advantage-denying motive is the firm's marginal benefit from preventing an improvement in its rival's competitive position (state $\mathbf{e}$ versus state (e_1, e_2+1)), 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 firm's marginal benefit 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:

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

The advantage-denying/survival motive is the firm's marginal benefit 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 firm's marginal benefit 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 $\phi_1(e_1, e_2+1)E_X\left[X_1|X_1 \geq \widehat{X}_1(e_1, e_2+1)\right]$.

3.1. Economic definitions of predation

The decomposition in (6) relates to economic definitions of predation formulated in the existing literature.

Cabral and Riordan (1997). Cabral and 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 and 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. We interpret "the different action would be more profitable" to mean that by a setting a higher price in the current period, 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 $\phi_2(\mathbf{e})$. Finally, in the spirit of Markov perfection, we assume that the firm returns to equilibrium play from the subsequent period onward after charging a higher price in the current period.

With these interpretations, Proposition 1 formalizes the relationship between the Cabral and Riordan definition of predation and our decomposition (6):

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

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

then the firm's equilibrium price $p_1(\mathbf{e})$ in state $\mathbf{e}$ is predatory according to the Cabral and Riordan (1997) definition.[8] *(b) If $p_1(\mathbf{e})$ is predatory according to the Cabral and Riordan definition, then $\Gamma_1^2(\mathbf{e}) > 0$ or $\Theta_1^2(\mathbf{e}) > 0$ and inequality (7) holds.*

Proof. See Appendix. □

Part (a) of Proposition 1 presents sufficient conditions for the price to be predatory under the Cabral and Riordan (1997) definition and part (b) necessary conditions. Inequality (7) plays a central role in both conditions. Loosely, inequality (7) includes terms that are "left over" when we take the difference between the derivative with respect to price of the firm's actual profit function and of a profit function constructed based on the Cabral and Riordan (1997) counterfactual.[9] Perhaps not surprising given the focus of the Cabral and Riordan (1997) definition on rival exit, inequality (7) involves both the advantage-building/exit and advantage-denying/exit motives. Inequality (7) further involves the *difference* between the advantage-building/survival motive in equilibrium and the advantage-building/survival motive evaluated at the fixed probability of rival exit $\phi_2(\mathbf{e})$, as well as on analogous differences between the baseline advantage-denying and advantage-denying/exit motives. These differences arise because in equilibrium the firm anticipates that the probability of rival exit evolves with the state $\mathbf{e}$ whereas it is fixed in the counterfactual profit function.

Ordover and Willig (1981). According to Ordover and 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 and Riordan (1997) observe, the premise in the Ordover and Willig definition is that the rival is viable with certainty.[10] We have:

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

[9] We elaborate on this idea below when we discuss the concept of an "everything-except-effects-on-competition" profit function.

[10] This observation indeed motivates Cabral and 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).

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

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

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

The proof follows the same logic as the proof of Proposition 1 and is therefore omitted.

Analogous to Proposition 1, part (a) of Proposition 2 presents sufficient conditions for the price to be predatory under the Ordover and Willig (1981) definition and part (b) necessary conditions. There are two key differences between inequalities (7) and (8). First, inequality (8) evaluates certain terms at a zero probability of rival exit because Ordover and Willig (1981) presume that the rival is viable with certainty whereas Cabral and Riordan (1997) presume that its exit probability remains unchanged. Second, inequality (8) includes the advantage-building/market structure motive $\Gamma_1^5(\mathbf{e})$ that captures the marginal benefit to an incumbent firm from improving its competitive position as a monopolist rather than a duopolist. Because in the Ordover and Willig (1981) counterfactual the rival is viable with certainty, $\Gamma_1^5(\mathbf{e})$ is "left over" when we evaluate the difference between the derivative with respect to price of the firm's actual profit function and the counterfactual profit function.[11]

4. Sacrifice tests

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. Sacrifice tests thus view predation as an "investment in monopoly profit" (Bork, 1978).[12]

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

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

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

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

The specification of the EEEC profit function determines what constitutes an illegitimate profit sacrifice—and thus predatory pricing—and there are as many sacrifice tests as there are possible specifications of the EEEC profit function. Because by construction $\Omega_1(p_1, p_2(\mathbf{e}), \mathbf{e}) = \Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e}) - \Pi_1^0(p_1, p_2(\mathbf{e}), \mathbf{e})$, specifying an EEEC profit function is equivalent to specifying the firm's predatory pricing incentives. Propositions 1 and 2 suggest starting from the predatory incentives to construct the corresponding EEEC profit function and sacrifice test. More generally, our decomposition (6) highlights the various incentives that a firm faces when it decides on a price. While some of these incentives may be judged to be predatory, others reflect the pursuit of efficiency. Using the decomposition, we therefore develop multiple alternative characterizations of a firm's predatory pricing incentives and, for each of these characterizations, we construct the corresponding EEEC profit function and sacrifice test.

Short-run profit. In the quote above, Edlin and Farrell (2004) go on to point out that "in practice sacrifice tests often use short-run data, and we will often follow the conventional shorthand of calling [this profit function] short-run profit"

[11] Note that $\phi_2(\mathbf{e}) = 0$ implies $\Gamma_1^5(\mathbf{e}) = 0$.

[12] Sacrifice tests are 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 have been criticized for "not generally [being] a reliable indicator of the impact of allegedly exclusionary conduct on consumer welfare—the primary focus of antitrust laws" (Salop, 2006, p. 313).

(p. 510). Equating predatory pricing with a failure to maximize short-run profit implies that the firm's predatory pricing incentives are its dynamic incentives in their entirety or, in other words, all decomposed advantage-building and advantage-denying motives. This then gives us our first definition of predatory incentives, which is identical to Definition 1 in Besanko et al. (2014):

Definition 1 : (short-run profit)**.** The firm's predatory pricing incentives are $[U_1(e_1+1,e_2)-U_1(\mathbf{e})]+\Upsilon(p_2(\mathbf{e}))[U_1(\mathbf{e})-U_1(e_1,e_2+1)]=\left[\sum_{k=1}^{5}\Gamma_1^k(\mathbf{e})\right]+\Upsilon(p_2(\mathbf{e}))\left[\sum_{k=1}^{4}\Theta_1^k(\mathbf{e})\right]$.

The EEEC profit function corresponding to Definition 1 is

$$\Pi_1^{0,SRP}(p_1,p_2(\mathbf{e}),\mathbf{e})=(p_1-c_1(e_1))D_1(p_1,p_2(\mathbf{e})).$$

It follows from our decomposition (6) that $\frac{\partial\Omega_1^{SRP}(p_1(\mathbf{e}),p_2(\mathbf{e}),\mathbf{e})}{\partial(-p_1)}>0$ if and only if $\left[\sum_{k=1}^{5}\Gamma_1^k(\mathbf{e})\right]+\Upsilon(p_2(\mathbf{e}))\left[\sum_{k=1}^{4}\Theta_1^k(\mathbf{e})\right]>0$.

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 $c(e_1)$.[13] 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 and Turner (1975) test that equates predatory pricing with below-cost pricing and underpins the current *Brooke Group* standard for predatory pricing in the U.S.

Dynamic competitive vacuum. By equating predatory pricing with a failure to maximize short-run profit, Definition 1 may be too broad for a dynamic environment like ours in which a firm has an incentive to price aggressively in order to realize experience-based cost reductions. Taking the resulting intertemporal trade-off into account, Farrell and Katz (2005) view an action as predatory only if it weakens the rival (see, in particular, p. 219 and p. 226). According to Farrell and Katz (2005), a firm should behave as if it were operating in a "dynamic competitive vacuum" by taking as given the competitive position of its rival in the current period but ignoring that its current price can affect the evolution of its rival's competitive position beyond the current period. 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 $[U_1(\mathbf{e})-U_1(e_1,e_2+1)]=\left[\sum_{k=1}^{4}\Theta_1^k(\mathbf{e})\right]$.

Definition 2 is identical to Definition 2 in Besanko et al. (2014). The corresponding EEEC profit function is

$$\Pi_1^{0,DCV}(p_1,p_2(\mathbf{e}),\mathbf{e})=(p_1-c(e_1))D_1(p_1,p_2(\mathbf{e}))+U_1(\mathbf{e})+D_1(p_1,p_2(\mathbf{e}))[U_1(e_1+1,e_2)-U_1(\mathbf{e})],$$

where we assume that from the subsequent period onward, play returns to equilibrium. To us, this best captures the idea that the firm is sacrificing something now in exchange for a later improvement in the competitive environment. It follows from our decomposition (6) that $\frac{\partial\Omega_1^{DCV}(p_1(\mathbf{e}),p_2(\mathbf{e}),\mathbf{e})}{\partial(-p_1)}>0$ if and only if $\left[\sum_{k=1}^{4}\Theta_1^k(\mathbf{e})\right]>0$.

The sacrifice test based on Definition 2 is equivalent to the inclusive price $mr_1(p_1(\mathbf{e}),\ p_2(\mathbf{e}))$ being less than *long-run* marginal cost $c(e_1)-\left[\sum_{k=1}^{5}\Gamma_1^k(\mathbf{e})\right]$. Note that a lower bound on long-run marginal cost $c(e_1)-\left[\sum_{k=1}^{5}\Gamma_1^k(\mathbf{e})\right]$ is out-of-pocket cost at the bottom of the learning curve $c(m)$ (Spence, 1981). Hence, if $mr_1(p_1(\mathbf{e}),\ p_2(\mathbf{e}))<c(m)$, then $mr_1(p_1(\mathbf{e}),p_2(\mathbf{e}))<c(e_1)-\left[\sum_{k=1}^{5}\Gamma_1^k(\mathbf{e})\right]$. This provides a one-way test for sacrifice that can be operationalized given some basic knowledge of demand and cost.

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

In light of Proposition 2 we have:

Definition 3 : (Ordover and Willig)**.** The firm's predatory pricing incentives are

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

The Ordover and Willig definition of predation implies

$$\Pi_1^{0,OW}(p_1,p_2(\mathbf{e}),\mathbf{e})=\Pi_1(p_1,p_2(\mathbf{e}),\mathbf{e})|_{\phi_2=0},$$

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.

[13] Edlin (2012) interprets the arguments of the U.S. Department of Justice in a predatory pricing case against American Airlines in the mid 1990s as implicitly advocating such a sacrifice test. Edlin and Farrell (2004) and Snider (2008) provide detailed analyses of this case.

Table 3
Baseline parameterization.

Parameter	Value
Maximum stock of know-how M	30
Price of outside good p_0	10
Gross utility v	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	0.9524

In light of Proposition 1 we further have:

Definition 4 : (Cabral and Riordan)**.** The firm's predatory pricing incentives are

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

The Cabral and Riordan definition of predation implies

$$\Pi_1^{0,CR}(p_1, p_2(\mathbf{e}), \mathbf{e}) = \Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})\big|_{\phi_2=\phi_2(\mathbf{e})}.$$

Our remaining definition of the firm's predatory pricing incentives comes from partitioning the predatory incentives in Definitions 3 and 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 as well as by the firm preventing its rival from winning the sale and moving further down its learning curve:

Definition 5 : (rival exit)**.** The firm's predatory pricing incentives are $\Gamma_1^2(\mathbf{e}) + \Upsilon(p_2(\mathbf{e}))\Theta_1^2(\mathbf{e})$.

Definition 5 is identical to Definition 3 in Besanko et al. (2014). The corresponding EEEC profit function is

$$\Pi_1^{0,REX}(p_1, p_2(\mathbf{e}), \mathbf{e}) = (p_1 - c(e_1))D_1(p_1, p_2(\mathbf{e})) + U_1(\mathbf{e}) + D_1(p_1, p_2(\mathbf{e}))\left[\sum_{k\neq 2}\Gamma_1^k(\mathbf{e})\right] + D_2(p_1, p_2(\mathbf{e}))\left[\sum_{k\neq 2}\Theta_1^k(\mathbf{e})\right].$$

It follows from our decomposition (6) that $\frac{\partial \Omega_1^{REX}(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})}{\partial(-p_1)} > 0$ if and only if $\Gamma_1^2(\mathbf{e}) + \Upsilon(p_2(\mathbf{e}))\Theta_1^2(\mathbf{e}) > 0$.

5. Illustrative example

To illustrate the types of behavior that can arise in our model, we compute the Markov perfect equilibria for the baseline parameterization in Table 3. Although this parameterization does not correspond to any specific industry, it is empirically plausible and in no way extreme. At the baseline parameterization there are three equilibria. For two of these three equilibria, Fig. 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). The third equilibrium is essentially intermediate between the two shown in Fig. 2 and is therefore omitted.

The upper panels of Fig. 2 illustrate what is called an *aggressive equilibrium* in Besanko et al. (2014). As can be seen in the upper left panel, there is a deep *well* in the pricing decision in state (1,1) with $p_1(1, 1) = -34.78$. In the well, the firms engage in a preemption battle to determine which will be first to move down from the top of its learning curve. There is also a deep *trench* along the e_1-axis, with $p_1(e_1, 1)$ ranging from 0.08 to 1.24 for $e_1 \in \{2, \dots, 30\}$.[14] A trench is a price war that the leader (firm 1) wages against the follower (firm 2), or an endogenous mobility barrier in the sense of Caves and Porter (1977). The trench in the pricing decision is mirrored by a ridge in the non-operating probability: the follower exits the industry with a positive probability of $\phi_2(e_1, 1) = 0.22$ for $e_1 \in \{2, \dots, 30\}$ as can be seen in the upper middle panel. As long as the follower does not win a sale, it remains in this "exit zone." If the follower exits, the leader raises its price and the industry becomes an entrenched monopoly.[15] This sequence of events resembles conventional notions of predatory pricing. On the other hand, the industry evolves into a mature duopoly if the follower wins a sale while in the midst of the

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

[15] 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. Note that, because of the trench in the pricing decision, the incumbent firm would meet entry with aggressive pricing. This is consistent with Edlin's (2012) discussion of above-cost predatory pricing and the idea that even though entry by a firm that can move down a learning curve and challenge the incumbent firm may enhance social welfare, it may not occur.

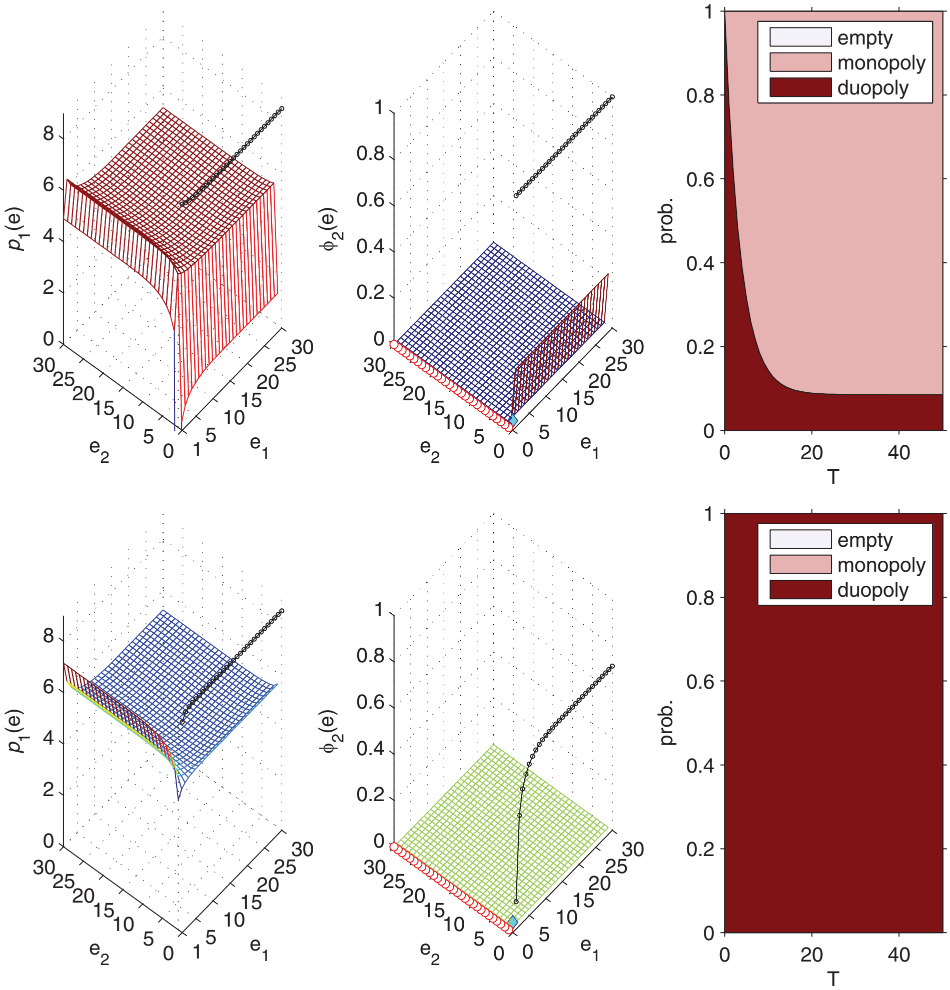

Fig. 2. Pricing decision of firm 1 (left panels), non-operating probability of firm 2 (middle panels), and time path of probability distribution over industry structures, starting from $\mathbf{e} = (1, 1)$ at $T = 0$ (right panels). Aggressive (upper panels) and accommodative (lower panels) equilibria.

price war. However, this is unlikely to happen and, as can be seen in the upper right panel, a mature duopoly is much less likely than an entrenched monopoly.[16]

The lower panels of Fig. 2 are typical for an *accommodative equilibrium*. There is a shallow well in state (1,1) with $p_1(1, 1) = 5.05$ as the lower left panel shows. 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.

The panel labeled "MPE" in Table 4 illustrates industry structure, conduct, and performance implied by the equilibria.[17] The expected long-run Herfindahl index HHI^{∞} reflects that the industry is substantially more likely to be monopolized under the aggressive equilibrium than under the accommodative equilibrium. In the entrenched monopoly prices are higher as can be seen from the expected long-run average price $\overline{p}^{\infty}$. Finally, consumer and total surplus are lower under the aggressive equilibrium than under the accommodative equilibrium. The difference between the equilibria is smaller for expected discounted consumer surplus CS^{NPV} than for expected long-run consumer surplus 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 aggressive equilibrium and mitigates the lack of *competition in the market* in the long run.

[16] Following Cabral and 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*.

[17] We use the policy functions $\mathbf{p}_1$ and $\boldsymbol{\phi}_1$ for a particular equilibrium to construct the matrix of state-to-state transition probabilities that characterizes the Markov process of industry dynamics. From this, we compute the transient distribution over states in period T starting from state (1,1) in period 0. Depending on T, the transient distributions can capture short-run or long-run (steady-state) dynamics, and we think of period 1000 as the long run. To succinctly describe the equilibrium, we finally use the transient distributions to compute six metrics of industry structure, conduct, and performance. See Section 3 of Besanko et al. (2014) for details.

Table 4
Industry structure, conduct, and performance. Aggressive, intermediate, and accommodative equilibria without conduct restriction (panel labeled "MPE") and with conduct restriction according to Definition 1 (panel labeled "SRP"), Definition 2 (panel labeled "DCV"), Definition 3 (panel labeled "OW"), Definition 4 (panel labeled "CR"), and Definition 5 (panel labeled "REX").

		HHI^{∞}	$\overline{p}^{\infty}$	CS^{∞}	TS^{∞}	CS^{NPV}	TS^{NPV}
MPE	Aggressive	0.96	8.26	1.99	6.09	104.18	110.33
	Intermediate	0.58	5.74	4.89	7.22	111.18	119.12
	Accommodative	0.50	5.24	5.46	7.44	109.07	120.14
SRP	Accommodative	0.50	5.24	5.46	7.44	59.72	106.07
DCV	Accommodative	0.50	5.24	5.46	7.44	102.10	119.70
OW	Aggressive	0.95	8.19	2.07	6.12	98.11	110.64
	Intermediate	0.63	6.07	4.51	7.07	109.79	118.19
	Accommodative	0.50	5.24	5.46	7.44	109.07	120.14
CR	Aggressive	0.92	8.04	2.24	6.18	98.84	111.25
	Intermediate	0.64	6.17	4.39	7.02	109.17	117.87
	Accommodative	0.50	5.24	5.46	7.44	109.07	120.14
REX	Aggressive	0.95	8.19	2.07	6.12	98.11	110.64
	Intermediate	0.62	6.06	4.52	7.07	109.83	118.21
	Accommodative	0.50	5.24	5.46	7.44	109.07	120.14

Table 5
Decomposed advantage-building and advantage-denying motives and sacrifice tests according to Definitions 1–5. √√ means that the predatory incentives are larger than 0.5, √ that they are between 0 and 0.5, and a blank that they are smaller or equal to 0. Aggressive equilibrium.

			Advantage building					Advantage denying				Sacrifice tests				
$\mathbf{e}$	$p_1(\mathbf{e})$	$c(e_1)$	$\Gamma_1^1(\mathbf{e})$	$\Gamma_1^2(\mathbf{e})$	$\Gamma_1^3(\mathbf{e})$	$\Gamma_1^4(\mathbf{e})$	$\Gamma_1^5(\mathbf{e})$	$\Theta_1^1(\mathbf{e})$	$\Theta_1^2(\mathbf{e})$	$\Theta_1^3(\mathbf{e})$	$\Theta_1^4(\mathbf{e})$	SRP	DCV	OW	CR	REX
(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	√	√			

In sum, predation-like behavior arises in aggressive equilibria. Aggressive equilibria often coexist with accommodative equilibria involving much less aggressive pricing. Aggressive equilibria involve more competition in the short run than accommodative equilibria but less competition in the long run.

5.1. Predation-like behavior and sacrifice tests

Our decomposition sheds light on the origins of the wells and trenches that are part and parcel of predation-like behavior and competition for the market. The upper panels of Table 5 illustrate the decomposition (6) for the aggressive equilibrium for a set of states where firm 2 is at the top of the learning curve. The competition for the market in the well in state (1,1) is driven mostly by the baseline advantage-building motive $\Gamma_1^1(1,1)$ and the advantage-building/exit motive $\Gamma_1^2(1,1)$. In contrast, the competition for the market in the trench in states $(e_1, 1)$ for $e_1 \in \{2, \ldots, 30\}$ is driven mostly by the baseline advantage-denying motive $\Theta_1^1(e_1, 1)$ and the advantage-denying/exit motive $\Theta_1^2(e_1, 1)$. The predation-like behavior in the

Table 6
Decomposed advantage-building and advantage-denying motives and sacrifice tests according to Definitions 1–5. √√ means that the predatory incentives are larger than 0.5, √ that they are between 0 and 0.5, and a blank that they are smaller or equal to 0. Accommodative equilibrium.

			Advantage building					Advantage denying				Sacrifice tests				
$\mathbf{e}$	$p_1(\mathbf{e})$	$c(e_1)$	$\Gamma_1^1(\mathbf{e})$	$\Gamma_1^2(\mathbf{e})$	$\Gamma_1^3(\mathbf{e})$	$\Gamma_1^4(\mathbf{e})$	$\Gamma_1^5(\mathbf{e})$	$\Theta_1^1(\mathbf{e})$	$\Theta_1^2(\mathbf{e})$	$\Theta_1^3(\mathbf{e})$	$\Theta_1^4(\mathbf{e})$	SRP	DCV	OW	CR	REX
(1,1)	5.05	10.00	6.21	0.00	0.00	0.00	0.00	0.73	0.00	0.00	0.00	√√	√√			
(2,1)	5.34	7.50	3.74	0.00	0.00	0.00	0.00	1.96	0.00	0.00	0.00	√√	√√			
(3,1)	5.45	6.34	2.65	0.00	0.00	0.00	0.00	2.43	0.00	0.00	0.00	√√	√√			
(4,1)	5.51	5.63	2.01	0.00	0.00	0.00	0.00	2.68	0.00	0.00	0.00	√√	√√			
(5,1)	5.54	5.13	1.58	0.00	0.00	0.00	0.00	2.84	0.00	0.00	0.00	√√	√√			
(6,1)	5.56	4.75	1.27	0.00	0.00	0.00	0.00	2.95	0.00	0.00	0.00	√√	√√			
(7,1)	5.57	4.46	1.02	0.00	0.00	0.00	0.00	3.03	0.00	0.00	0.00	√√	√√			
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
(14,1)	5.59	3.34	0.09	0.00	0.00	0.00	0.00	3.17	0.00	0.00	0.00	√√	√√			
(15,1)	5.59	3.25	0.00	0.00	0.00	0.00	0.00	3.18	0.00	0.00	0.00	√√	√√			
(16,1)	5.59	3.25	0.00	0.00	0.00	0.00	0.00	3.18	0.00	0.00	0.00	√√	√√			
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
(30,1)	5.59	3.25	0.00	0.00	0.00	0.00	0.00	3.18	0.00	0.00	0.00	√√	√√			
(1,4)	6.82	10.00	4.39	0.00	0.00	0.00	0.00	0.05	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	√	√			

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 $e_1 \in \{16, \dots, 30\}$ where the leader has exhausted all learning economies.

As can be seen in the 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 $e_1 \in \{1, \dots, 30\}$.

Table 6 complements Table 5 by illustrating the decomposition (6) for the accommodative equilibrium. The pricing decision is driven by the baseline advantage-building and advantage-denying motives.

While the various definitions of predatory incentives in Section 4 intuitively hone in on ever fewer terms in our decomposition (6) and thus become narrower, formally only Definitions 2 and 5 are nested in Definition 1. The right panels of Tables 5 and 6 mark states in which the predatory incentives according to a particular definition are positive for the example of the aggressive and, respectively, accommodative equilibrium. As noted above, the predatory incentives are positive if and only if the derivative of the EEEC profit function with respect to price is positive; hence, in the marked states firm 1 engages in an illegitimate profit sacrifice.

All sacrifice tests indicate predatory pricing in the deep well and trench of the aggressive equilibrium. The sacrifice tests according to Definitions 1 and 2 continue to indicate predatory pricing in other states involving much less aggressive pricing, such as state $(e_1, 4)$ for $e_1 \in \{5, \dots, 30\}$ in which firm 1 charges a price above its marginal cost, but those according to Definitions 3–5 do not. We see the same pattern for the accommodative equilibrium. The sacrifice tests according to Definitions 1 and 2 therefore capture a notion of above-cost predatory pricing (Edlin, 2002; 2012).

Note that the sacrifice tests according to Definitions 1 and 2 indicate predatory pricing not only when firm 1 is the leader in, say, state (4,1) but also when it is the follower in state (1,4). This contrasts with the practice of antitrust authorities to investigate predatory pricing conditional on a firm being dominant.

5.2. Sacrifice tests and conduct restrictions

As antitrust authorities flag and prosecute an illegitimate profit sacrifice, they prevent a firm from pricing to achieve that sacrifice. In this way, applying a sacrifice test is akin to imposing a conduct restriction. The various definitions of predatory

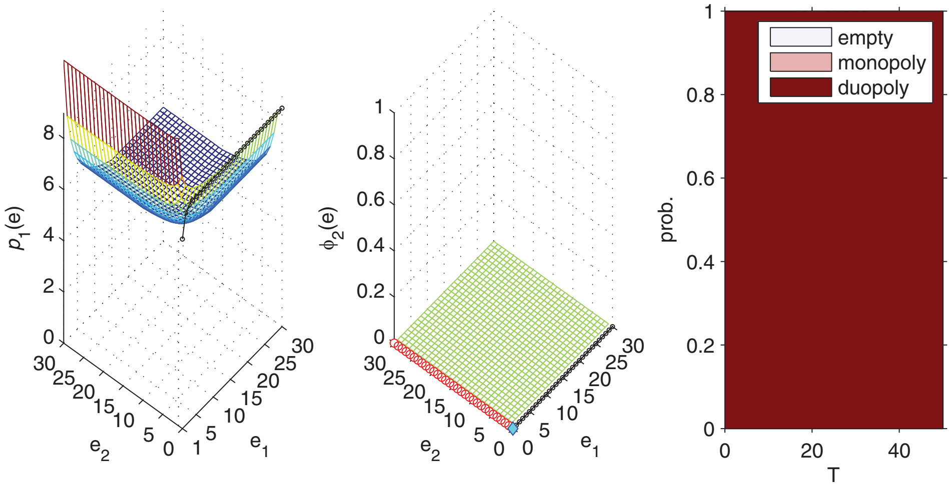

Fig. 3. Pricing decision of firm 1 (left panels), non-operating probability of firm 2 (middle panels), and time path of probability distribution over industry structures, starting from $\mathbf{e} = (1, 1)$ at $T = 0$ (right panels). Accommodative equilibrium with conduct restriction according to Definition 1.

incentives in Section 4 indeed restrict the range of the firm's price, e.g., Definition 1 prohibits the inclusive price, and thus also the actual price, from being less than marginal cost.

To gauge the consequences of applying a sacrifice test for industry structure and dynamics, we formalize a conduct restriction as a constraint $\Xi_1(p_1, p_2(\mathbf{e}), \mathbf{e}) = 0$ on the maximization problem on the right-hand side of the Bellman Eq. (3) that the firm solves in the price-setting phase. We form the constraint by rewriting our decomposition (6) as

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

and "switching off" the predatory incentives according to a particular definition.[18] For example, applying a sacrifice test according to Definition 2 in effect forces the firm to ignore $\left[\sum_{k=1}^{4} \Theta_1^k(\mathbf{e})\right]$ in setting its price, so the constraint is $\Xi_1(p_1, p_2(\mathbf{e}), \mathbf{e}) = mr_1(p_1, p_2(\mathbf{e})) - c(e_1) + \left[\sum_{k=1}^{5} \Gamma_1^k(\mathbf{e})\right] = 0$.

We compute the Markov perfect equilibria of the counterfactual game with a conduct restriction (according to a particular definition) in place. For the conduct restrictions according to Definitions 1 and 2, respectively, Figs. 3 and 4 show the pricing decision of firm 1, the non-operating probability of firm 2, and the time path of the probability distribution over industry structures. Comparing the left panels in Figs. 3 and 4 to the left panels in Fig. 2, we see that there are neither deep wells nor trenches in the pricing decision and that the counterfactuals are accommodative in nature. This is because the intense competition for the market in the trench of an aggressive equilibrium is driven almost entirely by the baseline advantage-denying motive and the advantage-denying/exit motive (see Table 5). By shutting down the advantage-denying motive in its entirety, the conduct restrictions according to Definitions 1 and 2 eliminate a trench and thus the mobility barrier that is likely to lead to an entrenched monopoly over time. As further discussed in Besanko et al. (2014), it is as if these conduct restrictions eliminate the aggressive (as well as the intermediate) equilibrium of the original game.

Just as there are multiple equilibria in the original game, there are multiple equilibria in the counterfactual game with a conduct restriction according to Definitions 3–5. For two of these three equilibria, Figs. 5–7 show the pricing decision of firm 1, the non-operating probability of firm 2, and the time path of the probability distribution over industry structures. The counterfactuals in the upper panels are aggressive in nature while those in the lower panels are accommodative.

Further comparing industry structure, conduct, and performance between counterfactuals and equilibria tells us how much bite the conduct restrictions have. The panels labeled "SRP", "DCV", "OW", "CR", and "REX" in Table 4 illustrate industry structure, conduct, and performance implied by the equilibria of the counterfactual game with a conduct restriction according to Definitions 1–5.

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

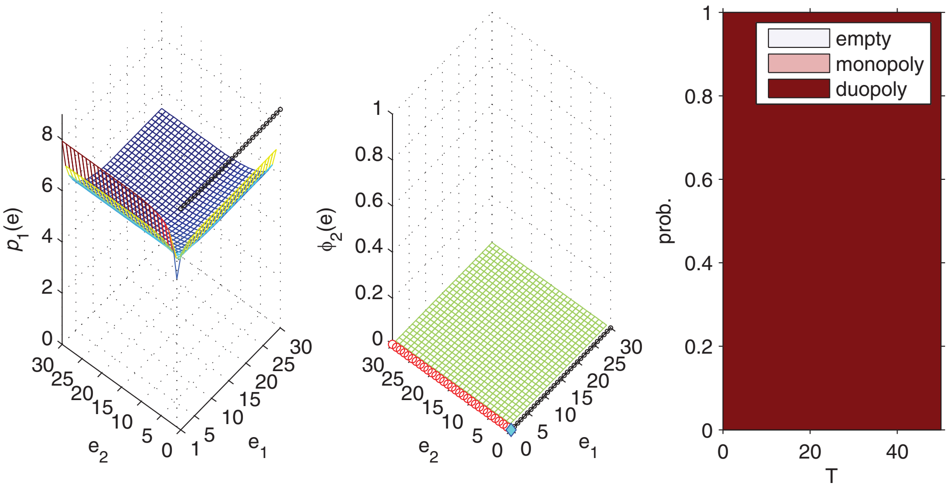

Fig. 4. Pricing decision of firm 1 (left panels), non-operating probability of firm 2 (middle panels), and time path of probability distribution over industry structures, starting from $\mathbf{e} = (1, 1)$ at $T = 0$ (right panels). Accommodative equilibrium with conduct restriction according to Definition 2.

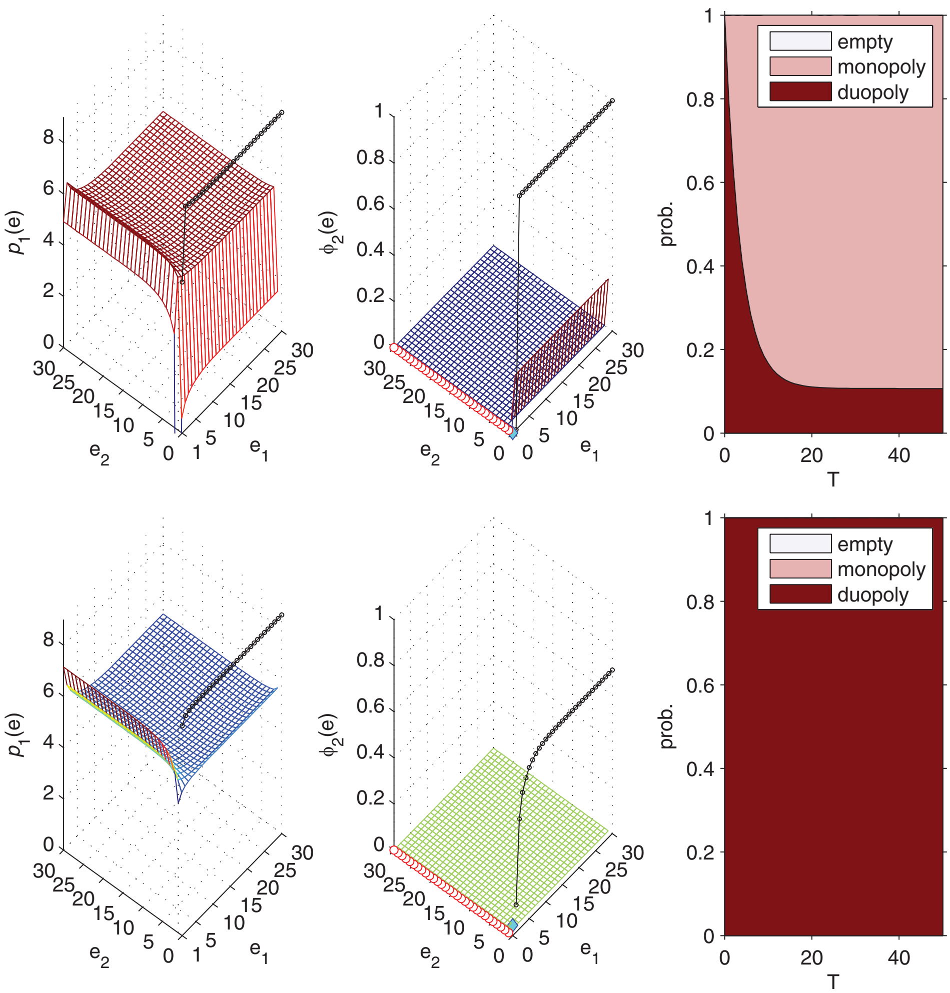

Fig. 5. Pricing decision of firm 1 (left panels), non-operating probability of firm 2 (middle panels), and time path of probability distribution over industry structures, starting from $\mathbf{e} = (1, 1)$ at $T = 0$ (right panels). Aggressive (upper panels) and accommodative (lower panels) equilibria with conduct restriction according to Definition 3.

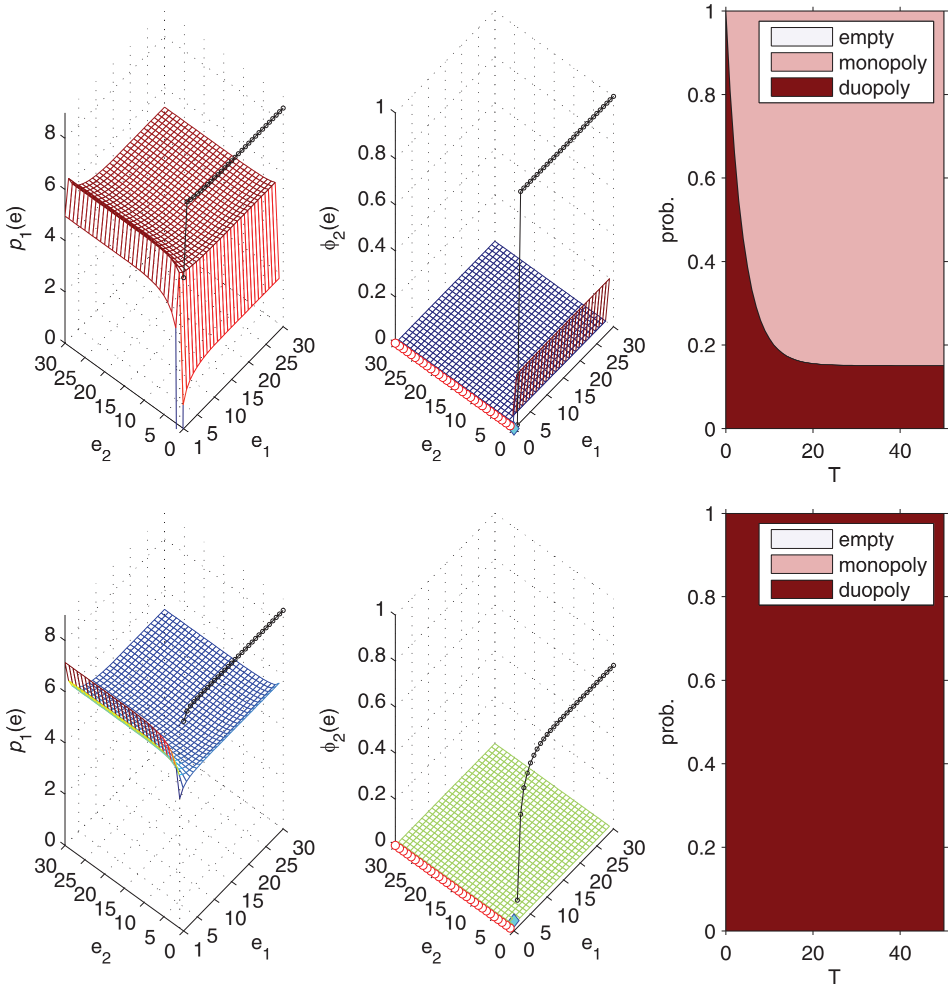

Fig. 6. Pricing decision of firm 1 (left panels), non-operating probability of firm 2 (middle panels), and time path of probability distribution over industry structures, starting from $\mathbf{e} = (1, 1)$ at $T = 0$ (right panels). Aggressive (upper panels) and accommodative (lower panels) equilibria with conduct restriction according to Definition 4.

Table 4 shows little changes between counterfactuals and equilibria, holding fixed the type of equilibrium behavior. To the extent that there are changes, they are sometimes for the better but sometimes for the worse. Compared to the intermediate equilibrium of the original game, the conduct restrictions according to Definitions 3–5 increase concentration and prices and decrease expected long-run consumer surplus CS^{∞}. The most striking feature of Table 4 is though that the conduct restrictions according to Definitions 1–5 decrease expected discounted consumer surplus CS^{NPV}, sometimes substantially so.

The conduct restriction according to Definition 1 substantially decreases CS^{NPV} because, by shutting down the dynamic incentives in their entirety, it denies the efficiency gains from pricing aggressively in order to move down the learning curve. In addition, the conduct restriction according to Definition 1 annihilates competition for the market. As can be seen by comparing the left panel of Fig. 3 with the lower left panel of Fig. 2, the shallow well in the accommodative equilibrium of the original game is absent. In contrast, the conduct restriction according to Definition 2 allows a shallow well, as can be seen in the left panel of Fig. 4. Because it preserves a modicum of competition for the market, the conduct restriction according to Definition 2 decreases expected discounted consumer surplus much more modestly.

The conduct restrictions according to Definitions 3–5 are similar, as may be expected given their more narrow focus on the immediate impact of a price cut on rival exit. These conduct restrictions, in particular, force the firm to ignore the advantage-building/exit motive—thereby limiting the competition for the market in the well of an aggressive equilibrium—and the advantage-denying/exit motive—thereby limiting the competition for the market in the trench. Especially because the well is less deep, the conduct restrictions according to Definitions 3–5 decrease expected discounted consumer surplus CS^{NPV} compared to the aggressive equilibrium of the original game.

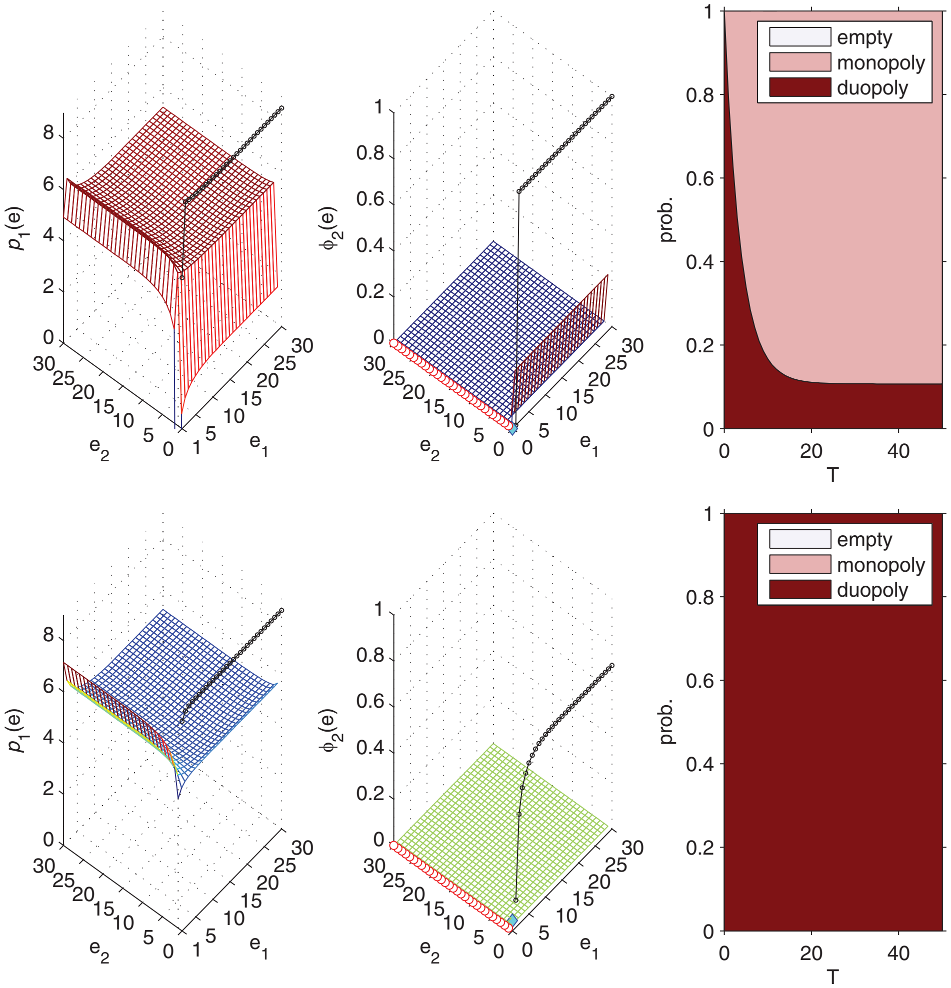

Fig. 7. Pricing decision of firm 1 (left panels), non-operating probability of firm 2 (middle panels), and time path of probability distribution over industry structures, starting from $\mathbf{e} = (1, 1)$ at $T = 0$ (right panels). Aggressive (upper panels) and accommodative (lower panels) equilibria with conduct restriction according to Definition 5.

6. Concluding remarks

To detect the presence of predatory pricing, antitrust authorities and courts routinely ask whether a firm sacrifices current profit in exchange for the expectation of higher future profit following the exit of its rival. Because predatory pricing is an inherently dynamic phenomenon, we show in this paper how to construct sacrifice tests for predatory pricing in a modern industry-dynamics framework along the lines of Ericson and Pakes (1995). In particular, we adapt the definitions of predation due to Ordover and Willig (1981) and Cabral and Riordan (1997) to this setting and construct the corresponding sacrifice tests.

To do so, we build on Besanko et al. (2014) and decompose the equilibrium pricing condition in a model of learning-by-doing. Our decomposition highlights the various incentives that a firm faces when it decides on a price. Some of these incentives may be judged to be predatory while others reflect the pursuit of efficiency. We establish formally that certain terms in our decomposition map into the definitions of predation due to Ordover and Willig (1981) and Cabral and Riordan (1997). We furthermore use our decomposition to develop multiple alternative characterizations of a firm's predatory pricing incentives and construct the corresponding sacrifice tests.

In a dynamic pricing model like ours, consumers benefit in the short run from competition for the market and in the long run from competition in the market. An antitrust policy boosting both seems ideal. To gauge the consequences of applying sacrifice tests, we note that as antitrust authorities flag and prosecute an illegitimate profit sacrifice, they prevent a firm from pricing to achieve that sacrifice. An illustrative example shows that, to the extent that forcing firms to ignore the predatory incentives in setting their prices has an impact, this impact arises largely because equilibria involving predation-like behavior are eliminated. The example finally illustrates that applying sacrifice tests may limit competition for the market and may thus harm consumers, at least in the short run.

Appendix

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

$$\begin{aligned}\Phi_2(p_1, p_2(\mathbf{e}), \mathbf{e}) &= \phi_2(\mathbf{e})D_0(p_1, p_2(\mathbf{e})) + \phi_2(e_1+1, e_2)D_1(p_1, p_2(\mathbf{e})) + \phi_2(e_1, e_2+1)D_2(p_1, p_2(\mathbf{e}))\\ &= [\phi_2(e_1+1, e_2) - \phi_2(\mathbf{e})]D_1(p_1, p_2(\mathbf{e})) - [\phi_2(\mathbf{e}) - \phi_2(e_1, e_2+1)]D_2(p_1, p_2(\mathbf{e})).\end{aligned}$$

We say that $p_1(\mathbf{e})$ is predatory according to the Cabral and 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

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

Subtracting Eq. (6) from Eq. (11), we have

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

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

Because $\Gamma_1^2(\mathbf{e}) \geq 0$ and $\Theta_1^2(\mathbf{e}) \geq 0$, with at least one of these inequalities being strict, under the maintained assumptions of Proposition 1 it follows that $\phi_2(e_1+1, e_2) - \phi_2(\mathbf{e}) \geq 0$ and $\phi_2(\mathbf{e}) - \phi_2(e_1, e_2+1) \geq 0$, with at least one of these inequalities being strict. Using Eq. (6),

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

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

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

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

Like $\Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})$, $\Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})}$ is strictly quasiconcave. 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 $\Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})$ is strictly increasing in p_1 at $p_1(\mathbf{e})$. (If not, then either $p_1(\mathbf{e})$ maximizes $\Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})$, contradicting the hypothesis that $\widetilde{p}_1$ is more profitable than $p_1(\mathbf{e})$, or $\Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})$ is strictly decreasing in p_1 at $p_1(\mathbf{e})$. In the latter case, $\widetilde{p}_1 > p_1(\mathbf{e})$ then implies $\Pi_1(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})} > \Pi_1(\widetilde{p}_1, p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})}$ because $\Pi_1(p_1, p_2(\mathbf{e}), \mathbf{e})$ is a single-peaked function, again contradicting the hypothesis that $\widetilde{p}_1$ is more profitable than $p_1(\mathbf{e})$.) Thus,

$$\begin{aligned}&\frac{\partial \Pi_1(p_1(\mathbf{e}), p_2(\mathbf{e}), \mathbf{e})|_{\phi_2=\phi_2(\mathbf{e})}}{\partial p_1} = \frac{\partial D_1(p_1(\mathbf{e}), p_2(\mathbf{e}))}{\partial p_1}\Bigg\{mr_1(p_1(\mathbf{e}), p_2(\mathbf{e})) - c(e_1)\\ &\quad + \left[\Gamma_1^1(\mathbf{e}) + \Gamma_1^3(\mathbf{e})\Big|_{\phi_2=\phi_2(\mathbf{e})} + \Gamma_1^4(\mathbf{e}) + \Gamma_1^5(\mathbf{e})\right]\\ &\quad + \Upsilon(p_2(\mathbf{e}))\left[\Theta_1^1(\mathbf{e})\Big|_{\phi_2=\phi_2(\mathbf{e})} + \Theta_1^3(\mathbf{e})\Big|_{\phi_2=\phi_2(\mathbf{e})} + \Theta_1^4(\mathbf{e})\right]\Bigg\} > 0\end{aligned}$$

or

$$\begin{aligned}&mr_1(p_1(\mathbf{e}), p_2(\mathbf{e})) - c(e_1) + \left[\Gamma_1^1(\mathbf{e}) + \Gamma_1^3(\mathbf{e})\Big|_{\phi_2=\phi_2(\mathbf{e})} + \Gamma_1^4(\mathbf{e}) + \Gamma_1^5(\mathbf{e})\right]\\ &\quad + \Upsilon(p_2(\mathbf{e}))\left[\Theta_1^1(\mathbf{e})\Big|_{\phi_2=\phi_2(\mathbf{e})} + \Theta_1^3(\mathbf{e})\Big|_{\phi_2=\phi_2(\mathbf{e})} + \Theta_1^4(\mathbf{e})\right] < 0. \qquad (13)\end{aligned}$$

Subtracting inequality (13) from Eq. (6) then yields

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

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