Open Access and Dynamic Efficiency[*]

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August 2009

Abstract

We consider a model in which production of a downstream good requires access to an excludable upstream resource owned by a vertically integrated firm. The quality of the resource depends on an investment made by the owner and impacts the demand curve in the downstream market. Under open access, the owner must share the resource with downstream competitors at a regulated tariff, determined after the investment is made. We show that the owner's investment exceeds the monopoly level if the access tariff is set according to a principle we call revenue neutrality. Revenue-neutral open access is consistent with current open access laws and requires only limited information on part of the regulator. Furthermore, quality increases with the number of entrants in the downstream market. Our results hence contradict the notion that dynamic efficiency must be sacrificed for gains in static (allocative) efficiency.

Keywords: Open access, dynamic efficiency, resource sharing, compulsory licensing, optimal patents, access regulation.

JEL codes: D23, D43, K21, L43, O31, O34.

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1 Introduction

Vertically integrated firms which control essential upstream resources often have an incentive to deny competitors access to these inputs. They can thus extend their upstream monopoly power into potentially competitive downstream markets, a practice known as vertical foreclosure. One way for policy makers to deal with the foreclosure problem is to accept a monopolized market, but regulate end-user prices. An alternative policy, named open access, calls for intervention in the upstream segment: The integrated firm is required to share its essential resources with downstream competitors, leaving end-user prices to be determined by competition in the downstream segment. Such open access requirements are chiefly found in two places. The first concerns access regulation to essential infrastructure facilities, such as communication networks, power transmission grids, or computer reservation systems. Open access to distribution and communication networks, for example, is mandated by the 1992 and 2007 U.S. Energy Policy Acts, and the 1996 U.S. Telecommunications Act. The second concerns intellectual property, where open access is typically referred to as compulsory licensing. Open access to patents is stipulated, for example, in the 1954 U.S. Atomic Energy Act and the 1970 U.S. Clean Air Act.[1]

While open access facilitates competition in the downstream market, requiring a firm to share its physical or intellectual resources with competitors may reduce the firm's incentive to invest in them in the first place. The welfare gain from increased competition in the downstream market may thus be offset by a degradation of upstream resources. Put differently, an open access policy that increases static efficiency can have adverse effects on dynamic efficiency. Much of the literature on innovation and optimal patent protection, for example, addresses this tradeoff explicitly. The question there is: How much static efficiency must be sacrificed to achieve a desired level of investments? In this paper, we take a fresh look at this efficiency tradeoff. In particular, we question whether such a tradeoff always exists.

In our model, an incumbent firm controls an excludable public good that cannot be duplicated but is essential for production of the end-user good. This upstream resource is characterized by its quality level, which depends on the incumbent's investment in it. Specifically, we assume that a higher upstream quality level shifts the downstream demand curve outward. Under open access, the incumbent must share the resource with a number of downstream competitors, who in return pay a regulated access fee to the incumbent.[2] Finally, all firms compete as Cournot oligopolists in the downstream market. In this frame-

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[1]These two provisions have rarely been used in practice since the 1980s. A historic overview of the use of compulsory licensing, imposed pervasively as an antitrust remedy by the U.S. government from the 1930s through the 1960s, is given in Scherer (2006). Access to certain pharmaceutical patents is also stipulated by the WTO's 1994 Agreement on Trade Related Aspects of Intellectual Property Rights (TRIPS).

[2]We stress that by the term *open* access we do not mean free access, but rather that access cannot be denied to any party willing to pay the access fee.

work, we examine a simple policy which we call *revenue-neutral open access.* It prescribes a linear access tariff, chosen after the investment is made and before the downstream outputs are chosen, with the following property: Ex-post, the firms will have paid for the upstream investment in proportion to their downstream market shares. Revenue neutrality thus embodies a number of general principles found in contemporary access legislation—namely that the terms of access be fair, reasonable, and non-discriminatory.[3] We show that, under this regime, the incumbent invests more in quality than a monopolist would, and that the investment increases with the number of downstream competitors. Thus, the goals of facilitating downstream competition through resource sharing, while at the same time giving the incumbent an incentive to invest, go hand in hand.

The intuition behind this result is the following. Because quality shifts the demand curve outward, the effect of an additional quality unit on the industry's revenue is larger, the larger the output in the downstream market. One way to increase output is to let many firms participate in the downstream market, which is precisely what an open access policy does. On the other hand, the effect of an additional quality unit on the industry's fixed cost is independent of the downstream output. If costs are now shared in the same proportion as revenues, this industry-wide effect is internalized: A more competitive downstream market raises the incumbent's private return to the investment relative to its marginal cost, thus leading to stronger incentives to invest in quality.

Investment incentives have been at the center of the debate surrounding open access. Critics of open access oppose the idea as a violation of property rights to productive assets; consequently, they argue, entrepreneurs will not invest in assets that are subject to access (e.g. Sidak and Spulber (1996)). Others have embraced open access because of the large gains in static efficiency it brings about, but warn that access tariffs must be designed with investment incentives in mind (e.g. Laffont and Tirole (2000), pp. 98–99). Our paper contributes to this debate in several ways.

First, we show that it is possible—by using a simple mechanism consistent with current law—to create a causal link from downstream competition to upstream investments. Since monopoly is statically as well as dynamically inefficient, this mechanism can increase welfare both directly by increasing output in the downstream market, and indirectly by increasing the quality of the upstream resource. For some parameter values, however, a quite unexpected welfare tradeoff does arise: The incumbent actually invests *too much* in the shared resource, relative to the social optimum, further underscoring our claim that the conventional under-investment narrative is flawed. Second, our model can illuminate the reasons why open access may fail to stimulate investments if the principles of fair, reason-

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[3]The 1996 U.S. Telecommunications Act, for example, stipulates all three of these requirements (Sect. 251 (c), Sect. 252 (d)), and similar language is contained in the 1992 Energy Policy Act (Sect. 722 (1)). European laws, such as the 2004 German Telecommunications Act, contain the same requirements as well (Sect. 19).

able, and non-discriminatory access are *not* observed: Regulators such as the FCC often base access tariffs not on historical investments, but on hypothetical "engineering costs." Due to technological progress the latter are often lower than the former, so that the incumbent's actual cost share exceeds its ex-post market share. We show that this practice can cause an effective shutdown of upstream investments. In particular, with a very competitive downstream market even a slight departure from historical cost accounting (and thus from revenue neutrality) can cause failures on the upstream side. Thus, the larger the potential benefits of open access, the less flexibility is there for the implementation of an access policy that actually realizes these benefits.

The remainder of the paper is organized as follows. In Section 2 we review the related literature. In Section 3 we develop our model and introduce the concept of revenue-neutral open access equilibrium. In Section 4 we characterize this equilibrium for a given quality level, and in Section 5 we turn to the incumbent's problem of choosing an optimal quality. This section contains our main results. In Section 6 we consider a number of extensions of particular policy interest, including the effects of engineering costs and technological change. Section 7 concludes. The proofs of all theoretical results are in the Appendix.

2   Relation to the Literature

The relationship between a monopolist's quantity and quality decisions has been first recognized by Spence (1975), who demonstrates the possibility that both variables may be set at inefficient levels. Spence (1975) examines the classical regulatory tools, including price regulation and rate-of-return constraints, to increase welfare. In this paper, we examine the interaction of quantity and quality in a framework where monopoly power arises specifically from vertical foreclosure. This allows us to focus our attention on the impact of open access policies and competition on static and dynamic efficiency.

Because our framework can be applied to intellectual as well as physical resources, it is related to previous work in both fields. A now classic literature concerns the tradeoff between static and dynamic efficiency in the protection of intellectual property rights. Nordhaus (1969) and Scherer (1972) describe the duration of patent protection that achieves a socially optimal balance between these goals (optimal patent *length*). Tandon (1982), Gilbert and Shapiro (1990), and Klemperer (1990) extend this analysis to the optimal scope of protection (patent *breadth*), and Ayres and Klemperer (1999) to probabilistic patent enforcement. Rey and Tirole (2007) examine the impact of free open access for the investment in cost-reducing technologies in cooperatives. This literature shows that less-than-full patent protection can increase social welfare through the gain in downstream allocative efficiency, even if it induces an innovative loss upstream.

To see how our model differs from this literature, consider the compulsory licensing framework of Tandon (1982). There, a mandatory access rate is chosen ex-ante, before the

firm's investment is made. Under such a policy, the firm's investment does in fact decrease, while social welfare can increase if the downstream efficiency gain is sufficiently strong. What constitutes a policy in our model, on the other hand, is not an access tariff itself, but a *rule* (namely revenue neutrality) by which the access tariff is determined at the interim stage, after the investment is made but before downstream outputs are chosen. In this case, not only will the downstream market operate more efficiently, but the firm's investment in quality will be higher than in monopoly. This is remarkable, since the mechanism entirely sidesteps the problem of having to compute an "optimal" access rate or policy. Instead it relies solely on the implementation of fair, reasonable, and non-discriminatory tariffs— principles described in most contemporary access legislation.[4]

From a practical perspective, too, our approach has significant advantages over ex-ante rate setting. Most importantly, no a-priori knowledge of the relationship between investment in the resource and the downstream demand function is needed by the regulator to compute a revenue-neutral access rate. All the information needed at the rate setting stage is the actual investment made by the facility owner, and the actual quality (i.e., demand curve) that resulted from it. The procedure itself can thus be implemented in isolation from any concerns about its potential impact on investments and quality. On the other hand, to choose a welfare-improving access rate ex-ante, the regulator must know the functional relationship between investment and quality.[5]

The literature on infrastructure sharing is more recent, but extensive as well. Good treatments of various access pricing rules used in the telecommunications sector are contained in Armstrong et al. (1996), Laffont and Tirole (2000), Vogelsang (2003), and Haucap and Dewenter (2006). While the importance of investment incentives is acknowledged within this literature, it has received relatively little attention in terms of an analytical treatment until recently. Laffont and Tirole (1994) point to the issue of investment incentives, but it is left as a research suggestion there. Gans and Williams (1998) and Gans (2001) examine a model in which two firms compete in a race to build an upstream facility, which could then be accessed by the other firm. Without regulation investment may occur too soon or too late, but a regulated two-part access tariff can restore the social optimum. Foros (2004) studies how access regulation affects a firm's investment incentive when firms differ in their downstream production technologies. In this model, it is assumed that the policy maker cannot commit to an access pricing rule. The vertically integrated firm, being exposed to

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[4]Interestingly, a property not unlike our revenue neutrality principle has been proposed, informally, in the early patent literature. In their analysis of the British patent system, Taylor and Silberston (1973) argue in favor of compulsory licensing and propose a royalty rate "such that the licensee contributes to the cost of discovery and development of the licensed product or process *at the same rate per unit of output* as the licensor."

[5]Current access legislation certainly does not require that access rates be set ex-ante, or even prohibits it. For example, while the interim approach we adopt in this paper is consistent with the procedures outlined in Sect. 252 of the U.S. Telecom Act, ex-ante rate setting is not.

the "regulatory risk" of below-cost access, tends to reduce its investments unless it is much more efficient than the rivals in the downstream market. Guthrie et al. (2006) demonstrate that the engineering cost approach to access pricing ("forward-looking prices") tends to retard investments in a model with stochastic costs. The reason is that a forward-looking rule exposes the investor to the risk of fluctuating access prices, whereas access prices based on historical costs ("backward-looking prices") are fixed and eliminate this risk.

Finally, investment incentives have also been studied in the context of two-way access, such as the interconnection between two competing communication networks. Foreclosure generally does not occur in this setup; thus, the primary goal of regulation is different from the one-way framework we adopt. Valletti and Cambini (2005) show that with two-way access, firms tend to reduce their investments if access fees are set at marginal cost or above. Jeon and Hurkens (2008) study an access pricing rule which depends on observed retail prices set by the firms. They show that this rule can induce both static and dynamic efficiency if the access charges can be set below marginal cost.

3 The Model

A final good can be produced at zero marginal cost by using an upstream resource, such as a specific technology, a communication network, or some other facility. The resource is a club good, i.e., it is non-rivalrous but excludable. Access to this resource is the only input in production, and we assume that it cannot be duplicated, bypassed, or otherwise substituted. That is, the resource is an essential facility.

The upstream good is characterized by a single scalar $\theta \geq 0$, which we refer to as its quality. A quality level θ requires an investment $f(\theta)$, which represents the initial investment in the upstream good and all capital costs associated with the investment. We make the following technical assumptions: f is continuous and three times differentiable, satisfies $f(0) = f'(0) = 0$, and $f'(\theta) > 0$, $f''(\theta) > 0$, $f'''(\theta) > 0$ for all $\theta > 0$.[6]

Given θ, the downstream market for the final good is characterized by a linear demand function

$$P = \theta - Q,$$

where P is the price and Q is the quantity demanded at P. Thus, an increase in the upstream good's quality results in an outward shift of the downstream demand curve.[7]

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[6]These assumptions ensure that the cost function f is sufficiently convex to yield interior profit maxima with respect to θ.

[7]The assumption that investments lead to increased demand is without loss of generality: Through relabeling, our model can be transformed into one where the upstream investment results in reduced production costs. On the other hand, the assumption that demand is linear in both θ and Q may seem strong. Numerical results which show that our main results are robust to several alternative demand specifications are available from the authors upon request.

3.1 The dual inefficiency in monopoly

We will describe the structure of both the upstream and downstream market in more detail in a moment. Before doing so, however, let us examine two benchmark cases: The quality level a monopolistic integrated firm chooses (i.e., the case that arises in a foreclosed market), and the quality level a social planner chooses.

Suppose θ and Q are set by a monopolistic integrated firm. Once θ is set, the monopolist supplies quantity $Q^M = \theta/2$ at price $P^M = \theta/2$ for a profit of $\pi^M = Q^M P^M - f(\theta) = \theta^2/4 - f(\theta)$. Thus, the monopolist's choice of quality, θ^M, satisfies the first-order condition

$$f'(\theta^M) = \frac{1}{2}\theta^M = Q^M. \tag{1}$$

Next, suppose θ is set by a social planner whose goal is to maximize social welfare. The planner sets $Q^S = \theta$ and $P^S = 0$, resulting in a maximized consumer surplus of $\theta^2/2$. Social welfare is given by $\theta^2/2 - f(\theta)$, and the planner's quality choice, θ^S, satisfies

$$f'(\theta^S) = \theta^S = Q^S. \tag{2}$$

Given our assumptions on f, unique values θ^M and θ^S exist and are such that $\theta^S > \theta^M$.

Thus, the monopolistic outcome is not only statically inefficient ($Q^M < Q^S$), but also dynamically inefficient ($\theta^M < \theta^S$). The respective first-order conditions (1) and (2) reveal that the source of dynamic inefficiency in monopoly is precisely the fact that the monopolist's quantity choice in the downstream market is too low, relative to the social optimum. This observation will play an important role for our main results.

Spence (1975) shows that when quality shifts the inverse demand curve vertically, the monopolist's quality choice is efficient *given a fixed quantity*. This is due to the fact that, for a fixed quantity, the marginal effect of quality on welfare equals the marginal effect on profits. On the other hand, once the fact is taken into account that the monopolist's quantity is too low relative to the social optimum, it becomes clear that quality is inefficiently low in monopoly as well. The two kinds of inefficiency are therefore linked. Notice further that this effect is not driven by the assumption that P is linear in Q: As long as P is linear in θ, the conditions $f'(\theta^M) = Q^M$ and $f'(\theta^S) = Q^S$ hold for every downward sloping demand function, as a consequence of the envelope theorem.[8]

3.2 Market structure

We now assume that there are $n + 1$ firms, which compete as Cournot players in the downstream market. Firm 0, the incumbent, owns and controls the upstream resource. Firms $1, \ldots, n$ are potential entrants in the downstream market. The timing is as follows:

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[8]In general, as shown in Spence (1975), if f is allowed to depend on Q as well as θ, and $\partial^2 P/\partial\theta\partial Q \neq 0$, the monopolist may underinvest or overinvest, depending on the severity of its quantity restriction relative to the social optimum.

First the incumbent sets the quality level θ and pays $f(\theta)$. Then the entrants observe θ, and compete with the incumbent by accessing the incumbent's upstream good. We assume a linear access tariff c, that is, for each unit that entrant i supplies in the downstream market it pays c to the incumbent. (We will describe how c is set further below.)

Given the demand curve $P = \theta - Q$ and the access rate c, a Cournot equilibrium in the downstream market can be defined in a straightforward manner. Let Q_i $(i = 0, \ldots, n)$ denote firm i's downstream output. The incumbent's profit function is then given by

$$\pi_0 \;=\; \underbrace{Q_0\Big(\theta - \sum_{j=0}^{n} Q_j\Big)}_{\substack{\text{Downstream} \\ \text{revenue}}} \;+\; \underbrace{c\sum_{j\neq 0} Q_j}_{\substack{\text{Access} \\ \text{revenue}}} \;-\; \underbrace{f(\theta)}_{\substack{\text{Upstream} \\ \text{investment}}}. \tag{3}$$

The incumbent maximizes π_0 with respect to Q_0, taking as given the quantities of the entrants Q_i $(i > 0)$. The entrants are active in the downstream market only, and their profit functions are given by

$$\pi_i \;=\; \underbrace{Q_i\Big(\theta - \sum_{j=0}^{n} Q_j\Big)}_{\substack{\text{Downstream} \\ \text{revenue}}} \;-\; \underbrace{c\,Q_i}_{\substack{\text{Access} \\ \text{cost}}}. \tag{4}$$

Firm $i > 1$ chooses Q_i to maximize π_i, taking as given the production quantities of the other firms.

3.3 Rate setting

To close the model, we now specify the principle by which the access rate c is determined. Let us denote by $Q(\theta, c)$ the total output in the Cournot equilibrium that prevails for a given quality level θ and a given access rate c. Suppose that, in this Cournot equilibrium, the following is condition is satisfied ex-post:

$$c \cdot Q(\theta, c) = f(\theta). \tag{5}$$

In this case, we say that the access rate c is *revenue-neutral*. If (5) holds, the $n + 1$ firms have paid for the upstream investment $f(\theta)$ in proportion to their (ex-post) downstream market shares. Equivalently, (5) implies that all firms have the same ex-post average cost, namely c.

The central idea of the paper is to impose revenue neutrality as an equilibrium condition, in addition to the profit maximization conditions. Specifically, we propose the following downstream equilibrium concept:

Definition 1. Given θ, a *revenue-neutral open access equilibrium* in the downstream market is a tuple (Q_0, Q_1, ..., Q_n, c) such that

  (i) Q_0 maximizes π_0 given $(Q_i)_{i>0}$ and c,

  (ii) for each $i \geq 1$, Q_i maximizes π_i given $(Q_j)_{j \neq i}$ and c,

  (iii) the access rate c satisfies $c \sum_{i=0}^{n} Q_i = f(\theta)$.

In the next section we will characterize the downstream equilibrium as defined in Definition 1 further. Before doing so, however, let us discuss in some detail the idea behind our equilibrium concept. In particular, why focus on revenue-neutral access, and "who" sets the revenue-neutral access rate c?

A. Why revenue-neutral access?

The idea underlying the revenue neutrality condition is that all profits or losses the incumbent generates are accounted for by its downstream operation. That is, leasing the upstream resource to competitors should not be an independent "profit center" for the incumbent, nor should it inflict any "undue losses." Thus, the firms share the investment in proportion to their usage of the upstream good. This idea has real regulatory counterparts. First, what we call revenue neutrality corresponds, in important aspects, to the so-called *long-run incremental cost (LRIC)* approach to access pricing (see Berg and Tschirhart (1988)). The LRIC rate is a linear tariff that is the sum of the network's marginal usage cost (which in this paper is zero) and a markup for volume-neutral costs, calculated as the ratio of the investment in the network and the downstream quantity (our access fee c).[9] Second, the revenue neutrality condition reflects several general principles stipulated in many open access laws. For example, the 1996 U.S. Telecommunications Act mandates that access rates meet standards of "fairness and reasonableness" and be "non-discriminatory" (Sect. 251 (c), Sect. 252 (d)). One obvious interpretation of what fair and reasonable means is that firms pay for facilities they access in proportion to their usage, and the payment received by the incumbent equals the share of the upstream resource used by the entrants. Revenue-neutral access rates are then also non-discriminatory, as the terms of access are the same for all entrants, and the incumbent pays the same average cost for facility use as does each entrant.

B. Who sets the access rate?

Our model is deliberately parsimonious with respect to the process by which the access rate c is found. Instead, to endogenize c we make revenue neutrality an equilibrium condition, similar in spirit to a market clearing condition which endogenizes prices in a competitive equilibrium. The downstream market may reach such a state of revenue neutrality through

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[9]In Section 6.1, we discuss the actual use of LRIC prices in more detail.

an (unmodelled) tâtonnement process by which the equilibrium access rate c is found. In practice, of course, this process will most likely be facilitated by some regulatory agency.[10] It is, however, important that that this regulator is not opportunistic and does not replace revenue-neutral access rates with free access after the investment is made, even though this would increase welfare in the downstream market. That is, we assume commitment to a revenue-neutral mechanism, whatever the procedural details of this mechanism may be. The incumbent therefore knows that, whichever investment it chooses to make, the resulting downstream market will play out in the way described in Definition 1.

4 Analysis of the Downstream Equilibrium

In this section we characterize the revenue-neutral open access equilibrium in the downstream market, for a given value of θ. To begin with, note that the maximal producer surplus that can be extracted in the downstream market (for given θ) is the monopoly revenue $\theta^2/4$. By our assumptions on f, there exists a unique $\bar{\theta} > 0$ such that

$$f(\theta) \begin{array}{c} < \\ = \\ > \end{array} \frac{\theta^2}{4} \quad \text{iff} \quad \theta \begin{array}{c} < \\ = \\ > \end{array} \bar{\theta}.$$

As stated in the following result, depending on whether $\theta < \bar{\theta}$ or $\theta \geq \bar{\theta}$, either all firms or only the incumbent are active in the downstream market:

Lemma 1. *A revenue-neutral open access equilibrium exists for all θ. If $\theta < \bar{\theta}$, all firms are active and earn a positive profit in equilibrium. If $\theta > \bar{\theta}$, only the incumbent is active, and it earns a negative profit. If $\theta = \bar{\theta}$, only the incumbent is active, and it earns a zero profit.*

Lemma 1 implies that the incumbent never chooses a quality level $\theta \geq \bar{\theta}$. Thus, we can focus on the case $\theta < \bar{\theta}$ from now on. The assumption of a linear demand curve makes it straightforward to compute the resulting downstream market outcome in closed form. Letting q be the quantity produced by each of the entrants, the first-order conditions for maxima of (3) and (4), respectively, are given by

$$\theta - 2Q_0 - nq = 0, \tag{6}$$

$$\theta - Q_0 - (n+1)q = c. \tag{7}$$

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[10] Consider, for example, an institutional environment in which the incumbent submits proposals for an access tariff to a regulator, and potential entrants can either comment on these or respond with alternative proposals of their own. Each proposal could be accompanied by an analysis of the anticipated market outcome that is likely to prevail under the proposed tariff. In this process, the regulator acts as a mediator who reads the proposals and, if necessary, returns them to the firms for adjustments. (In the U.S., regulatory agencies such as the FCC or FERC use such procedures to determine access rates to communication networks and gas pipelines.) If the regulator is satisfied that a particular access rate would yield a revenue-neutral downstream outcome, it approves this tariff and the industry implements it.

Together with the condition in (5), we can solve these conditions for the revenue-neutral open access equilibrium:

$$Q_0 = \frac{(n+3)\theta - A}{2(n+2)}, \quad q = \frac{-\theta + A}{n(n+2)}, \quad c = \frac{(n+1)\theta - A}{2n}, \tag{8}$$

where $A = \left[(n+1)^2\theta^2 - 4n(n+2)f(\theta)\right]^{1/2}$. The values Q_0, q, and c are well-defined and positive if $\theta < \bar{\theta}$. The aggregate equilibrium quantity, and the equilibrium price for the final good, are then given by

$$Q = \frac{(n+1)\theta + A}{2(n+2)}, \quad P = \frac{(n+3)\theta - A}{2(n+2)}. \tag{9}$$

It can be verified that $P > c$, so that each firm indeed earns a positive profit.

We now examine how the downstream equilibrium adjusts in response to changes in the quality level, as well as the number of entrants. Our results reveal several interesting aspects of downstream competition under open access, and will be used later in proving our main results. We let

$$\gamma \equiv Q_0/Q$$

denote the incumbent's market share. Note that since the entrants face a positive marginal cost, while the incumbent does not, we have $Q_0 > q$ and thus $\gamma > 1/(n+1)$. We then have the following result:

Lemma 2. *For $\theta \in (0, \bar{\theta})$, the following holds in every symmetric revenue-neutral open access equilibrium:*

(a) *The incumbent's market share γ increases in θ, and $\gamma \to 1$ as $\theta \to \bar{\theta}$.*

(b) *The incumbent's quantity Q_0, as well as the access rate c and the market price P, increase in θ and are strictly convex functions of θ. An entrant's quantity q, as well as the total output Q, are strictly concave functions of θ.*

Observe that $Q_0 = P$ in equilibrium (by (8)–(9)), so the incumbent's market share γ equals the negative of the elasticity of demand in the downstream equilibrium. Since $\gamma < 1$, the industry operates on the elastic part of the demand curve. However, by part (a) of Lemma 2, an increase in quality makes increases the incumbent's market share and consequently moves the downstream market outcome closer to the inelastic part. This observation demonstrates that quality investments can be used by the incumbent strategically, to influence the extent to which it remains a dominant firm.

Next, we examine how the downstream equilibrium adjusts in response to changes in n, the number of entrants. An upper bound for the aggregate quantity in the downstream market is given by the relation $Q \cdot (\theta - Q) = f(\theta)$ (i.e., the industry as a whole breaks even). Solving for this bound we get

$$\bar{Q} \equiv \frac{1}{2}\theta + \sqrt{\frac{1}{4}\theta^2 - f(\theta)} \quad \in (\theta/2, \theta).$$

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Note that this is well-defined, since $f(\theta) < \theta^2/4$. The average cost in the downstream market at this quantity equals the market price. The quantity $\overline{Q}$ can be interpreted as the perfectly competitive point on the demand curve. It is not, however, characterized by the usual condition that price equals marginal cost of production (which is zero)—because an upfront investment is required, the market price must include a markup to cover this fixed cost. At the point $\overline{Q}$, the market price equals this markup; hence each firm earns a zero profit. We then have the following analogue to the classic Cournot limit theorem:

Lemma 3. *For given $\theta \in (0, \overline{\theta})$, the aggregate output in a revenue-neutral open access equilibrium increases in the number of entrants, n, and satisfies $Q \to \overline{Q}$ as $n \to \infty$. The incumbent's market share, γ, decreases, but stays bounded away from zero as n increases.*

Lemma 3 implies that the incumbent remains a quantitatively large firm, even with a large number of entrants. The reason is that, unlike the entrants, the incumbent does not regard the access fee c as a marginal cost of production in the downstream market. Thus, while the incumbent will always have the same average cost as its rivals (namely c), it retains an advantage in terms of marginal cost which will translate into a larger market share in equilibrium.

5   The Incumbent's Investment Decision

In the first stage of the model, the incumbent chooses θ in anticipation of the revenue-neutral open access equilibrium that will obtain in the downstream market. Specifically, the incumbent sets θ to maximize the resulting downstream equilibrium profit π_0. In this section, we characterize this optimal quality level.

Recall from Lemma 1 that the incumbent makes a positive profit if and only if $0 < \theta < \overline{\theta}$. We can therefore focus on the interior equilibrium characterized in (8). The incumbent's profit function is

$$\pi_0 = Q_0(\theta - Q) + nqc - f(\theta),$$

that is, the incumbent's downstream revenue plus the access fee revenue, minus the investment in the upstream resource. The first-order condition for a profit maximum is therefore

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\begin{aligned}
\frac{d\pi_0}{d\theta} &= \frac{dQ_0}{d\theta}(\theta - Q) + Q_0\left(1 - \left(\frac{dQ_0}{d\theta} + n\frac{dq}{d\theta}\right)\right) + n\frac{d}{d\theta}[qc] - f'(\theta) \\
&= \frac{dQ_0}{d\theta}[\theta - 2Q_0 - nq] + Q_0\left(1 - n\frac{dq}{d\theta}\right) + n\frac{d}{d\theta}[qc] - f'(\theta) \\
&= Q_0\left(1 - n\frac{dq}{d\theta}\right) + \frac{d}{d\theta}[nqc] - f'(\theta) \\
&= 0. \tag{10}
\end{aligned}
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In the third line of (10), we have used (6), the incumbent's downstream first-order condition. Thus, in the spirit of the envelope theorem, the incumbent may neglect its own quantity adjustments when making its investment decision. The following result states that this first-order condition pins down the incumbent's quality choice uniquely.

Lemma 4. *The incumbent's first-order condition for a profit maximum is sufficient, and there exists a unique $\theta^* \in (0, \overline{\theta})$ which satisfies it.*

5.1   The main results

We now characterize the incumbent's quality choice in detail. Our main results concern the question whether, in the open access regime, the incumbent invests more than if it was a monopolist. Under the assumptions made so far, the answer is affirmative:

Theorem 1. *The quality level θ^* under revenue-neutral open access exceeds the monopoly level θ^M.*

Recall that the maximal feasible quality level for which the industry as a whole makes a non-negative profit is $\overline{\theta}$, so $\theta^* \leq \overline{\theta}$. Thus, as long as $\overline{\theta} < \theta^S$, Theorem 1 implies that under revenue-neutral open access, the tradeoff between static efficiency and dynamic efficiency disappears: Not only does the market outcome move from the monopoly point on the demand curve into the elastic region, but the demand curve itself shifts outward toward the socially optimal one.

Given a fixed quality level, we have shown in the previous section that an increase in the number of firms leads to a more competitive downstream outcome. In the limit, the market reaches a "perfectly competitive" point where all firms earn a zero profit. At this point, consumer surplus is maximized subject to the constraint that the firms earn enough revenue to recover the fixed cost of the upstream resource. This is true even though the incumbent remains a large firm relative to the entrants. We now examine how the incumbent's optimal choice θ^* responds to an increase in n. Interestingly, under the assumptions we have made so far, it increases:

Theorem 2. *The quality level θ^* under revenue-neutral open access strictly increases in the number of entrants.*

Thus, as the number of firms grows, welfare in the downstream market grows and at the same time the demand curve itself shifts outward. Note that this does not imply that $\theta^* \to \theta^S$. However, as long as $\overline{\theta} < \theta^S$, Theorem 2 strengthens our claim that static and dynamic efficiency need not be traded off against each other.

If $\overline{\theta} > \theta^S$, there exists a theoretical possibility of over-investment in the resource, as the incumbent may choose a quality level $\theta^* \in [\theta^S, \overline{\theta}]$. We now identify a sufficient condition for over-investment to occur. Recall that the maximal surplus that can be generated, given

quality level θ, is $\theta^2/2 - f(\theta)$. This is the surplus that can be achieved if the downstream good is provided to consumers at its marginal cost, which is zero. Thus, an efficiency measure of social provision is the following:

$$\rho(\theta) \equiv \frac{\theta^2/2 - f(\theta)}{f(\theta)},$$

that is, the "social rate of return" of an upstream resource of quality θ. We then have the following result:

Theorem 3. *If $\rho(\theta^S) > \sqrt{2}$, the quality level θ^* under revenue-neutral open access exceeds the socially optimal level θ^S if n is sufficiently large.*

For cost functions of the form $f(\theta) = \theta^k$, for example, the condition in Theorem 3 is satisfied if $k > 4.8284$. This does not imply that open access then automatically leads to over-investment—only that it does when n is sufficiently large. Hence, under the condition identified in Theorem 3, it is possible that a tradeoff between static and dynamic efficiency arises. However, the nature of this tradeoff is quite unexpected: An increase in static efficiency reduces dynamic efficiency, but not because investment incentives are diminished. Instead, they are amplified too much.

5.2   Intuition and strategic effects

To give an intuition for our results, observe that an investment in quality has two effects on market outcomes. First, it creates a larger market in that it raises consumers' willingness to pay for the final good, which can then be exploited through participation in the downstream markets. Second, a strategic effect arises: From Lemma 2 (a), we know that an additional quality unit increases the incumbent's market share; the incumbent can hence use quality to shape the degree to which it remains a dominant firm in the downstream market. We will examine these effects in more detail now.

The incumbent's first-order condition for a profit maximum, already given (10), is reproduced below:

$$\frac{d\pi_0}{d\theta} = Q_0 \left(1 - n\frac{dq}{d\theta}\right) + \frac{d}{d\theta}[nqc] - f'(\theta) = 0. \tag{11}$$

Recall that $\gamma = Q_0/Q$ is the incumbent's market share, and that the revenue neutrality condition implies $nqc = (1 - \gamma)f(\theta)$. Making these substitutions in (11), the first-order condition for a profit maximum can be expressed as follows:

$$\underbrace{\gamma f'(\theta)}_{\substack{\text{Direct} \\ \text{cost effect}}} + \underbrace{\frac{d\gamma}{d\theta}f(\theta)}_{\substack{\text{Indirect} \\ \text{cost effect}}} = \underbrace{\gamma Q}_{\substack{\text{Direct} \\ \text{revenue effect}}} + \underbrace{\gamma Q\frac{d}{d\theta}[-(1 - \gamma)Q]}_{\substack{\text{Indirect} \\ \text{revenue effect}}}. \tag{12}$$

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Condition (12) has the following interpretation. The left-hand side is the incumbent's marginal cost of quality level θ at the upstream stage, while the right-hand side is the marginal revenue with respect to θ in the downstream stage. In the optimum, marginal cost equals marginal revenue. Both marginal cost and marginal revenue can be decomposed into two parts, a direct and a strategic effect; these are the effects we alluded to in the beginning.

Consider first the direct cost and revenue effects, and suppose, for the time being, that there were no other terms in (12). Observe that the first-order condition (12) would then mirror the first-order condition of a single decision maker:

$$\gamma f'(\theta) = \gamma Q \quad (\text{i.e., } f'(\theta) = Q). \tag{13}$$

This is in fact what we found in the two benchmark cases examined earlier: A monopolist sets $f'(\theta) = Q^M = \theta/2$, and a planner sets $f'(\theta) = Q^S = \theta$. Based on the direct effects, therefore, convexity of f implies that market interventions which increase downstream output also increase quality, as long as costs and benefits are shared proportionally. This is, in fact, the intuition behind Theorems 1 and 2.

What complicates the picture is that, in addition to the direct effects, there are also indirect effects on both the cost and the revenue side. The indirect effects arise from the strategic interaction between the incumbent and the entrants in the downstream market. Note that a change in quality leads to an adjustment of the entrants' downstream output, and thereby also to an adjustment of the incumbent's downstream market share (γ increases in θ): On the cost side, not only does an increase in θ increase the incumbent's expenditure, but it also increases the fraction of the investment the incumbent must pay (the indirect effect given by $d\gamma/d\theta \cdot f(\theta)$). On the revenue side, an increase in θ not only shifts the demand curve, but also results in a movement along the demand curve toward the monopoly point (the indirect effect given by $-\gamma Q \cdot d(1-\gamma)Q/d\theta$). Unlike adjustments of the incumbent's own output Q_0, the adjustments in q and γ have first-order effects on the incumbent's profit and are thus not enveloped away from its decision how much to invest.

In general, these strategic effects may weaken or strengthen the non-strategic investment incentives, but they never weaken the direct incentives so much as to result in a quality below the monopoly level. They are, however, precisely the reason why open access may lead to over-investment relative to the social optimum. As Lemma 2 (a) shows, the incumbent can use quality investments to increase its market share. When absolute costs are sufficiently low, the indirect cost effect is small relative to the indirect revenue effect. In this situation, making a large quality investment is a relatively inexpensive way for the incumbent to reduce its rivals' market shares and increase its own. The condition in Theorem 3 is therefore based on absolute, instead of marginal, cost.

5.3 Comparison to ex-ante rate setting

As discussed in Section 2, the patent literature contains treatments of compulsory licensing, which is open access to intellectual property (e.g., Tandon (1982)). In these models, the royalty rate is chosen before the incumbent makes its investment decision. In our model, on the other hand, a policy is not simply an access tariff or a royalty rate, but a principle (namely revenue neutrality) by which an access tariff is determined in a given market, once the market has been established by way of the incumbent's quality choice. If we changed the timing in our model—so that first a regulator sets the access tariff c, then the incumbent chooses the quality level θ, and finally all firms compete as Cournot oligopolists—a tradeoff between downstream competition and upstream investments does arise:

Theorem 4. *Suppose the access rate c is chosen before the incumbent chooses the quality level θ. Then the following holds: If $c \geq \theta^M/2$, the incumbent chooses the monopoly quality level θ^M and no entry occurs, and if $c < \theta^M/2$ the incumbent chooses a quality level strictly less than the monopoly level θ^M, and entry occurs.*

Thus, as long as an ex-ante access rate is successful in enhancing static efficiency, it weakens investment incentives. With revenue-neutral open access, on the other hand, the downstream efficiency gain actually strengthens the upstream investment incentives. Of course, ex-ante rate setting may increase welfare, provided the upstream loss is not too large. Similarly, with revenue-neutral access the possibility of over-investment may ultimately decrease welfare.

When comparing these mechanisms it is important to keep in mind that, in order to set a welfare-enhancing access rate ex-ante, the regulator must understand the relationship between quality (i.e., market size) and investments. If such information was available to the regulator, the question arises why, in this case, the regulator would not simply compute the socially optimal quality level and then require the incumbent to install this quality. On the other hand, no such information is required in the revenue neutral mechanism. The only party that needs to know the function f is the incumbent, while the regulator can simply observe the realized values θ and $f(\theta)$, and then apply the revenue neutrality criterion. Thus, the same mechanism can work for different f, using only information observable from the actual market that is created by the incumbent.

5.4 Remarks

We conclude this section with a few short remarks on the mechanism described.

A. Profits vs. incentives

Subjecting the upstream good to open access clearly decreases the incumbent's profit. As we have shown, the profit reduction under open access does not imply that the profit maximum occurs at a lower investment level than in monopoly. Some vocal critics of open access, on

the other hand, have equated reduced profits with disincentives to invest (e.g. Thierer and Crews (2003)). In our view, their argument neglects a basic economic insight: The incentives to do something, or not to do something, have little to do with the ex-post payoff level one obtains, and a lot with the slope of the payoff function at the relevant points. The suggestion that, because open access reduces the firm's profit it will invest little, is therefore disingenuous.

B. Imperfect vs. perfect competition

An imperfectly competitive downstream market matters for our results only in so far as the incumbent's optimal quality choice is then unique. Imperfect competition allows the incumbent to make a positive profit in the downstream market. If the downstream market was perfectly competitive ($P = c$) the incumbent's only source of revenue would be the access fee revenue. If the revenue neutrality principle was employed in this case, the incumbent's overall profit would be zero for all $\theta \in [0, \overline{\theta}]$, and hence *any* $\theta \in [0, \overline{\theta}]$ would be optimal. This is in fact what happens in the limit of our model: As n increases the maximizer of π_0 shifts further out while π_0 itself becomes flatter; in the limit, π_0 becomes zero.

C. Linear vs. non-linear access tariffs

The observation that increased competition in the downstream market increases quality seems to suggest that the following mechanism may be even more successful in stimulating investments: After the incumbent has paid $f(\theta)$, each entrant pays a lump-sum transfer of $f(\theta)/(n + 1)$ to the incumbent for the right to access the resource at no cost thereafter. Since this increases the downstream quantity compared to the case where the access rate is positive, it may seem that investment incentives are then even stronger. With a large number of entrants, however, the industry's downstream revenue would be close to zero and thus insufficient to recoup the initial investment. In equilibrium, therefore, a bound on the number of active firms exists. This limits competition and thus counteracts the positive effects of flat-rate access on quantity. A linear tariff, on the other hand, has the advantage of allowing an arbitrarily large number of firms.

D. Investments vs. social welfare

Because of its dual effect on both downstream efficiency and upstream investments, revenue-neutral open access tends to increase overall social welfare relative to monopoly. We performed computations that show that these welfare gains can be quite large. Moreover, the welfare gain from an optimally chosen fixed access rate (see Section 5.3) is often small, compared to the revenue-neutral mechanism.[11] As shown in Theorem 3, however, under revenue-neutral access it is possible that the incumbent sets a quality level that is higher than in the social optimum. In this case, the downstream efficiency gains will be (at least partially) offset by an efficiency loss due to over-investment. If the latter is too large, a net

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[11]Computational welfare results are available from the authors upon request.

loss in overall welfare may result. In our computations, this happened for rather extreme parameter values. For example, if the cost function is $f(\theta) = \theta^{25}$, welfare in a revenue-neutral open access regime will be lower than in monopoly as well as in a fixed-rate regime, provided the number of entrants is at least 18.

6 Extensions and Policy Implications

In this section we extend our basic model by introducing technological change as well as uncertainty. Both have been recognized as potential impediments to investments under open access (see Pindyck (2004) for a thorough discussion). For the case of revenue-neutral open access—which, as we have shown, has surprisingly positive properties with regard to investments—we now quantify the extent to which investments are sensitive to technological change and risk. We regard the results of this section and those of Section 5.1 as complementary. We believe that our basic model elucidates a rather general insight: That it is possible, by using the right mechanism, to create a causal link from static efficiency to dynamic efficiency. In the present section, we put this insight into a number of contexts that matter in practice. By doing so, we are able derive further useful policy implications.

6.1 Engineering costs and technological progress

When computing access prices, regulatory agencies often eschew the historical investment made into the shared facility and replace it with a *hypothetical* investment: The investment a firm would have to make if it were to invest in the same facility today, in the most cost-efficient way possible. This investment is typically arrived at by using an "engineering model" of the facility subject to access. For example, the 1996 U.S. Telecom Act mandates the Federal Communications Commission to set LRIC (*long-run incremental cost*) access rates on the basis of such engineering costs. The use of engineering costs for the computation of access rates is one of the most controversial aspects of access regulation in the U.S. and elsewhere (see Pindyck (2004), Guthrie et al. (2006)). The approach is believed to give operators an incentive to exert managerial effort and deploy their infrastructure in a cost-effective manner. In the presence of technological progress, however, the cost of quality decreases over time. Thus, even if the incumbent operates efficiently, access rates computed on the basis of hypothetical costs may not allow the incumbent to recover a fraction of the historical investment that is sufficient to ensure a non-negative profit.

Let us consider cost sharing rules in which the "recovered investment," Qc, differs from the actual investment $f(\theta)$ the incumbent has made. Specifically, let us modify condition (iii) of Definition 1 by imposing that the access fee c satisfy

$$c \sum_{i=0}^{n} Q_i = \alpha f(\theta), \tag{14}$$

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where $\alpha \geq 0$ is called the recovery factor. If $\alpha = 1$, we have the case of revenue-neutral access. If $\alpha < 1$, the access rate is *sub-neutral*, in the sense that the upstream investment recovered by the incumbent through its fee revenue is less than the entrants' share of the downstream market. A recovery factor less than one can be regarded as a measure of technological progress, by letting $1 - \alpha$ be the rate at which the cost of establishing a given facility has decreased between the time it was built and the time the access rate is determined.

Given α, the incumbent's ex-post profit can now be written as follows:

$$\pi_0(\theta, \alpha) = Q_0(P - c) - (1 - \alpha)f(\theta) \tag{15}$$

(of course, Q_0, P, and c also depend on α now). The term $-(1 - \alpha)f(\theta)$ arises since the actual investment is $f(\theta)$ and not $\alpha f(\theta)$. Thus, the incumbent must pay the difference $(1 - \alpha)f(\theta)$ as the "residual cost" not accounted for by the sub-neutral sharing rule. Let $\theta^*(\alpha, n)$ be the incumbent's quality choice that maximizes (15), as a function of α and n. We then have the following result:

Theorem 5. *Fix $\delta \in (0, \theta^*)$. For each $n \geq 1$ there exists a bound $\overline{\alpha}(n) < 1$ such that $\alpha < \overline{\alpha}(n)$ implies $\theta^*(\alpha, n) < \delta$. Furthermore, $\overline{\alpha}(n)$ increases in n and $\overline{\alpha}(n) \to 1$ as $n \to \infty$.*

Theorem 5 says the following: Suppose we want to achieve some desired minimal quality level $\delta > 0$. Then, with an increasingly competitive downstream market, the set of non-neutral sharing rules that result in at least a δ-quality shrinks, and in the limit only the revenue-neutral rule is left. If exactly the revenue-neutral cost sharing rule is implemented, we know from the Section 5 that increasing the number of competitors increases the incumbent's investment, and that this investment will be above the level a monopolistic firm would make. Theorem 5 now implies that, if n is large, this investment falls sharply for sharing rules that are even slightly sub-neutral.[12]

Thus, the larger the benefits of open access, the larger is the sensitivity of investments to the details of the rate setting mechansim used. This implies that success and failure of open access lie very close together: Policy makers do not have to trade off static against dynamic efficiency—it is possible to increase downstream efficiency while at the same time promoting upstream investments. To have it both ways, however, it is important that sub-neutral access rates be avoided. In particular, our results call into question the usefulness of engineering cost approaches in access rate setting.

6.2 Uncertainty and the option to access

We now turn to the case where investments in quality have risky outcomes. We do not simply claim that investments may be lower if they carry risks—this is the case also in monopoly.

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[12]Because δ can be arbitrarily small, this essentially amounts to a shutdown of the upstream segment and hence of the downstream market.

The appropriate question to ask is: How much does an access-regulated incumbent invest under uncertainty, compared to the investment made by a monopolist under the same uncertainty?

To introduce risk to our model, we reverse notation and make quality a function of the investment instead of the other way around; this change in notation is merely for convenience. Suppose that the incumbent chooses an investment y, which then yields quality level $\theta(y) = f^{-1}(y)$ with probability $p \in (0, 1)$ (the good state of nature), and a reduced quality level $r\theta(y)$ ($r < 1$) with the remaining probability (the bad state of nature). One can think of this model as one in which the incumbent chooses an "intented quality" θ and pays $f(\theta)$. With probability $1 - p$ the investment partially fails and yields only a fraction r of the intented quality. Thus, the risky environment is characterized by the two parameters p and r. We let $y^M(p, r)$ be the monopoly investment level in this environment, and $y^*(p, r, n)$ be the investment under open access with n entrants.

We assume that in both states of nature a revenue-neutral access rate is implemented. If y is the investment and θ the realized quality level, we let $Q_0(\theta, y), q(\theta, y), c(\theta, y)$ be the revenue-neutral open access equilibrium. Thus, the access rate $c(\theta, y)$ satisfies

$$c(\theta, y) \ (Q_0(\theta, y) + nq(\theta, y)) = y$$

for all θ and y. We let $P(\theta, y)$ be the price, and $\pi_i(\theta, y)$ ($i \geq 0$) be firm i's profit, in this equilibrium. The expected payoff for the incumbent is then

$$E\pi_0(y) = p\pi_0(\theta(y), y) + (1 - p)\pi_0(r\theta(y), y).$$

Similar to the risk-free case, we define two thresholds $\bar{y}_g$ and $\bar{y}_b(r)$ implicitly as follows:

$$\bar{y}_g = \frac{\theta(\bar{y}_g)^2}{4}, \quad \bar{y}_b(r) = \frac{(r\theta(\bar{y}_b(r)))^2}{4}.$$

The threshold $\bar{y}_g$ (resp. $\bar{y}_b(r)$) is the maximal investment that can be recovered in the good (resp. bad) state. It can be easily verified that $\bar{y}_g > \bar{y}_b(r)$ for $r < 1$; the incumbent therefore always chooses an investment such that $y < \bar{y}_g$.

Now consider the following scenario: Suppose the actual investment y is such that

$$\bar{y}_b(r) < y < \bar{y}_g. \tag{16}$$

By following the argument of Lemma 1, the incumbent shares the market with all entrants in the good state (because $y < \bar{y}_g$), but is the only firm in the market in the bad state (because $y > \bar{y}_b$). The incumbent's profit in each case is given by

$$\pi_0(\theta(y), y) = Q_0(\theta(y), y) \cdot \left[P(\theta(y), y) - c(\theta(y), y) \right],$$

$$\pi_0(r\theta(y), y) = \frac{(r\theta(y))^2}{4} - y.$$

Given $y \in (\overline{y}_b(r), \overline{y}_g)$, the latter is a negative constant while the former is positive and approximately zero if n is large (by Lemma 3). The expected profit $E\pi_0(y)$ is therefore negative if n is large, and the incumbent would have been better off setting $y \leq \overline{y}_b(r)$. In other words, the entrants' option to make profits in the good state and *not* make losses in the bad state is what may reduce investments to below $\overline{y}_b(r)$ if the environment is risky. A monopolist, on the other hand, would be more willing to take the risk of a negative profit in the bad state because of the expectation that the positive profit in the good state will not be diluted through sharing. Whether (16) holds depends on the parameters of the model:

Theorem 6. *There exist constants $\overline{p} < 1$ and $\overline{r} > 0$ such that the following holds: Given $\overline{p} < p < 1$ and $r < \overline{r}$, there exists a finite $\overline{N}(p, r)$ such that $n > \overline{N}(p, r)$ implies $y^*(p, r, n) < y^M(p, r)$.*

We now illustrate this result in Table 1, assuming the cost function $f(\theta) = \theta^3/3$. The first row depicts the incumbent's investment under revenue-neutral access in the risk-free case. The investment increases with the number of entrants, as expected given Theorem 2. The other rows represent various risky environments, using two values for p and three values for r. y^S denotes the socially optimal investment.

p	r	y^M	y^* (for varying n)								y^S
			1	2	3	4	$\cdots$	10	$\cdots$	25	
1.0		.042	.052	.062	.068	.072	$\cdots$	.083	$\cdots$	.092	.333
.9	.9	.039	.050	.059	.062	.065	$\cdots$	.072	$\cdots$	.072	.314
.9	.7	.035	.044	.047	.047	.047	$\cdots$	.032	$\cdots$	.017	.286
.9	.5	.032	.039	.042	.042	.039	$\cdots$	.017	$\cdots$	.003	.260
.5	.9	.030	.039	.044	.047	.050	$\cdots$	.055	$\cdots$	.059	.351
.5	.7	.017	.016	.014	.014	.014	$\cdots$	.014	$\cdots$	.014	.135
.5	.5	.010	.007	.005	.003	.002	$\cdots$	.002	$\cdots$	.002	.079

Table 1: Optimal investment under uncertainty ($f(\theta) = \theta^3/3$)

It is particularly interesting to compare the cases ($p=0.9, r=0.5$) and ($p=0.5, r=0.9$). In the first case, there is a small chance of a relatively bad outcome, while in the second there is a relatively large chance of a mildly bad outcome. In terms of the monopoly investment level y^M, both types of uncertainty are comparable (y^M is similar in both cases). Under open access, this changes. With a small number of entrants, open access increases y^* relative to monopoly in each case. However, once the number of entrants becomes sufficiently large, y^* falls below monopoly in the first case, but continues to increase in the second.

This result has implications for the implementation of open access policies in risky environments. Insisting on an ex-post revenue-neutral access policy may fail to stimulate investments because doing so neglects the ex-ante risk the investor has taken. One "solution" to this problem is to enforce access in all states of the world and hence facilitate a fair sharing of upside *and* downside risks; however, this seems hardly feasible. What our results indicate, then, is that the decision *whether or not to adopt open access in the first placce* should be responsive to the specific risks associated with the case at hand. For example, the 2004 German *Telekommunikationsgesetz* (Telecommunications Act) expressly states that the "the aims of regulation shall be [...] to encourage efficient investment in infrastructure and to promote innovation," and that "in considering whether an access obligation is justified and proportionate to the regulatory aims [...] the Regulatory Authority has to take into account [...] the initial investment by the facility owner, bearing in mind the risks involved in making the investment."[13]

An assessment of the relative downside risks of an investment could hence be useful in determining whether an open access policy should be implemented. For significant downside risk (low r), protection of the incumbent's monopoly status, perhaps over a limited time horizon, may well be preferable to access. In particular, these considerations suggest that open access to intellectual property should perhaps be approached differently than open access to physical facilities: Investments in physical facilities are often routine maintenance and upgrade expenditures which carry significantly less risk than investments in research and development activities.[14]

7 Conclusion

Measures which enhance allocative efficiency in an otherwise monopolistic market do not necessarily require a sacrifice in dynamic efficiency. To the contrary, we showed that a policy of revenue-neutral open access can advance both objectives simultaneously. The paper thus demonstrates that market outcomes under open access lie outside the previously perceived "efficiency frontier." We do have specific, but important, applications in mind—namely the sharing of intellectual property and infrastructure facilities. The logic of our results goes beyond particular applications, however: If the right cost-sharing rule is employed, it is precisely the increase in static efficiency under open access that leads to larger quality investments, and hence to an increase in dynamic efficiency.

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[13]Sect. 2 (2), Sect. 21 (1). The English text of the law can be found at `http://www.bmwi.de/BMWi/Redaktion/PDF/Gesetz/telekommunkationsgesetz-en`. (Accessed: August 15, 2009.)

[14]Several empirical studies, summarized in Scherer (2006), found compulsory licensing to have had no negative impact on innovative activity in U.S. and British corporations, with the exception of the pharmaceutical sector. Our model with risky investments offers an explanation, as pharmaceutical R&D often has a pronounced "all or nothing" flavor, and this is precisely the type of risk we identify as an impediment to dynamic efficiency under open access.

There are important issues which we do not treat in this paper. First, we do not consider what happens if the incumbent's resource is subject to congestion. While this is clearly not a problem for intellectual property, one may want to relax the non-rivalry assumption in applications to physical facilities. Second, our model does not allow us to examine settings with competing upstrem resources (e.g., network bypass). Third, we do not examine the entry decisions made by firms, as the number of entrants was exogenous. Fourth, we do not consider the case of differentiated downstream offerings (in this case the incumbent may not necessarily want to foreclose the downstream market). Despite these limitations, we believe that our paper demonstrates the potential benefits of open access, as well as some potential pitfalls which can arise in the implementation of such policies. On a more general level, it suggests that the debate over the optimal protection of property rights to productive assets may have been misguided by its focus on the "wrong" efficiency tradeoff.

Appendix: Proofs

Preliminaries

In this section we compile comparative statics results regarding the behavior of the downstream equilibrium in response to changes in θ, n, and α. These will be used in the proofs later. Note that in all of our theorems except Theorem 5 (in Section 6.1) the recovery factor α equals one, as these results apply to the case of revenue-neutral access. In this preliminary section, however, we leave α a general parameter in order to not have to repeat the same exercises twice.

Note that we can express the open access equilibrium in the downstream market as a solution (Q_0, q, c) to the following system of equations:

$$
\begin{aligned}
F_1 &\equiv \theta - 2Q_0 - nq = 0, \\
F_2 &\equiv \theta - Q_0 - (n+1)q - c = 0, \\
F_3 &\equiv (Q_0 + nq)c - \alpha f(\theta) = 0.
\end{aligned}
$$

The Jacobian matrix associated with (F_1, F_2, F_3) is

$$
J \equiv \begin{pmatrix} \partial F_1/\partial Q_0 & \partial F_1/\partial q & \partial F_1/\partial c \\ \partial F_2/\partial Q_0 & \partial F_2/\partial q & \partial F_2/\partial c \\ \partial F_3/\partial Q_0 & \partial F_3/\partial q & \partial F_3/\partial c \end{pmatrix} = \begin{pmatrix} -2 & -n & 0 \\ -1 & -(n+1) & -1 \\ c & nc & Q \end{pmatrix}
$$

and has determinant $|J| = (n+2)Q - nc$. Note that $|J|$ is positive for all $\theta < \bar{\theta}$ (this follows from the fact that $Q > Q_0 = P > c$). We can now express the behavior of the open access

equilibrium in response to changes in θ as the following linear system:

$$J \times \begin{pmatrix} dQ_0/d\theta \\ dq/d\theta \\ dc/d\theta \end{pmatrix} = - \begin{pmatrix} \partial F_1/\partial\theta \\ \partial F_2/\partial\theta \\ \partial F_3/\partial\theta \end{pmatrix} = \begin{pmatrix} -1 \\ -1 \\ \alpha f'(\theta) \end{pmatrix}.$$

The derivatives of the downstream equilibrium variables with respect to θ are given (in implicit form) by the following solution:

$$\frac{dQ_0}{d\theta} = \frac{n\alpha f'(\theta) - nc + Q}{|J|}, \tag{17}$$

$$\frac{dq}{d\theta} = \frac{-2\alpha f'(\theta) + c + Q}{|J|}, \tag{18}$$

$$\frac{dc}{d\theta} = \frac{(n+2)\alpha f'(\theta) - (n+1)c}{|J|}. \tag{19}$$

This implies that

$$\frac{dQ}{d\theta} = \frac{dQ_0}{d\theta} + n\frac{dq}{d\theta} = \frac{-n\alpha f'(\theta) + (n+1)Q}{|J|}. \tag{20}$$

Similarly, we can express the behavior of the equilibrium in response to changes in n as

$$J \times \begin{pmatrix} dQ_0/dn \\ dq/dn \\ dc/dn \end{pmatrix} = - \begin{pmatrix} \partial F_1/\partial n \\ \partial F_2/\partial n \\ \partial F_3/\partial n \end{pmatrix} = \begin{pmatrix} q \\ q \\ -qc \end{pmatrix},$$

yielding the following derivatives with respect to n:

$$\frac{dQ_0}{dn} = \frac{-qQ}{|J|}, \tag{21}$$

$$\frac{dq}{dn} = \frac{-q(Q-c)}{|J|}, \tag{22}$$

$$\frac{dc}{dn} = \frac{-qc}{|J|}. \tag{23}$$

This implies that

$$\frac{dQ}{dn} = \frac{dQ_0}{dn} + n\frac{dq}{dn} + q = \frac{qQ}{|J|}. \tag{24}$$

We repeat the same steps once more for the recovery factor α:

$$J \times \begin{pmatrix} dQ_0/d\alpha \\ dq/d\alpha \\ dc/d\alpha \end{pmatrix} = \begin{pmatrix} -\partial F_1/\partial\alpha \\ -\partial F_2/\partial\alpha \\ -\partial F_3/\partial\alpha \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ f(\theta) \end{pmatrix},$$

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to get

$$\frac{dQ_0}{d\alpha} = \frac{nf(\theta)}{|J|}, \tag{25}$$

$$\frac{dq}{d\alpha} = \frac{-2f(\theta)}{|J|}, \tag{26}$$

$$\frac{dc}{dn} = \frac{(n+2)f(\theta)}{|J|} \tag{27}$$

as well as

$$\frac{dQ}{d\alpha} = \frac{dQ_0}{d\alpha} + n\frac{dq}{d\alpha} = \frac{-nf(\theta)}{|J|}. \tag{28}$$

Proof of Lemma 1

Consider first the case $\theta > \bar{\theta}$ and thus $\theta^2/4 < f(\theta)$. Since the incumbent has a zero marginal cost, it will produce a positive quantity whenever the price exceeds zero. The revenue neutrality condition requires that all firms that produce a positive quantity have the same average cost c, and that this cost satisfy $Qc = f(\theta)$. Hence, if $\theta > \bar{\theta}$ any firm that produces a positive quantity must make a negative profit. Since every entrant $i \geq 1$ can guarantee a zero profit by staying out of the market, we have $Q_i = 0 \ \forall i \geq 0$. Firm 0 is then the only active firm in the market, so it produces the monopoly quantity $\theta/2$ and earns revenues $\theta^2/4 < f(\theta)$, resulting in a negative profit. Setting $c = 2f(\theta)/\theta$, then, this outcome can be supported as the unique revenue-neutral open access equilibrium according to Definition 1.

Next, consider the case $\theta = \bar{\theta}$ and thus $\bar{\theta}^2/4 = f(\bar{\theta})$. This implies that $Q = \bar{\theta}/2$. To see this, suppose first that $Q_i = 0$ for all $i > 0$. In this case, firm 0 is the only active firm and sets $Q_0 = Q = \bar{\theta}/2$, the monopoly quantity. Next, suppose $Q_i > 0$ for some $i \geq 1$. If $Q \neq \bar{\theta}/2$, the industry makes a negative profit, and thus firm i (who obtains a share of the overall profit that equals its market share) makes a negative profit. Because i can guarantee itself zero, this cannot be the case; thus $Q = \bar{\theta}/2$. Therefore, $Q_0 = \bar{\theta}/2 - \sum_{j>0} Q_j$. Since the incumbent has a zero marginal cost, it produces quantity $Q_0 = (\bar{\theta} - \sum_{j>0} Q_j)/2$ (its best response), a contradiction unless $\sum_{j>0} Q_j = 0$. Thus, if $\theta = \bar{\theta}$, firm 0 is the only active firm in the market, so it produces the monopoly quantity $\bar{\theta}/2$ and earns revenues $\bar{\theta}^2/4 = f(\theta)$, resulting in a zero profit. Setting $c = 2f(\bar{\theta})/\bar{\theta}$, this outcome can be supported as the unique revenue-neutral open access equilibrium.

Finally, consider the case $0 < \theta < \bar{\theta}$ and thus $\theta^2/4 > f(\theta)$. If the incumbent was the only active firm in the market, it would earn the monopoly revenue $\theta^2/4$ and make a positive profit. This profit can be written as $\pi_0 = Q_0(P - c)$, where $c = f(\theta)/Q_0$ is the average cost. Thus, $\pi_0 > 0$ implies $P > c$. But since the market price P as well as the access fee c are

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continuous in the aggregate quantity Q, any entrant could change its quantity from zero to a small positive value and earn a positive profit. Therefore, if $0 < \theta < \bar{\theta}$, there cannot be an open access equilibrium in which only the incumbent is active. Instead, all firms are active. $\qquad\square$

Proof of Lemma 2

We first prove (b). The incumbent's quantity in (8) can be expressed as

$$Q_0 = \theta \cdot \frac{1}{2(n+2)} \left(n + 3 + \sqrt{(n+1)^2 - 4n(n+2)\frac{f(\theta)}{\theta^2}} \right).$$

Provided the term multiplying θ in the above expression increases in θ strictly, then Q_0 is strictly increasing and strictly convex. To show that this is the case, we must show that $f(\theta)/(\theta^2)$ increases in θ, i.e.

$$\frac{d}{d\theta} \frac{f(\theta)}{\theta^2} = \frac{f'(\theta)\theta^2 - 2\theta f(\theta)}{\theta^4} > 0.$$

The middle term is positive if and only if $f'(\theta)\theta - 2f(\theta)$ is positive, and this condition can in turn be written as

$$f'(\theta)\theta - 2f(\theta) = \int_0^\theta f''(t)t + f'(t) - 2f'(t)dt = \int_0^\theta f''(t)t - f'(t)dt > 0.$$

Given that f' is strictly convex by assumption (i.e. $f'''(t) > 0$), the term inside the integral is positive for all $t > 0$ and thus $f'(\theta)\theta - 2f(\theta) > 0$. This proves that Q_0 is strictly increasing and convex, and analogous steps can be carried out to show that c and P are strictly increasing and convex, and that Q and q are strictly concave (they are not monotonic, however).

We now prove (a). The first statement follows from (b), since Q strictly concave implies $\gamma = (\theta - Q)/Q$ increases. To show the second claim, note that as $\theta \to \bar{\theta}$, in order for the industry to make a positive profit it must be the case that $Q \to \theta/2$ and $P \to \theta/2$ (the monopoly quantity and price); thus $\gamma = P/Q \to 1$. $\qquad\square$

Proof of Lemma 3

First, using (24), we have $dQ/dn > 0$, so Q increases monotonically as n increases. Now suppose $Q \not\to \bar{Q}$ as $n \to \infty$. By definition of $\bar{Q}$, there exists then a subsequence of equilibria along which the downstream price P remains bounded away from $c = f(\theta)/Q$. Since c is also an entrant's marginal cost, and $q = P - c$ by (7), this would imply that q remains bounded away from zero, and therefore $nq \to \infty$. Obviously this cannot be the case for fixed θ, as $\theta \geq Q \geq nq$, and we conclude that $Q \to \bar{Q}$ as $n \to \infty$. Finally, note that by (6) we can write the incumbent's market share as $\gamma = Q_0/Q = (\theta - Q)/Q$, which must be decreasing in n since Q is increasing. Because $Q < \bar{Q}$, and $\bar{Q} < \theta$ when $\theta < \bar{\theta}$, the incumbents market share remains bounded away from zero, i.e. $\gamma \geq (\theta - \bar{Q})/\bar{Q} > 0$. $\qquad\square$

Proof of Lemma 4

We begin by rewriting the first-order condition in (10). In the revenue-neutral open access equilibrium, the incumbent (like every entrant) has average cost c. This means that we can write the incumbent's profit as $\pi_0 = Q_0(P - c)$. Note further that (8)–(9) imply that $P - c = q$, so that $\pi_0 = Q_0 q$. The first-order condition in (10) can thus be stated equivalently as

$$\frac{dQ_0}{d\theta} q + \frac{dq}{d\theta} Q_0 = 0. \tag{29}$$

We show that whenever (29) holds, π_0 is strictly concave in θ. Because π_0 is continuous, differentiable on $(0, \bar{\theta})$, and $\pi_0 > 0$ if and only if $\theta \in (0, \bar{\theta})$, there must exist a unique θ^* that satisfies (29) and that maximes π_0 with respect to θ.

First, we show that $2Q_0 > nq$ at θ^*. Using (17)–(18), write (29) as follows:

$$\frac{d\pi_0}{d\theta} = \frac{1}{|J|} \times \underbrace{[q\,(n(f'(\theta) - c) + Q) - Q_0\,(2f'(\theta) - c - Q)]}_{\equiv K_1},$$

Since $|J| > 0$, as argued before, $\mathrm{sg}\,(d\pi_0/d\theta) = \mathrm{sg}\,(K_1)$. The downstream market first-order conditions (6)–(7) allow us to express Q_0, q, and c as functions of the quality level θ and the aggregate quantity Q:

$$Q_0 = \theta - Q, \quad q = \frac{2Q - \theta}{n}, \quad c = \frac{(n+1)\theta - (n+2)Q}{n}. \tag{30}$$

Substituting these expressions into K_1, we get

$$K_1 = \frac{2Q - \theta}{n} \left[n \left(f'(\theta) - \frac{(n+1)\theta - (n+2)Q}{n} \right) + Q \right]$$
$$- (\theta - Q) \left[2f'(\theta) - \frac{(n+1)\theta - (n+2)Q}{n} - Q \right].$$

Consolidating terms, this becomes

$$K_1 = \frac{1}{n} \times \underbrace{[(2n+2)\theta^2 - (4n+8)\theta Q + (2n+8)Q^2 + f'(\theta)n(4Q - 3\theta)]}_{\equiv K_2},$$

so that $\mathrm{sg}\,(d\pi_0/d\theta) = \mathrm{sg}\,(K_2)$. The first three terms in K_2 constitute a quadratic function of Q, which can be verified to be positive for all $\theta > 0$ and $n \geq 1$. Since $f'(\theta) > 0$, for $K_2 = 0$ we therefore must have $4Q - 3\theta < 0$ at θ^*. Using (30), we can write $4Q - 3\theta = nq - 2Q_0$. Thus, at the optimal quality level θ^* it will be the case that $2Q_0 > nq$.

We now return to the task of showing that π_0 is strictly concave when (29) holds. To shorten notation, let us write (29) as

$$Q_0'q + q'Q_0 = 0. \tag{31}$$

π_0 is concave if $Q_0''q + 2Q_0'q' + q''Q_0 < 0$, or

$$Q_0''q < -\left(2Q_0'q' + q''Q_0\right). \tag{32}$$

Suppose (31) holds, i.e. suppose $Q_0' = -q'Q_0/q$. Then (32) can be expressed as

$$\frac{Q_0''}{Q_0} < 2\left(\frac{q'}{q}\right)^2 - \frac{q''}{q},$$

and it is sufficient to show

$$\frac{Q_0''}{Q_0} < \frac{-q''}{q}. \tag{33}$$

Closed form expressions for Q_0 and q were given in (8) in Section 4, and differentiating them twice we get

$$Q_0'' = \frac{-A''}{2(n+2)} \quad \text{and} \quad q'' = \frac{A''}{n(n+2)}$$

(where A was also defined in Section 4). Because $Q_0'' > 0$ by Lemma 2 (b), $A'' < 0$. Condition (33) can now be written as

$$\frac{-A''}{2(n+2)Q_0} < \frac{-A''}{n(n+2)q},$$

or simply $2Q_0 > nq$. As shown earlier in the proof, this is indeed the case whenever the incumbent's first-order condition holds. Therefore, π_0 must be strictly concave at any such point. □

Proof of Theorem 1

We prove that $d\pi_0/d\theta > 0$ at θ^M. By Lemma 4 this implies that the incumbent's profit maximum must occur at $\theta^* > \theta^M$.

In the proof of Lemma 4 we have shown that the incumbent's profit function is upward-sloping at θ if and only if

$$K_2 = (2n+2)\theta^2 - (4n+8)\theta Q + (2n+8)Q^2 + f'(\theta)n(4Q - 3\theta) > 0. \tag{34}$$

Since θ^M satisfies the condition $f'(\theta^M) = \theta^M/2$, we replace $f'(\theta)$ by $\theta/2$ in (34) to get

$$\left.\frac{d\pi_0}{d\theta}\right|_{\theta=\theta^M} > 0 \quad \Leftrightarrow \quad \left(\frac{1}{2}n + 2\right)\theta^2 - (2n+8)\theta Q + (2n+8)Q^2 > 0. \tag{35}$$

After dividing by $2n+8$ this becomes

$$\frac{1}{4}\theta^2 - Q\theta + Q^2 > 0$$

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or $\theta^2/4 > Q(\theta - Q)$, which is satisfied since $\theta^2/4$ is the monopoly revenue at θ and $Q(\theta - Q)$ is the industry revenue in oligopoly at the same θ, and this must be strictly smaller than the monopoly revenue (recall that the industry operates on the elastic part of the demand curve). $\square$

Proof of Theorem 2

We show that an increase in n increases $d\pi_0/d\theta$ at every $\theta^M < \theta < \bar{\theta}$. By Lemma 4 and Theorem 1, this implies that θ^* increases in n.

In the proof of Lemma 4 we have shown that $d\pi_0/d\theta$ has the sign of

$$q[n(f'(\theta) - c) + Q] - Q_0[2f'(\theta) - c - Q].$$

Using (21)–(24), we have

$$\frac{d}{dn}\left(q[n(f'(\theta) - c) + Q]\right) = \frac{1}{|J|}\left[-q(Q - c)(n(f'(\theta) - c) + Q)\right.$$

$$\left. + q(nqc + qQ) + q(f'(\theta) - c)|J|\right] \quad (36)$$

and

$$\frac{d}{dn}\left(Q_0[2f'(\theta) - c - Q]\right) = \frac{1}{|J|}\left[-qQ(2f'(\theta) - c - Q) - qQ_0(Q - c)\right]. \quad (37)$$

We thus have to show that the term in (36) is larger than the term in (37).

Divide both expressions by $q/|J| = q/((n+2)Q - nc) > 0$ and substitute $Q - nq$ for Q_0 in (36). After consolidating terms, the resulting inequality can be written as

$$C_1 \equiv (f'(\theta) - c)3Q + Qf'(\theta) - Q^2 + 2qnc - (n-1)qQ > 0.$$

Because $\theta > \theta^M$ by Theorem 1, $f'(\theta) > \theta/2$, and therefore

$$C_1 > C_2 \equiv \left(\frac{\theta}{2} - c\right)3Q + Q\frac{\theta}{2} - Q^2 + 2qnc - (n-1)qQ.$$

Thus it is sufficient to show that $C_2 > 0$. Substituting the terms in (30) for q and c and rearranging, we get

$$C_2 = \frac{1}{n} \times \underbrace{\left[-4nQ^2 + (6n + 4)\theta Q - 2(n+1)\theta^2\right]}_{\equiv C_3},$$

and we must show that $C_3 > 0$. Recall that the explicit solution for the aggregate quantity is given in (9), i.e.

$$Q = \frac{1}{2(n+2)}\left((n+1)\theta + A\right),$$

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with $A \equiv \sqrt{(n+1)^2\theta - 4n(n+2)f(\theta)}$. Making this substitution and rearranging terms, C_3 can be written as

$$C_3 = \frac{1}{(n+2)^2} \times \underbrace{[(n^2+5n+4)\theta - nA](A-\theta)}_{\equiv C_4},$$

and we must show that $C_4 > 0$. Since $f(\theta) > 0$, $A < (n+1)\theta$ and thus

$$[(n^2+5n+4)\theta - nA] > 0.$$

Furthermore, $f(\theta) < \theta^2/4$ for $\theta < \bar{\theta}$, which implies $A > \theta$. Thus $(A-\theta) > 0$, and therefore $C_4 > 0$, as desired. $\qquad\square$

Proof of Theorem 3

We show that under the condition stated in the result (i.e. $\rho(\theta^S) > \sqrt{2}$) the incumbent's profit is upward-sloping at θ^S. By Lemma 4 this implies that the incumbent's profit maximum must occur at $\theta^* > \theta^S$.

Recall from the proof of Theorem 1 that (34) is sufficient and necessary for $d\pi_0/d\theta > 0$. Since θ^S satisfies the condition $f'(\theta^S) = \theta^S$, we replace $f'(\theta)$ by θ in (34) to obtain the following:

$$\left.\frac{d\pi_0}{d\theta}\right|_{\theta=\theta^S} > 0 \quad\Leftrightarrow\quad (2-n)\theta^2 - 8\theta Q + (2n+8)Q^2 > 0.$$

After rearranging, this becomes

$$\frac{1}{4}\theta^2 > Q(\theta - Q) + \frac{1}{8}n\left(\theta^2 - 2Q^2\right). \tag{38}$$

Since $\theta^2/4 \geq Q(\theta - Q)$, a sufficient condition for (38) to hold is $n\left(\theta^2 - 2Q^2\right)/8 < 0$, or $\theta/\sqrt{2} < Q$. Since $Q \to \bar{Q}$ when $n \to \infty$ (by Lemma 3), this condition will be satisfied for large enough n if

$$\frac{1}{\sqrt{2}}\theta < \bar{Q} = \frac{1}{2}\theta + \sqrt{\frac{1}{4}\theta^2 - f(\theta)}.$$

After some manipulations this can be expressed as the condition on the efficiency of social provision stated in the result, i.e.

$$\rho(\theta) \equiv \frac{\theta^2/2 - f(\theta)}{f(\theta)} > \sqrt{2}.$$

If this condition holds, then it also implies $f(\theta) < \theta^2/4$ (otherwise $\rho(\theta) < 0$), and thus (by Lemma 1) that a revenue-neutral equilibrium exists in which all firms are active. Thus, a sufficiently large number of entrants ensures that $d\pi_0/d\theta > 0$ at θ^S. $\qquad\square$

Proof of Theorem 4

With ex-ante rate setting, the downstream equilibrium will satisfy conditions (i) and (ii) of Definition 1, while the access rate c is now a parameter. It is easy to verify that an interior symemtric downstream equilibrium is given by

$$Q_0 = \frac{\theta + nc}{n+2}, \quad q = \frac{\theta - 2c}{n+2}.$$

In this interior equilibrium, the incumbent's profit is

$$\pi_0 = \left(\frac{\theta + nc}{n+2}\right)^2 + \frac{n}{n+2}c(\theta - 2c) - f(\theta).$$

The interior equilibrium exists if $c < \theta/2$. If $c \geq \theta/2$, the equilibrium will be a corner equilibrium with $q = 0$ and $Q_0 = \theta/2$, in which the incumbent's profit is

$$\pi_0 = \frac{1}{4}\theta^2 - f(\theta).$$

The incumbent's first-order condition for an optimal quality level is therefore given by

$$0 = \begin{cases} \dfrac{2}{(n+2)^2}(\theta + nc) + \dfrac{n}{n+2}c - f'(\theta) & \text{if } \theta \geq 2c, \\[3mm] \dfrac{1}{2}\theta - f'(\theta) & \text{if } \theta < 2c. \end{cases} \tag{39}$$

Now consider two cases. First, suppose $c \geq \theta^M/2$. In this case, it is clearly optimal to set $\theta = \theta^M$; there will hence be no entry and the incumbent earns the monopoly profit. Next, suppose $c < \theta^M/2$. We claim that, in this case, it is optimal to set $\theta < \theta^M$. We prove the claim by contradiction. Assume that $\theta \geq \theta^M$. Since $c < \theta^M/2$, the first case in (39) must hold. However, we have

$$
\begin{aligned}
\frac{2}{(n+2)^2}(\theta + nc) + \frac{n}{n+2}c - f'(\theta) \quad &< \quad \frac{2}{(n+2)^2}(\theta + n\theta^M/2) + \frac{n}{n+2}\theta^M/2 - f'(\theta) \\[2mm]
&\leq \quad \frac{2}{(n+2)^2}(\theta + n\theta/2) + \frac{n}{n+2}\theta/2 - f'(\theta) \\[2mm]
&= \quad \theta/2 - f'(\theta) \\[2mm]
&\leq \quad 0,
\end{aligned}
$$

a contradiction. (The first inequality follos from $c < \theta^M/2$, the second from the assumption that $\theta \geq \theta^<M$, and the last inequality follows from the fact the slope of the monopolist's payoff, $\theta/2 - f'(\theta)$, is non-positive at $\theta \geq \theta^M$.) Thus, if $c < \theta^M/2$, the incumbent's quality choice satisfies $\theta < \theta^M$. $\qquad\square$

Proof of Theorem 5

Fix $0 < \delta < \bar{\theta}$, $\alpha < 1$, and $\theta > 0$, and write the incumbent's profit as

$$\pi_0 = Q_0 \, q - (1 - \alpha) f(\theta). \tag{40}$$

Observe that the term $Q_0 \, q$ in (40) is positive and monotonically goes to 0 as $N \to \infty$ (by Lemma 3), while the term $(1-\alpha)f(\theta)$ is a positive constant. Thus there exists $\overline{m}(\theta, \alpha) < \infty$ such that $n > \overline{m}(\theta, \alpha) \Leftrightarrow \pi_0 < 0$. Because π_0 is continuous in θ on $[\delta, \bar{\theta}]$, there exists $\overline{N}(\alpha) < \infty$ (independent of θ) such that $n > \overline{N}(\alpha)$ implies $\pi_0 < 0$ for all $\theta \in [\delta, \bar{\theta}]$. Since the incumbent can earn a zero profit by setting $\theta = 0$, we have $n > \overline{N}(\alpha) \Rightarrow \theta^*(\alpha, n) < \delta$.

Next, differentiate (40) with respect to α, using (25)–(26):

$$\frac{\delta\pi_0}{\delta\alpha} = \frac{nf(\theta)q - 2f(\theta)Q_0}{|J|} + f(\theta) = \frac{nq - 2Q_0 + (n+2)Q - nc}{|J|}f(\theta).$$

Substituting the terms in (30) for Q_0, q, and c, this becomes,

$$(n + 4)[2Q - \theta]\frac{1}{|J|}f(\theta) > 0,$$

as $|J| > 0$ and $Q > \theta/2$. Therefore π_0 increases strictly in α for all θ, which means $\overline{m}(\theta, \alpha)$ increases strictly in α for all θ. Thus $\overline{N}(\alpha)$ increases strictly in α and is therefore invertible (for $n \geq \overline{N}(0)$). Furthermore, $\overline{N}(\alpha) \to \infty$ as $\alpha \to 1$. To see this, suppose to the contrary that $\overline{N}(\alpha) \not\to \infty$ as $\alpha \to 1$. Since $\overline{N}(\alpha)$ increases strictly, this implies that there exists $\widetilde{N} < \infty$ such that $\overline{N}(\alpha) \to \widetilde{N}$. Then, by continuity of π_0 in α, this would imply that under revenue-neutral cost sharing (i.e. $\alpha = 1$) the incumbent's profit is $\pi_0 \leq 0$ for all $\theta \in (\varepsilon, \bar{\theta})$ and $n > \widetilde{N}$, which is a contradiction (the argument is given in Section 4). Now set

$$\overline{\alpha}(n) = \begin{cases} \overline{N}^{-1}(n) & \text{if } n \geq \overline{N}(0), \\ 0 & \text{otherwise,} \end{cases}$$

which increases is n and satisfies $\overline{\alpha}(n) \to 1$ as $n \to \infty$. The result now follows. $\square$

Proof of Theorem 6

Let $y_g^M > 0$ be the monopolist's optimal investment if the good state was guaranteed, i.e. $y_g^M = f(\theta^M)$, where θ^M is the monopolist's optimal quality choice in the risk-free case. Choose $\bar{r} \in (0, 1)$ such that $\bar{y}_b(\bar{r}) < y_g^M$; since $\bar{y}_b(0) = 0$, such $\bar{r}$ exists. By continuity of expected profits in p, one can therefore find $\bar{p} < 1$ such that $(p, r) \in (\bar{p}, 1) \times [0, \bar{r})$ implies $y^M(p, r) \in (\bar{y}_b(r), y_g^M)$.

Fix such r and p now. The incumbent's expected profit under open access if it invests y is

$$E\pi_0(y) = p\pi_0(\theta(y), y) + (1 - p)\pi_0(r\theta(y), y).$$

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As $n \to \infty$, for all $\overline{y}_b(r) < y < \overline{y}_g$ the following holds: $p\pi_0(\theta(y), y) \to 0$, while $(1 - p)\pi_0(r\theta(y), y) < 0$ remains bounded away from zero. The first observation follows from Lemma 3 and the fact that $y < \overline{y}_g$ implies entry in the good state. The second follows from Lemma 1 and the fact that $y > \overline{y}_b(r)$ implies no entry in the bad state. Thus, for each $\delta > 0$ there exists $n(\delta)$ such that $n > n(\delta)$ implies $E\pi_0(y) < 0$ at all $y > \overline{y}_b(r) + \delta$. At the same time, $E\pi_0(y) > 0$ for all $y \leq \overline{y}_b(r)$. Because $y^M(p, r) > \overline{y}_b(r)$, this implies that for large enough n the optimal investment by the incumbent satisfies $y^*(p, r, n) < y^M(p, r)$. $\qquad \square$

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