Patents, Invalidity, and the Strategic Transmission of Enabling Information

James J. Anton
Fuqua School of Business
Duke University
Durham, NC 27708-0120
james.anton@duke.edu

Dennis A. Yao
Wharton School
University of Pennsylvania
Philadelphia, PA 19104-6372
yao@wharton.upenn.edu

The patent system encourages innovation and knowledge disclosure by providing exclusivity to inventors. Exclusivity is limited, however, because a substantial fraction of patents have some probability of being ruled invalid when challenged in court. The possibility of invalidity—and an ensuing market competition—suggests that when an innovator's capability (e.g., cost of production) is private information, there is potential value to an innovator from signaling strong capability via a disclosure that transfers technical knowledge to a competitor. We model a product-innovation setting in which a valid patent gives market exclusivity and find a unique signaling equilibrium. One might expect that as the probability that a patent will be invalid becomes low, greater disclosure will be induced. We do not find this expectation to be generally supported. Further, even where full disclosure arises in equilibrium, it is only the less capable who make full disclosures. The equilibrium analysis also highlights many of the novel and appealing features of enabling knowledge disclosure signals.

1. Introduction

Consider a product innovation in which the advance opens up a new market. A critical determinant of the economic value of that innovation is the extent to which other firms can be excluded from its use. The

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right to exclusion is a cornerstone of intellectual-property systems such as the patent system, but that right comes in exchange for public dissemination of technical information of value to future advances.

Exclusivity facilitates a number of other purposes relating to knowledge transfer. Given exclusivity, innovators may be more willing to release enabling knowledge that is useful for inducing complementary innovations by buyers and suppliers. And, because the actual extent of the innovation is privately known, the innovator may find it effective to use enabling disclosures to signal to competitors or to complementary asset providers, consumers, and the capital market as part of a general strategy to gain attention and investment (Jolly, 1997).

Unfortunately, the exclusivity provided by a patent is not usually a sure thing. Many important patents have been invalidated or vitiated in subsequent legal challenges (e.g., tetracycline, ENIAC computer patent), and it is common for patents to be somewhat vulnerable to validity challenges. The possibility of invalidity and, hence, market access means that the benefit of signaling strong capability is now compromised by the cost of transferring usable knowledge to competitors. Given the incentive to reduce technology transfer, competition in this market now takes place under incomplete information (regarding the innovator's capability), and the extent of the actual disclosure may well be read as a signal of the innovator's strength in market competition. For example, a competitor may be unwilling to take aggressive market actions or incur entry costs against an innovator who is perceived to have a substantial advantage.

The purpose of this paper is to show that enabling disclosures can result in a signaling equilibrium and to characterize this equilibrium.[1] The analysis allows us to address how the trade-off between signaling capability and transferring knowledge is determined as the extent of innovation and the strength of the patent vary. Do strong patents provide sufficient protection to mitigate technology transfer concerns and make signaling incentives the dominant factor? Or does even the potential for invalidity significantly increase an innovator's reliance on secrecy by reducing the amount of disclosure? When the

1. The danger that enabling disclosures will transfer valuable knowledge to a competitor might suggest that such disclosures would be used only as necessary to gain exclusivity via the patent process. But in practice we observe voluntary enabling disclosures outside of patents. (Our model also admits of this interpretation of disclosure.) A historical but important example of disclosure with an apparent signaling motive is the 1908 publication by Gilbreth of his pioneering system of concrete construction. Morley (1990) reports that Gilbreth published this system to promote the sale of his patented inventions. A related form of voluntary disclosure is liberal licensing of technologies to competitors to promote adoption of a standard. See, e.g., Garud and Kumaraswamy (1993) on Sun Microsystems's "open systems strategy."

amount of disclosure (technology transfer) affects the probability that the patent is valid, another important, though straightforward, trade-off becomes relevant. We extend the analysis of the signaling equilibrium to this case and to the case in which there is incomplete information about the capability of a competitor.

In our two-firm model an innovator discovers a patentable product, which can be manufactured at a privately observed cost, and decides how much enabling knowledge to disclose publicly in its patent application. A patent issues, and the product opens up a new market. The excluded firm, however, can challenge the patent's validity and, if the patent is invalidated, can use the disclosed knowledge in a subsequent market competition. The market exclusion assumption means that our model is best suited to a product rather than a process-innovation setting, though effective market exclusion can also be the consequence of a drastic process innovation.

In a strategic-substitutes setting, low-capability innovators would like to be perceived as strong (having low costs).[2] The structure of the economic costs and benefits generated in the downstream (Cournot) market competition makes it possible for stronger types to separate from weaker types by making (larger) disclosures that are on net too costly for the weaker types to mimic. Thus, the signaling distortion that arises when innovation capability is private information always pushes toward excess disclosure relative to the innovator's complete-information preference. Separation, however, does not require full disclosure.

The withholding of knowledge (disclosures modest relative to the actual innovation) can be substantial, even in cases where the patent is quite strong and the *ex ante* probability that one's competitor can take advantage of the knowledge is small. Intuitively, with a valid patent, the resulting market monopoly renders technology transfer and cost signals irrelevant for current market competition. It is only in the state where the patent is ruled invalid and rivals compete in the market that information effects matter. Further, when withholding affects the relative probabilities of each state (there exists an underlying trade-off between disclosure and validity), it is the marginal effects relative to the absolute size of the effect that will matter, so substantial withholding is still possible in strong patents. Thus, in the product-innovation setting, our model predicts that one will often see consid-

2. The critical aspect of the strategic-substitutes story is that a signal of toughness or greater capability causes the competitor to become more timid. In our cost story, a timid response results in less production; in a product-location story, the response would be to locate farther away.

erable withholding of knowledge even under strong patents. Such withholding does not depend on an innovator's concerns about the effect of disclosure on next-generation competition in innovation; it emerges from concerns with current capabilities.

The basic analysis also provides a framework for examining how the disclosure trade-off changes with different assumptions about the competitive relationship between the innovator and the follower. For example, when the follower is expected to have some valuable implementation knowledge independent of the patent disclosure, lesser inventions (product associated with high costs) will be fully disclosed because the benefits of signaling overwhelm the costs of technology transfer to one's competitor. These costs are small for patentholders with lesser inventions, because it is likely that the competitor has lower costs via its independent knowledge. Thus, a disclosure of enabling knowledge is an extremely efficient signal from the viewpoint of high-cost types, because it corresponds closely to what the competitor is trying to infer, and the signal is not costly.

1.1 The Patent System and Invalidity

The overturning of patents is not uncommon, because patent-issuing offices lack the resources to thoroughly examine every patent application (Kingston, 1984) and therefore rely on private-party court challenges for an in-depth examination of important, but questionable, issued patents. Commercially significant patents are often declared invalid or restricted in important ways.[3] A typical source of invalidity is the existence of prior art that causes the patent to fail the novelty requirement. Thus, patents do not always grant secure property rights to the patentholders, and, given this vulnerability, knowledge transmission issues become relevant for current market competition.[4]

The recent history of the competition between Procter & Gamble (Pampers) and Kimberly-Clark (Huggies) in the multibillion-dollar disposable-diaper market illustrates the importance of patent validity considerations in market competition. Since the mid-1980s, the com-

3. Prior to the formation of the Federal Circuit in 1982, it was generally believed that most of the patents that were challenged were held invalid. Although that situation has changed in favor of the patentholder since the advent of the Federal Circuit, it is still the case that a significant fraction of challenged patents are invalidated. See also Aoki and Hu (1999).

4. The survey by Levin et al. (1987) on the appropriability of rents to innovation provides evidence that patent invalidity is viewed as an important limitation to patent protection. Uncertainty about property rights can be especially great with respect to inventions in emerging high-technology industries (e.g., biotechnology and computer software), where litigation sometimes raises as yet unanswered questions about what can be patented.

panies have been involved in patent infringement and validity lawsuits concerning key technologies that added either production efficiencies or functionality. One lawsuit involved a P&G-owned patent that permitted high-speed production of elastic waistbands, a technology with significant cost-saving implications. In that case the court found the P&G-owned patent to be invalid because the patent claims were anticipated by a previous, long-expired patent.[5] Another case involved a P&G patent on a "compression technology" that enabled the creation of Ultra Pampers, an ultimately well-received thinner and more absorbent diaper. The compression technology patent was declared unenforceable, however, because P&G had withheld material test results that might have caused the patent examiner to reject the patent in the first place.[6]

Challenges of property-right issues can occur at various times in the innovation and commercialization cycle. Both pre- and post-competition challenges are common. Our *ex ante* barrier perspective corresponds to settings in which court-imposed preliminary injunctions are likely, commercialization following innovation is slow (e.g., pharmaceutical companies face lengthy clinical trials and regulatory review prior to going to market with a patented drug), or imitation involves large sunk costs that cause the imitator to delay investment until validity is determined.[7]

1.2 Relevant Literature

Our paper explores strategic-information revelation questions related to those examined in Battacharya and Ritter (1983), Milgrom and Roberts (1986), Okuno-Fujiwara et al. (1990), and Anton and Yao (1994). As in those papers, we also constrain the information revealed to be truthful. Our model is most closely related to Battacharya and Ritter's signaling model, in which partial public disclosure of technical information reduces the cost of capital to a firm that is anticipating competing in an R&D race, but induces additional entry into that race. Our model differs from Battacharya and Ritter by focusing on a

5. Procter & Gamble Co. v. Kimberly-Clark Corp., CA 3-85-1539-G (N.D. Texas, July 23, 1987), aff'd 862 F.2d 320 (CAFC 1988).

6. Procter & Gamble Co. v. Kimberly-Clark Corp. 740 F.Supp. 1177 (D.S.C. 1989) at 1199.

7. To gain a preliminary injunction the patentholder needs to show ". . . a reasonable likelihood of success on the merits and the lack of adequate remedy at law or other irreparable harm." H.H. Robertson Co. v. United Steel Deck, Inc. 820 F.2d 384, 2 U.S.P.Q.2d (BNA) 1926 (Fed. Cir. 1987). If a preliminary injunction is granted, the court enjoins the use of the potentially infringing knowledge until the full litigation has run its course. Such a finding is more likely when the patent is strong.

different downstream competitive interaction and allowing for the influence of competing-firm implementation on disclosure. We differ from Milgrom and Roberts and from Okuno-Fujiwara et al. in that revealed information not only affects beliefs but also, through technology transfer, affects the production capabilities of a competitor. Finally, Anton and Yao (1994) allows for a private rather than public technology transfer, but not strategic choice of how much to transfer.

This paper is a companion to Anton and Yao (1999), which examines a model with an *ex post* penalty for imitation. The *ex ante* perspective developed here corresponds to product innovation settings in which the probability of patent validity is high and courts are most likely to grant preliminary injunctions on follower imitation. The *ex post* perspective is better applied to more incremental innovation settings (e.g., incremental process innovations) where property-right protection is weaker and competition always occurs. Thus, the companion paper focuses on issues regarding implicit licensing and the management of competition. In contrast, some of the more interesting *ex ante* questions involve how disclosure changes as the likelihood that the patent will be upheld approaches one. The structure of the *ex ante* model also allows an exploration of the impact of disclosure on the probability of patent validity as well as the effect of uncertainty about imitator costs.

In the next three sections we describe and then analyze the basic model. Section 5 examines a setting in which the amount of disclosure affects the probability of validity. Section 6 provides an extension to the case in which the follower firm has private information about its implementation capabilities, and Section 7 concludes.

2. The Model

We examine knowledge disclosure via a patent and subsequent market interactions in a model with two risk-neutral firms: an innovating firm (*innovator*) and an imitating firm (*imitator*). There are three stages to our model. The first stage involves an R&D invention outcome by the innovator, followed by a patent-filing disclosure decision. The second stage allows for a patent challenge and a ruling on validity. In the third stage, market outcomes are determined. After specifying each stage, we consider equilibrium.

We model disclosure decisions associated with a product patent in which the validity of the patent depends primarily on whether the product is sufficiently novel (different from prior art). The extent of the enabling disclosure provided by the patent, while affecting the cost at which an imitator can achieve the product innovation, does not affect the probability of validity. (The model also admits of an interpretation in which the enabling disclosure is made outside the patent.) In Section 5 we examine the case in which patent validity increases as a function of the amount of disclosure contained in the patent. This case can be interpreted as one in which the firm filing the patent withholds information that might be necessary to allow a party "skilled in the art" to duplicate the innovation or, in the US, that does not meet the legal requirements of providing the "best mode" of achieving the innovation.

2.1 Stage 1

Firm i has pursued a product innovation based on a given prior R&D investment. It obtains a patent that, if held to be valid, would effectively preclude the imitator from competing in the (new) product market. The R&D outcome involves the discovery of a product invention and a privately observed marginal cost for producing the invention (fixed costs are set to zero). We assume that the cost draw is from a distribution with c.d.f. H and support $[c_L, c_H]$.

The patent specifies the new product and provides a technical description that enables the making of the product. We assume that the disclosed information can be summarized by an implied marginal cost of production. Think of the patent as disclosing how to produce the product at cost s_i. Thus, the innovator discloses enabling knowledge $s_i \in [c_L, c_H]$. We require that

$$s_i \geq c_i, \tag{1}$$

so that a firm cannot make disclosures that specify a cost below its actual cost draw. In other words, a firm may underdisclose the true extent of cost innovation, but it cannot disclose more knowledge than it has.[8] We assume that filing this patent is optimal and that a patent will not be issued without an enabling disclosure of at least c_H.

From (1), the disclosure of s_i allows the other firm j to infer that firm i has costs no higher than s_i. Public disclosure also transfers enabling knowledge to firm j allowing it to produce at cost s_i (if not for the patent).

8. One could also think of s_i as representing the extent of cost reduction that the imitator (firm j) can acquire upon examination of the technical information. Then $s_i \geq c_i$ will apply when the technology transfer is bounded below by the underlying technology (c_i) that firm i actually possesses. In the disclose-via-patent interpretation, implicitly we are assuming in (1) that the patent office can accurately verify a stated claim but that it cannot detect information a firm has chosen to withhold.

2.2 Stage 2

The imitator, firm j, can challenge the validity of the patent in court, and we often refer to j as the challenger. With probability γ, the patent is ruled invalid and firm j has the (legal) option to produce.[9] With $1 - \gamma$, the patent is valid and firm j is barred from producing.[10] We assume that court costs are zero and consequently it is a dominant choice to challenge. More generally, with positive court costs, a firm will challenge as long as these court costs do not exceed the expected payoff (from duopoly competition if the patent is ruled invalid).

2.3 Stage 3

If the patent is ruled invalid, then the firms engage in duopoly competition. We model the duopoly competition as Cournot (quantity competition) with linear demand

$$P(Q) = \alpha - \beta Q, \tag{2}$$

where Q is the sum of outputs from the firms. If the patent is valid, then firm i earns a monopoly profit of $\pi^M(c_i) = (4\beta)^{-1}(\alpha - c_i)^2$. To ensure interior solutions we assume $\alpha > 2c_H - c_L$.

2.4 Equilibrium

We examine perfect Bayesian equilibria for this game. Strategic options for the firms are as follows. A disclosure function maps a cost draw into a disclosure, so a disclosure strategy is $\varphi : [c_L, c_H] \rightarrow [c_L, c_H]$. Thus, if c is observed, the innovator makes a disclosure $\varphi(c)$. We focus on equilibria in which the disclosure strategy is separating (i.e., φ is one-to-one). As we show below, such a strategy must be strictly increasing, and so higher costs are associated with higher (cost) disclosures. Pooling equilibria are discussed in Section 4.

In this model it is dominant for the imitator to challenge the patent's validity. If a patent is ruled invalid, the duopoly competition involves asymmetric information between the firms. At this stage, the observable history of the game is the public disclosure s_i. The beliefs of firm j regarding the cost type of i will depend on the

9. γ can also be interpreted as the probability that the imitator can overcome a technological bottleneck that prevents the use of the leader's disclosures, or as the probability that the patent can be circumvented. See, e.g., Gallini (1992), Klemperer (1990), and Scotchmer and Green (1990).

10. We leave aside licensing or settlement possibilities, as these are complicated by issues involving bargaining under incomplete information.

history. In the Cournot stage, each firm chooses a quantity, $q_i(c_i, s_i)$ for i and $q_j(s_i)$ for j.

A perfect Bayesian equilibrium, or *equilibrium* for short, is a disclosure strategy φ, a pair of quantity choices q_i and q_j, and beliefs such that (i) for each history, quantity choices are optimal for beliefs in the duopoly competition, (ii) the disclosure strategy is optimal for each cost draw and satisfies the constraint (1), and (iii) beliefs are formed using the disclosure strategy and Bayes' law.

3. Duopoly Competition

Suppose s_i was publicly disclosed, but the patent was ruled invalid. Then firms i and j will engage in duopoly Cournot competition in the market for the new product invention. In this section we solve for the resulting market outcome and identify how the disclosure influences market structure. First, we characterize the belief and cost structure for a given disclosure. Next, we solve for the outcome in equilibrium. Finally, we characterize the payoffs to deviating from the equilibrium disclosure strategy.

3.1 Belief and Cost Structure

The observed disclosure influences beliefs and costs. Information is revealed to firm j in two ways. First, we have a structural effect as j acquires the technology embodied in the disclosure s_i so that the marginal cost of production for j is $c_j = s_i$. Second, firm j makes the equilibrium inference that s_i is an optimal disclosure for firm i. Whenever possible (i.e., s_i is in the range of φ), this inference must be based on the equilibrium disclosure strategy.[11] Let φ^{-1} denote the inverse of the disclosure strategy. Then, under the hypothesis that φ is one-to-one, firm j will infer that the cost type of firm i is $\varphi^{-1}(s_i)$ and the belief of j is simply the point estimate $\varphi^{-1}(s_i)$. Firm i knows that $c_j = s_i$. The economic effect of the disclosure is that technology transfer and the implicit cost signal lead to a (Cournot) market setting with complete information.

11. We show below that φ is continuous and strictly increasing. Hence, equilibrium disclosures lie in the interval $[\varphi(c_L), \varphi(c_H)]$. From (1), we have $\varphi(c_H) \geq c_H$. Disclosures below c_L are not feasible, and disclosures above c_H transfer no technology. For disclosures in the interval $[c_L, c_H]$ we then have $\varphi(c_H) = c_H$, and there can be no out-of-equilibrium disclosures at the high end. As we show when we verify the equilibrium, the "natural" point belief that assigns all weight to c_L if $s_i < \varphi(c_L)$ makes a deviation into this out-of-equilibrium range unprofitable.

3.2 Cournot Equilibrium

Suppose that firm i makes the equilibrium disclosure $s_i = \varphi(c_i)$, where c_i is i's cost. Then it is straightforward to derive the resulting Cournot outcome. The Cournot equilibrium strategies (see Appendix A) are given by

$$q_i^*(c_i, s_i) = (3\beta)^{-1}[\alpha - 2c_i + s_i], \tag{3}$$

$$q_j^*(s_i) = (3\beta)^{-1}[\alpha - 2s_i + c_i]. \tag{4}$$

Consider how these quantities vary with the underlying cost draws and the disclosure. As c_i rises, there are two competing effects on q_i^*. First, firm i becomes less aggressive and scales back production, which is a familiar Cournot effect. Second, firm i makes a higher equilibrium disclosure of $\varphi(c_i)$, which reduces technology transfer to j, and as a result firm i becomes more aggressive as c_j rises. The quantity effects on firm j are analogous to those for firm i.

The price pattern is easily calculated. From (3) and (4), we have

$$P^* = \tfrac{1}{3}[\alpha + c_i + s_i]. \tag{5}$$

Firm i's own-cost effect (c_i) and j's transferred technology cost effect (s_i) lead to higher realized prices. Equilibrium expected profits for the firms are given by

$$\pi_i^*(c_i, s_i) = (9\beta)^{-1}[\alpha - 2c_i + s_i]^2, \tag{6}$$

$$\pi_j^*(s_i) = (9\beta)^{-1}[\alpha - 2s_i + c_i]^2. \tag{7}$$

These profits are calculated at the point where quantities are chosen.

3.3 Deviations

To characterize an equilibrium disclosure strategy we evaluate the profit potential in the duopoly continuation game for a deviation disclosure. The substantive case arises when the patent is later held invalid. The publicly revealed disclosure then affects the duopoly market. Thus, suppose that c_i is the actual cost draw of i and that a deviation disclosure of $s_i' \neq \varphi(c_i)$ was made and then the patent is ruled invalid. The opposing firm j then infers that i has cost type $c_i' = \varphi^{-1}(s_i') \neq c_i$. (Out-of-equilibrium disclosures, $s_i' \notin \text{Range}[\varphi]$, are analyzed in the Appendix in the proof of the Propositions.) As a result, firm j makes quantity choices as given by the equilibrium strategy in the Cournot duopoly against a type c_i', namely $q_j^*(s_i')$ from (4): $q_j^*(s_i') = (3\beta)^{-1}[\alpha - 2s_i' + c_i']$. Firm i chooses the following quantity as a best response: $q^* \in \arg\max_q [P(q_j^*(s_i') + q) - c_i]q$, as i takes account of the influence of the revealed disclosure of s_i' on the cost structure and beliefs of j. The optimal quantity choice and associated deviation profits are

$$q^* = \frac{1}{3\beta}\left[\alpha - \frac{3}{2}c_i + s_i' - \frac{1}{2}c_i'\right], \tag{8}$$

$$\pi^* = \frac{1}{9\beta}\left[\alpha - \frac{3}{2}c_i + s_i' - \frac{1}{2}c_i'\right]^2. \tag{9}$$

Two effects influence the incentive to deviate. Suppose first that type c_i discloses $s_i' > \varphi(c_i)$ and underdiscloses the cost reduction relative to the equilibrium disclosure. This causes firm j to infer that i is type $c_i' = \varphi^{-1}(s_i') > c_i$. Hence, j becomes more aggressive. Second, the technology transfer is reduced. This raises j's cost, and firm i becomes more aggressive. These incentive effects work in opposite directions. In equilibrium, φ will balance these effects to make $\varphi(c_i)$ optimal for the type c_i.

In summary, given an invalid patent, in equilibrium we have $s_i = \varphi(c_i)$, and the disclosure reveals the cost of the (former) patentholder. The quantities and profits then follow (3), (4) and (6), (7), respectively. For a patentholder who deviates in the first stage and discloses $s_i' \neq \varphi(c_i)$, equation (9) describes the profit the patentholder can earn when quantity is chosen optimally following a given deviation disclosure. This deviation profit is fundamental for the determination of disclosure incentives.

4. Equilibrium Disclosures

Consider now the decision in stage 1 to disclose. An equilibrium disclosure strategy has the property that a disclosure of $\varphi(c)$ is optimal for each cost type $c \in [c_L, c_H]$. We begin by constructing the *ex ante* decision for the innovator and then solve for the equilibrium.

The innovator's patent is ruled invalid with probability γ. Given a cost draw of c, expected profits to a disclosure are given by $\pi = (1-\gamma)\pi^M + \gamma\pi_i^D$, where the firm earns monopoly profits of π^M with a valid patent and π_i^D as the initial patentholder in a duopoly when its patent is ruled invalid. The expected profit of the imitator is $\gamma\pi_j^D$, where π_j^D is the duopoly profit of the imitator when the patent is invalid (and zero when the patent is valid). From (9), we see that a disclosure of s leads to profits of

$$\pi_i^D = \pi_i^D(s, c) = \frac{1}{9\beta}\left[\alpha - \frac{3}{2}c - \frac{1}{2}\varphi^{-1}(s) + s\right]^2. \tag{10}$$

An optimal disclosure for type c must therefore solve

$$\max_{s \geq c} (1 - \gamma)\pi^M(c) + \gamma\pi_i^D(s, c). \tag{11}$$

Note that the disclosure s influences *ex ante* profits only through the effect on a former patentholder's duopoly profit. This reflects the public disclosure. When the innovator retains a monopoly, the public disclosure is irrelevant. Consequently, the (unconstrained) first-order condition reduces to

$$\frac{d}{ds}\pi_i^D(s, c) = 0 = -\frac{1}{2}\frac{d}{ds}\varphi^{-1}(s) + 1. \tag{12}$$

Condition (12) reflects two competing disclosure incentives. The first term, which involves a negative effect, arises because the disclosure allows the opposing firm to infer the cost type via φ^{-1}. This is disadvantageous in the Cournot duopoly competition and creates an incentive to disclose more knowledge (reduce s) so that an opponent is led to infer lower costs. Second, we have the effect of technology transfer. As s rises, technology transfer is reduced. Reduced technology transfer will render an opponent less aggressive in the duopoly and allow the innovator to increase quantity, as reflected by the second term in (12). This effect provides an incentive to increase s.

In equilibrium, $s = \varphi(c)$ must hold. Substituting into (12), we obtain the first-order differential equation

$$1 = 2\varphi'(c). \tag{13}$$

with the solution of the form $\varphi(c) = c/2 + A$ where A is a free constant that is determined by the constraint on disclosures, $\varphi(c) \geq c \; \forall c \in [c_L, c_H]$. Using the constraint $\varphi(c_H) = c_H$, then implies

$$\varphi^*(c) = \frac{c + c_H}{2}. \tag{14}$$

We then have our main result.

Proposition 1: *Let φ^* be the disclosure strategy in* (14). *Then*

(a) $\varphi^*(c)$ *is an optimal disclosure (solves* (11)*) for each $c \in [c_L, c_H]$ and satisfies the differential equation* (13) *for $c \in [c_L, c_H]$;*
(b) *the disclosure strategy φ^* together with the quantity strategies in* (3), (4), *and associated beliefs form a perfect Bayesian equilibrium (PBE);*
(c) φ^* *and the associated quantities and beliefs constitute the unique separating PBE, up to beliefs for out-of-equilibrium disclosures ($s < \varphi^*(c_L)$);*

(d) φ^* *is strictly increasing, linear, and satisfies* $\varphi^*(c) \geq c$;
(e) φ^* *is independent of* γ.

The equilibrium disclosure strategy has a number of intuitive properties. First, φ^* is structured so that the competing disclosure incentives offset each other in equilibrium. In other words, the marginal benefit of a higher disclosure arising from reduced technology transfer is equal to the marginal cost of a higher disclosure arising from the opponent's inference of higher costs. If φ^* were not increasing, then the cost to higher disclosures would be absent. The technology transfer incentive would then lead to an uninformative disclosure involving the highest cost level from all types.

In previous work, Milgrom and Roberts (1986) and Okuno-Fujiwara et al. (1990) examined the strategic revelation of information when agents can make certifiable or verifiable statements. They showed that (sequential) equilibrium often requires complete information revelation. In our model the certifiable statement is the disclosure. Complete revelation would obtain in our model if the technology transfer effect were eliminated. This is because duopoly profits, $\pi_i^D(s, c)$, would then be strictly decreasing in the disclosure, reflecting the Cournot incentive to reveal low cost via the (certifiable) disclosure. As a result, each type would reveal fully, and $s = c$ would apply. The structural effect of technology transfer on the costs of the imitator thus leads to withholding of the invention, and information is partially, rather than fully, revealed.

Note that the separating equilibrium is unique and that disclosures must follow φ^*.[12] This reflects the structural role played by technology transfer in our model. With respect to signaling costs, any strictly increasing disclosure strategy will allow the imitator to infer the cost draw. Technology transfer, however, means that the disclosure has a structural effect on the imitator's production costs, and φ^* emerges as the unique disclosure strategy.[13]

12. Pooling equilibria are also possible in the Cournot setting by specifying supporting beliefs that eliminate the signaling incentive [e.g., a disclosure of $s < c_H$ leads to a point belief of $b(s) = s$].

13. The equilibrium incentive to signal costs via disclosures, which offsets the incentive to underdisclose due to technology transfer, depends on the underlying duopoly market competition. The familiar distinction between strategic substitutes and complements (Bulow et al., 1985) is helpful for understanding this dependence. In our Cournot competition setting (substitutes), a firm has an incentive to appear "tough" (i.e., low-cost) to induce a more passive competitor response. In contrast, this incentive is not present in a market setting with price competition when strategic complementarities are present. (We are grateful to Esther Gal-Or for suggesting this point.) Applying a standard differentiated Bertrand model of price competition creates a situation in which the disclosure incentive and the technology transfer incentive cannot offset each other,

Proposition 1 states that φ^* does not depend on γ, the likelihood a patent is ruled invalid, because there is no trade-off involving γ and the monopoly and duopoly outcomes. As we see in the next section, this property is a special case of a more general result, the scale invariance of disclosure, that applies when disclosure impacts the chances of validity.

5. Endogenous Patent Validity

In our base model we viewed the enabling knowledge disclosure s as uncoupled from the probability γ that the patent is valid. Patentholders sometimes, however, withhold some enablement knowledge.[14] The benefit to such a strategy is that it raises an imitator's cost. The disadvantage is that it increases the patentholder's invalidity risk given a patent challenge.

In this section we consider a setting in which the probability that the patent is ruled invalid depends on the extent of disclosure by the innovator: greater disclosure results in a stronger patent. Suppose that a disclosure s results in $\gamma = \Gamma(s)$ for the probability that the patent is invalid. We assume that $\Gamma : [c_L, c_H] \to (0, 1)$ is strictly increasing with a continuous derivative; this avoids trivial corner cases in which disclosure renders the validity question moot. Thus, if a type-c innovator chooses s, then with $1 - \Gamma(s)$ the patent is valid and the result is a monopoly market with payoff $\pi^M(c)$. With $\Gamma(s)$, the patent is ruled invalid. The result is duopoly competition and, by (8) and (9), the payoff is $\pi_i^D(s, c)$ from (10). An optimal patent disclosure then satisfies $\max_{s \geq c} \pi(s, c)$, where $\pi(s, c) \equiv [1 - \Gamma(s)]\pi^M(c) + \Gamma(s)\pi_i^D(s, c)$.

The fundamental question involves the influence of endogenous validity on the equilibrium patent disclosure incentives of the innovator. Proceeding by analogy with the construction of φ^* in Proposition 1, let ϕ be a candidate disclosure strategy. Optimal disclosures then satisfy

as they do in the Cournot competition setting. Thus, the differentiated Bertrand setting has no separating equilibrium. Instead, there is a pooling equilibrium in which all cost types file a disclosure at c_H.

14. Historically, ". . . many patents, especially in the chemical and electrical fields, contain faulty claims" (Vaughn, 1956, p. 28). Vaughn describes examples involving the expropriation of enemy-held patents during World War II. US chemists had a very difficult time determining how to make synthetic rubber from these prewar patents. Similarly, problems were experienced with German patents involving extracting nitrogen from the air (efforts not successful), coal-tar dyes (patent information did not aid in manufacturing those dyes commercially), tungsten carbide (GE took 6 years to get to market), and insulin and synthetic quinine (took several years to develop).

$$\frac{\partial \pi_i^D(s, c)}{\partial s} = \frac{\Gamma'(s)}{\Gamma(s)} [\pi^M(c) - \pi_i^D(s, c)],$$

or equivalently

$$[\alpha - \tfrac{3}{2}c - \tfrac{1}{2}\phi^{-1}(s) + s]\left\{1 - \frac{1}{2}\frac{d\phi^{-1}(s)}{ds}\right\}$$
$$= \frac{\Gamma'(s)}{\Gamma(s)}\left[\frac{9(\alpha - c)^2}{8} - \tfrac{1}{2}[\alpha - \tfrac{3}{2}c - \tfrac{1}{2}\phi^{-1}(s) + s]^2\right],$$

when partial disclosure, $s > c$, is optimal. When full disclosure is optimal, $\leq$ holds in the above first-order condition. The left-hand side reflects the competing disclosure incentives, identified above, of signaling low costs and technology transfer. The right-hand side reflects the impact of disclosure on validity. As monopoly payoffs always exceed duopoly, there is a positive incentive for greater disclosure when $\Gamma'(s) > 0$. The resulting differential equation for the disclosure equilibrium is then

$$[\alpha - 2c + \phi(c)]\left\{-\frac{1}{2}\frac{1}{\phi'(c)} + 1\right\}$$
$$= \frac{\Gamma'(\phi(c))}{\Gamma(\phi(c))}\left[\frac{9(\alpha - c)^2}{8} - \tfrac{1}{2}[\alpha - 2c + \phi(c)]^2\right].$$

Despite the apparent complexity, several features of the resulting equilibrium follow easily. First, note that only the ratio Γ'/Γ matters for the innovator disclosure choice, since the impact of disclosure on validity is to shift likelihood across the monopoly and duopoly outcomes. The immediate result is

Lemma 1 (Scale Invariance): *Suppose ϕ is an equilibrium disclosure strategy when $\Gamma(s)$ is the probability relationship for invalidity. Then ϕ is also an equilibrium disclosure strategy for $\kappa\Gamma$, where κ is any constant satisfying $0 < \kappa < 1/\Gamma(c_H)$.*

This generalizes the earlier result in which the extent of disclosure was independent of (exogenous) γ.[15] The level of $\Gamma(s)$ matters for the overall profit impact of changes in disclosure on the duopoly payoff, whereas $\Gamma'(s)$ is important for the gain from monopoly outcomes over duopoly ones. Thus, when validity depends on the extent

15. The proof is immediate: if $\phi(c)$ is optimal for c under Γ, then it is also optimal under $\kappa\Gamma$. This holds at interior disclosure choices and at corner-solution (full-disclosure) choices. Note that $0 < \kappa < 1/\Gamma(c_L)$ applies if we have $\Gamma' < 0$.

of disclosure, it is the growth rate of the validity probability, rather than the level or pure rate of change, that determines the extent of equilibrium disclosure.

To illustrate the implications of scale invariance for equilibrium disclosure, let us compare two settings. Suppose $\Gamma(s) = \gamma_0 + \gamma_1 s$ and $c \in [0, 1]$. First, consider a *strong patent* where $\gamma_0 = \gamma_1 = 0.1$. Then, even the minimal level of disclosure ($s = c_H = 1$) implies an 80% chance of a valid patent. The marginal impact of added disclosure is small, however, as full disclosure by the lowest type ($c = s = 0$) only raises validity chances to 90%. Now consider a *weak patent,* with $\gamma_0 = \gamma_1 = 0.5$, where minimal disclosure implies $\Gamma(1) = 1$ and the patent is always invalid. The marginal impact of disclosure is much larger now, and at $c = s = 0$ the chance of validity rises to 50%. Intuitively, we might expect the high marginal impact of disclosure with the weak patent to translate into a strong incentive for equilibrium disclosure. Since both cases have $\Gamma'(s)/\Gamma(s) = \frac{1}{1+s}$, however, the disclosure is the same in both cases. The reason, of course, is that the higher marginal impact of disclosure is offset by the higher overall likelihood of invalidity. Thus, as this simple example reveals, disclosure incentives with a strong patent can coincide with those for a much weaker one.

In turn, it is easy to see that firms may substantially withhold the extent of the innovation even when patents are quite solid (small Γ). Thus, even a small probability of having a patent overturned can have disproportionately large influence on the decision how much of an invention to patent and disclose. This is to say that unavoidable imperfections in the ability of the patent office and the court system to act in a perfectly reliable and consistent fashion can lead to a setting where the incentives for partial disclosure identified in this paper are relevant. Further, it may be that allocating more resources to tighten such a system may achieve very little in terms of encouraging additional disclosure.

We return to a comparison of disclosure incentives with endogenous validity in the next section after we have examined imitator implementation and identified when full disclosure arises in equilibrium.

6. Imitator Implementation

It is not uncommon for imitators to develop and commercialize a copied innovation more effectively than the original innovator. To get some understanding for how this possibility affects the innovator's incentives to disclose, we now extend the base exogenous-γ model to allow for incomplete information regarding the implementation by the imitator, firm j. Suppose that the imitator has a base of know-how that might aid it in implementing the product invention described by s_i. We model this imitator implementation capability as a privately observed cost draw from a (common knowledge) distribution with c.d.f. F and support $[c_L, c_H]$. Firm j's cost position is then affected by both s_i and the implementation capability, resulting in a marginal cost of $\hat{c}_j = \min\{c_j, s_i\}$ for firm j. Depending on the draw, c_j could be less than either c_i or s_i. As before, the market use of this technological information is circumscribed by the innovator's patent.

The analysis of the imitator implementation case is analogous to that in the base case except that imitator j also has a private cost draw. This difference complicates the belief structure of the model. We highlight other differences below.

6.1 Belief and Cost Structure

Firm i knows that j's cost after the technology transfer cannot exceed s_i. Moreover, firm i knows that j can produce at $\hat{c}_j = \min\{c_j, s_i\}$; given s_i, firm i then assesses the distribution of $\hat{c}_j$ as

$$G(c|s_i) = \begin{cases} F(c) & \text{for } c < s_i, \\ 1 & \text{for } c \geq s_i, \end{cases} \tag{15}$$

and so there is an atom of size $1 - F(s_i)$ at $c = s_i$. Thus, firm i calculates the expected (mean) value of j's cost according to

$$\bar{c}_j = \bar{c}(s_i) \equiv \int_{c_L}^{c_H} x \, dG(x) = s_i - \int_{c_L}^{s_i} F(x) \, dx. \tag{16}$$

Clearly, $\bar{c}_j$ is increasing in s_i. Because the expected cost of a competitor is what matters for quantity choices in a Cournot equilibrium, firm i is effectively competing with a firm j whose type is distributed as $\hat{c}_j$. In contrast to the base case, here the economic effect of the disclosure is that technology transfer and the implicit cost signal lead to a (Cournot) market setting with one-sided incomplete information with an "informed" player j and an "uninformed" player i.[16]

16. Consider an alternative model in which $\delta \in [0, 1]$ is the probability that firm j's additional capability is useless, so that j's production costs are given by the disclosure s_i. Here, firm i expects the cost of a challenger to be $\delta s_i + (1 - \delta)\bar{c}(s_i)$. In equilibrium, φ^* shifts up as δ rises. Intuitively, the marginal benefit from withholding more of the invention increases with δ. This is because with larger δ it is more likely that the imitator has to rely exclusively on the disclosure. In equilibrium, the signaling cost must adjust to offset this increased benefit. As a result, the equilibrium disclosure strategy shifts up and becomes flatter. Letting $\delta \to 1$, the equilibrium converges to the base case.

6.2 Cournot Equilibrium (Imitator Implementation)

Suppose that firm i makes the equilibrium disclosure $s_i = \varphi(c_i)$, where c_i is i's cost. Firm j competes with an opponent whose cost is inferred to be $c_i = \varphi^{-1}(s_i)$. Firm i, however, remains uncertain about j's cost and expects the quantity choice of j to vary with the (unknown to i) value of $\hat{c}_j$. The Cournot equilibrium strategies are given by

$$q_i^*(c_i, s_i) = (3\beta)^{-1}[\alpha - 2c_i + \bar{c}_j], \tag{17}$$

$$q_j^*(c_j, s_i) = (3\beta)^{-1}\left[\alpha - \frac{3}{2}\hat{c}_j + c_i - \frac{\bar{c}_j}{2}\right], \tag{18}$$

and the price pattern is

$$P^* = \tfrac{1}{3}[\alpha + c_i + \tfrac{3}{2}\hat{c}_j - \tfrac{1}{2}\bar{c}_j]. \tag{19}$$

Firm i's own-cost effect (c_i) and j's own-cost effect ($\hat{c}_j$) lead to higher realized prices, while the expectation effect ($\bar{c}_j$) leads to lower realized prices. Through $\hat{c}_j$, P^* rises with increases in c_j when $c_j < \varphi(c_i)$. Equilibrium expected profits for the firms are given by

$$\pi_i^*(c_i, s_i) = (9\beta)^{-1}[\alpha - 2c_i + \bar{c}_j]^2, \tag{20}$$

$$\pi_j^*(c_j, s_i) = (9\beta)^{-1}[\alpha - \tfrac{3}{2}\hat{c}_j + c_i - \tfrac{1}{2}\bar{c}_j]^2. \tag{21}$$

6.3 Deviations (Imitator Implementation)

The deviation disclosure when firm j has a cost draw is similar to that calculated for the base case. Firm j makes quantity choices as given by the equilibrium strategy in the Cournot duopoly (18) against a type c_i', namely $q_j^*(c_j, s_i') = (3\beta)^{-1}[\alpha - \frac{3}{2}\hat{c}_j' + c_i' - \frac{1}{2}\bar{c}_j']$, where $\hat{c}_j' = \min\{c_j, s_i'\}$, and $\bar{c}_j' = \bar{c}(s_i')$. Firm i chooses $q^* \in \arg\max_q \int_{c_L}^{c_H}[P(q_j^*(x, s_i') + q) - c_i]q\, dF(x)$, which allows for the influence of the revealed disclosure of s_i' on the cost structure and beliefs of j. The optimal quantity choice and associated profits are

$$q^* = \frac{1}{3\beta}[\alpha - \tfrac{3}{2}c_i + \bar{c}_j' - \tfrac{1}{2}c_i'], \tag{22}$$

$$\pi^* = \frac{1}{9\beta}[\alpha - \tfrac{3}{2}c_i + \bar{c}_j' - \tfrac{1}{2}c_i']^2. \tag{23}$$

The deviation profit in (23) allows us to derive the equilibrium disclosure for the imitator implementation case.

6.4 Equilibrium Disclosures (Imitator Implementation)

From (23), we see that a disclosure of s leads to profits of

$$\pi_i^D = \pi_i^D(s, c) = \frac{1}{9\beta}\left[\alpha - \frac{3}{2}c - \frac{1}{2}\varphi^{-1}(s) + s - \int_{c_L}^{s} F(x)\,dx\right]^2, \tag{24}$$

and solving (11) leads to the (unconstrained) first-order condition

$$\frac{d}{ds}\pi_i^D(s, c) = 0 = -\frac{d}{ds}\varphi^{-1}(s) + 2[1 - F(s)]. \tag{25}$$

In equilibrium, $s = \varphi(c)$ must hold. Substituting into (25), we obtain the nonlinear first-order differential equation

$$1 = 2[1 - F(\varphi(c))]\varphi'(c). \tag{26}$$

In addition, the disclosure strategy must satisfy the constraint $\varphi(c) \geq c$ $\forall c \in [c_L, c_H]$. To solve for the equilibrium disclosure function note that (26) is a separable differential equation. Thus, define $N(y) = \int_{c_L}^{y} [1 - F(x)]\,dx$ for $y \in [c_L, c_H]$; N is strictly increasing and strictly concave. Solutions to (26) then take the form of $N^{-1}(c/2 - A)$, where A is a constant to be determined by the constraint on disclosures, $\varphi(c) \geq c$. To specify the equilibrium, let s^* be the median cost type, as given by $F(s^*) = \frac{1}{2}$. Then set $A = s^*/2 - N(s^*)$. Now construct the disclosure strategy φ^* according to

$$\varphi^*(c) = \begin{cases} N^{-1}[(c - s^*)/2 + N(s^*)] & \text{for } c \leq s^*, \\ c & \text{for } c > s^*. \end{cases} \tag{27}$$

The constraint on disclosures is binding for cost types above s^* in the disclosure strategy above. Thus, we have

Proposition 2: *Let φ^* be the disclosure strategy in* (27). *Then*

(a) $\varphi^*(c)$ *is an optimal disclosure (solves* (11)*) for each $c \in [c_L, c_H]$ and satisfies the differential equation* (26) *for $c \in [c_L, s^*]$;*
(b) *the disclosure strategy φ^* together with the quantity strategies in* (17), (18), *and associated beliefs form a perfect Bayesian equilibrium (PBE);*
(c) φ^* *and the associated quantities and beliefs constitute the unique separating PBE, up to beliefs for out-of-equilibrium disclosures* ($s < \varphi^*(c_L)$);
(d) φ^* *is strictly increasing, is strictly convex, and satisfies $\varphi^*(c) > c$ for $c < s^*$;*
(e) φ^* *is completely determined by F and is independent of γ.*

There are two main differences between this equilibrium disclosure strategy and that found in the base case (Proposition 1). First, the competing disclosure incentives offset each other exactly only for types below s^*. For types above s^*, the constraint on disclosures is binding. In this range, the benefit from reduced technology transfer, $2[1 - F(\varphi^*(c))]$, is less than 1, which is the constrained cost of a higher disclosure. Thus, a disclosure of $\varphi^*(c) = c$ is optimal as a "corner" solution. The constraint binds because the benefit from reducing technology transfer vanishes as we get near c_H [since $1 - F(c_H) = 0$], and so the incentive to make a lower cost disclosure becomes dominant. Thus, over the high end of the cost-type range, there is no withholding of knowledge in equilibrium. Rather, it is in the low end, where invention is greatest, that enabling knowledge is withheld. See Figure 1.

Second, the equilibrium disclosure function is strictly convex—the extent of withheld knowledge is greater with lower cost types. The reason is that the benefit from higher disclosure, $2[1 - F(\varphi^*(c))]$, is decreasing in c. Intuitively, the benefit from reducing technology transfer is larger for lower-cost types because the probability that the imitator independently will have a lower cost than $\varphi^*(c)$ increases with c. To offset this, the cost associated with a higher disclosure must also be large. This means that a small increase in the disclosure will lead to a relatively rapid increase in the inference of a higher cost type, and so φ^* is convex.

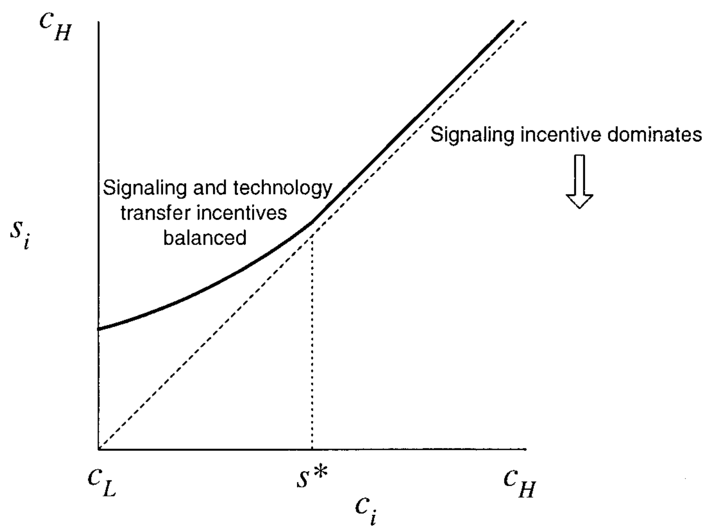

FIGURE 1. SIGNALING FUNCTION WITH IMITATOR IMPLEMENTATION

For high cost types, disclosure of enabling information is an efficient signal in that it bears directly on the object of the imitator's inference and is nearly without cost because the probability that the imitator will use the transferred technology is low. These features confer an advantage on disclosure over indirect signals (e.g., price or advertising) with respect to high cost types.

The disclosure strategy is fully determined by the prior cost distribution F. For example, if $F(c)$ is essentially constant over a range, then from (26), $\varphi^*(c)$ will be approximately linear in that range. Intuitively, the disclosure strategy becomes linear when the technology-transfer benefit from a higher disclosure is not sensitive to underlying cost type; the slope of the disclosure strategy is held constant in order to maintain a constant cost of higher disclosure. Analogously, the disclosure strategy will be highly convex in regions where cost types are highly likely to occur (e.g., around the mode of a unimodal distribution).[17]

We now return to the comparison of disclosure incentives with endogenous validity (Section 5). Consider the set of types who will find full disclosure to be optimal. When γ is exogenous, all types in $[s^*, c_H]$ disclose fully. Extending the endogenous validity analysis to allow for imitator implementation and setting $\phi(c) = c$ in the disclosure first-order condition, we see that

$$\frac{2}{9\beta}\left[\alpha - c - \int_{c_L}^{c} F(x)\,dx\right]\{\tfrac{1}{2} - F(c)\} < \frac{\Gamma'(c)}{\Gamma(c)}\,[\pi^M(c) - \pi_i^D(c, c)]$$

applies for full disclosure in equilibrium. Since $F(s^*) = \frac{1}{2}$ and monopoly profits exceed duopoly profits, all types at or above s^* still have a strict incentive to disclose fully. Now, however, the signaling technology-transfer trade-off must be pushed to a positive level, so that it balances the positive impact of disclosure on validity probability when $\Gamma' > 0$. Thus, a larger range of types will find full disclosure to be optimal: all innovator types in $[t^*, c_H]$, where t^* is necessarily below s^* and solves with equality the above corner condition for disclosure, will optimally choose $\phi(c) = c$.

The range where partial disclosure occurs also exhibits this push toward greater disclosure. To see this, consider the differential equation for ϕ (from the left) at the type t^*. We know that $t^* = \phi(t^*) < \varphi^*(t^*)$, and that disclosure is greater than when γ is exogenous. It is clear that ϕ must be steeper than φ^*: if the slopes were equal (ϕ flatter), then

17. Even in the case of a uniform distribution over [0, 1], the lowest cost type (0) will claim 0.13.

the left-hand side would be zero (negative), as $d\varphi^*(c)/dc = 1 - F(c)$. This implies that ϕ remains below φ^* for a (lower) neighborhood of t^*, and we can apply the same argument again to see that this remains true at any c below t^*. Intuitively, disclosure is more valuable to the innovator when it increases the probability of validity, because then it makes a monopoly outcome more likely. Then, in equilibrium, the innovator discloses more and is willing to incur the greater technology-transfer cost associated with a more-competitive imitator in the event of a duopoly market (patent ruled invalid).

7. Conclusion: Enabling Knowledge as a Signal

This paper has examined the relationship between patent validity and disclosure signaling. We conclude with some thoughts on enabling disclosures as signals.

Enabling disclosure signals are interesting because they have unusual features relative to other signals and advantages over other signals of technological capability in many circumstances. Compare enabling disclosures with price or advertising signals, for example. Those signals do not change a competitor's capability, nor are there obvious structural limitations on their choice, whereas enabling disclosures change the capability of the competitors and are limited by the underlying capability of the innovator. The latter structural element forces a change in beliefs, since higher disclosure levels are not feasible for lesser types. And, in settings involving uncertainty about competitor capability, enabling knowledge signals can be nearly costless and therefore very attractive for high cost types.

Further, other signals must be "translated" into a technology-capability-type inference by the receiver. This last point also speaks to the fit between the signal and the desired effect. Price and advertising choices, for example, need not reveal any information about technology. Disclosures, whether in a patent or outside (e.g., research papers, conference presentations), are direct statements about a firm's technology. When such disclosures are made, they point directly to inferences about capability.

Appendix A. Cournot Duopoly Competition

This appendix verifies the claims in Section 6 regarding outcomes in the Cournot duopoly stage. Section 3 results then follow as a special case (take F to be degenerate at c_H). For this analysis, we maintain the hypotheses that φ is one-to-one and that the observed disclosure s_i

satisfies $s_i = \varphi(c_i)$ for some $c_i \in [c_L, c_H]$. We deal with out-of-equilibrium disclosures $s_i \notin \text{Range}[\varphi]$, and the associated beliefs in Appendix B when we verify the equilibrium.

The following lemma characterizes equilibrium quantity choices.

Lemma 2: *Suppose φ is one-to-one, and let s_i be the observed disclosure. Then in any (perfect Bayesian) equilibrium, the quantity choices $q_i^*(c_i, s_i)$ and $q_j^*(c_j, s_i)$ in the duopoly stage are unique and are given by* (17) *and* (18), *respectively.*

Proof. First, we show that (17) and (18) necessarily apply in equilibrium. Then we show that these quantity choices are optimal in the duopoly stage.

To begin, let $q_i(c_i, s_i)$ and $q_j(c_j, s_i)$ be a candidate pair of quantity choices. Consider the quantity choice of firm j. In equilibrium, we have $s_i = \varphi(c_i)$ for some type c_i. Since φ is one-to-one, firm j necessarily infers that c_i is the cost type of firm i. Also, j can produce at marginal cost $\hat{c}_j = \text{Min}\{c_j, s_i\}$. Then an optimal quantity choice for j must solve $\max_{q_j \geq 0}[\alpha - \beta q_i(c_i, s_i) - \beta q_j - \hat{c}_j]q_j$, as j expects i to produce $q_i(c_i, s_i)$ in equilibrium. The best response is easily calculated to be

$$q_j^* = \begin{cases} (\alpha - \hat{c}_j)/2\beta - \frac{1}{2}q_i(c_i, s_i) & \text{for } q_i(c_i, s_i) < (\alpha - \hat{c}_j)/\beta, \\ 0 & \text{for } q_i(c_i, s_i) \geq (\alpha - \hat{c}_j)/\beta. \end{cases} \tag{28}$$

Now consider firm i. In equilibrium, the type c_i discloses $s_i = \varphi(c_i)$ and firm j produces according to $q_j(c_j, s_i)$. Let $\bar{q}_j(s_i) = \int_{c_L}^{c_H} q_j(c_j, s_i)\, dF(c_j)$ denote firm i's expectation of j's output. Then, an optimal choice for i solves $\max_{q_i \geq 0}[\alpha - \beta\bar{q}_j(s_i) - \beta q_i - c_i]q_i$, and the best response for i is easily found to be

$$q_i^* = \begin{cases} (\alpha - c_i)/2\beta - \frac{1}{2}\bar{q}_j(s_i) & \text{for } \bar{q}_j(s_i) < (\alpha - c_i)/\beta, \\ 0 & \text{for } \bar{q}_j(s_i) \geq (\alpha - c_i)/\beta. \end{cases} \tag{29}$$

Next, we show that $\bar{q}_j(s_i) < (\alpha - c_i)/\beta$ necessarily holds in equilibrium. Suppose not. Then, by (29), we must have $q_i(c_i, s_i) = 0$, as i must be at a best response. Hence, by (28), we have $q_j(c_j, s_i) = (2\beta)^{-1}(\alpha - \hat{c}_j)$. Taking expectations over c_j, we have $\bar{q}_j(s_i) = (2\beta)^{-1}[\alpha - \bar{c}(s_i)]$, where $\bar{c}(s_i)$ is as defined in the main text. We then have

$$\begin{aligned} \alpha > 2c_H - c_L \geq 2c_i - \bar{c}(s_i) &\Rightarrow 2(\alpha - c_i) > \alpha - \bar{c}(s_i) \\ &\Rightarrow \beta^{-1}(\alpha - c_i) > \bar{q}_j(s_i), \end{aligned}$$

which contradicts the hypothesis.

Similarly, we can show $q_i(c_i, s_i) < (\alpha - \hat{c}_j)/\beta$ will hold in equilibrium. From the above result for $\bar{q}_j(s_i)$, we know $q_i(c_i, s_i)$ follows the upper branch in (29) and hence $q_i(c_i, s_i) \leq (2\beta)^{-1}(\alpha - c_i)$ as $\bar{q}_j(s_i) \geq 0$. We then have

$$\alpha > 2c_H - c_L > 2\hat{c}_j - c_i \Rightarrow 2(\alpha - \hat{c}_j) > \alpha - c_i$$
$$\Rightarrow \beta^{-1}(\alpha - \hat{c}_j) > (2\beta)^{-1}(\alpha - c_i),$$

which establishes the claim for $q_i(c_i, s_i)$.

Thus, in equilibrium, quantities for j and i must follow the upper branch in (28) and (29), respectively. Substituting for $q_i(c_i, s_i)$ in (28) from (29), and taking expectations over c_j, we then calculate $\bar{q}_j(s_i) = (3\beta)^{-1}[\alpha - 2\bar{c}(s_i) + c_i]$. Then (17) and (18) follow directly by solving for $q_i(c_i, s_i)$ and $q_j(c_j, s_i)$ from (28) and (29).

We now verify that the quantities in (17) and (18) are, in fact, optimal for each of i and j. Given s_i and that j produces as in (18), the type $c_i = \varphi^{-1}(s_i)$ will produce as in (17) provided that $\bar{q}_j(s_i) < (\beta)^{-1}(\alpha - c_i)$, so that the upper branch in (29) applies for the best response of i. We have $\alpha > 2c_H - c_L \geq 2c_i - \bar{c}(s_i) \Rightarrow 2\alpha > 4c_i - 2\bar{c}(s_i) \Rightarrow 3(\alpha - c_i) > \alpha - 2\bar{c}(s_i) + c_i$, and dividing through by 3β yields the desired inequality for $\bar{q}_j(s_i)$. Similarly, given s_i and that i produces as in (17), the type c_j will produce as in (18) provided $q_i(c_i, s_i) < (\beta)^{-1}(\alpha - \hat{c}_j)$. We have $\alpha > 2c_H - c_L \Rightarrow 2\alpha > 4c_H - 2c_L > \bar{c}(s_i) + 3\hat{c}_j - 2c_i \Rightarrow 3(\alpha - \hat{c}_j) > \alpha - 2c_i + 3\hat{c}_j$, and dividing through by 3β yields the desired inequality for $q_i(c_i, s_i)$. □

The second claim in Section 6 regards optimal production by firm i following a deviation disclosure. Given the analysis in the text, it only remains to show that the quantity in (22) solves $\max_{q_i \geq 0} [\alpha - \beta\bar{q}_j^*(s_i') - \beta q_i - c_i]q_i$. Since $\bar{q}_j^*(s_i') = (3\beta)^{-1}[\alpha - 2\bar{c}(s_i') + c_i']$,

$$\alpha > 2c_H - c_L \Rightarrow 2\alpha > 4c_H - 2c_L > 3c_i + c_i' - 2\bar{c}(s_i')$$
$$\Rightarrow 3(\alpha - c_i) > \alpha - 2\bar{c}(s_i') + c_i'$$

holds, and dividing through by 3β yields $\bar{q}_j^*(s_i') < \beta^{-1}(\alpha - c_i)$. Hence, from (29), the optimal quantity choice for type c_i given the disclosure s_i' is given by $(2\beta)^{-1}(\alpha - c_i) - \bar{q}_j^*(s_i')/2$, and (22) follows directly.

Appendix B. Proof of Propositions 1 and 2

Proposition 1 is a special case of Proposition 2, so the proof of Proposition 1 is omitted.

Parts (d) and (e) of Proposition 2 are easily verified with φ^* as given by (27). For (a), it is obvious that φ^* satisfies (26) for types $c \in$

$[c_L, s^*]$; note that the constraint $\varphi^*(c) \geq c$ is binding for types $c \in [s^*, c_H]$.

For the first part of (a), we must show that a disclosure of $\varphi^*(c)$ is optimal for each $c \in [c_L, c_H]$. From (11), an optimal disclosure for c must solve $\max_{s \geq c} \pi_i^D(s, c)$. Recall that any disclosure in the range of φ^*, that is, $s \in [\varphi^*(c_L), \varphi^*(c_H)]$, leads firm j to make the necessary equilibrium inference that i is of type $[\varphi^*]^{-1}(s)$. Hence, we calculate profits $\pi_i^D(s, c)$ via (24). A disclosure $s < \varphi^*(c_L)$ is out of equilibrium; we specify the belief for j that i is type c_L in this case.

- *Case 1:* $c > s^*$. Since $\varphi^*(c) = c$, any disclosure $s \in [c, c_H]$ is in equilibrium, and

  $$\frac{\partial \pi_i^D(s, c)}{\partial s} = 2(36\beta)^{-1}\left[2\alpha - s + 2\left(s - \int_{c_L}^{s} F(x)\, dx\right) - 3c\right]$$
  $$\{-1 + 2[1 - F(s)]\}$$

  follows from (24). The first factor in brackets is positive, since, from (22), the Cournot quantity is positive for any deviation s. Since $F(s) > F(s^*) = \frac{1}{2}$, the second factor in brackets is negative. Hence, a disclosure of $s = \varphi^*(c) = c$ is optimal over $s \in [c, c_H]$.
- *Case 2:* $c = s^*$. This is identical to case 1 except that at $s = c = s^*$ we have $\partial\pi_i^D(s^*, s^*)/\partial s = 0$ by construction of s^*. The partial is negative for $s > s^*$.
- *Case 3:* $c < s^*$. For disclosures $s > s^*$, we find that $\pi_i^D(s, c)$ is strictly decreasing in s, as in case 1. For disclosures $s \in [\varphi^*(c_L), s^*)$, we have, from (24),

  $$\frac{\partial \pi_i^D(s, c)}{\partial s} = \frac{2}{36\beta}\left[2\alpha - [\varphi^*]^{-1}(s) + 2\left(s - \int_{c_L}^{s} F(x)\, dx\right) - 3c\right]$$
  $$\times\left[-\frac{d}{ds}[\varphi^*]^{-1}(s) + 2[1 - F(s)]\right].$$

  As before, the first factor in brackets is positive. The second factor is identically zero, since φ^* is constructed to solve the differential equation (26). Thus, deviation profits are constant for disclosures in this range.

For $c \in [(\varphi^*)^{-1}(c_L), s^*)$, the constraint $s \geq c$ implies that each disclosure $s \in [c, s^*)$ occurs in equilibrium. Then the argument in the previous paragraph implies a disclosure of $s = \varphi^*(c)$ is optimal. For $c \in [c_L, (\varphi^*)^{-1}(c_L))$, a disclosure of $s = \varphi^*(c)$ is optimal over $s \geq \varphi^*(c_L)$. A disclosure $s < \varphi^*(c_L)$ is feasible for these types, but it is also out of equilibrium. Since firm j infers type c_L whenever $s < \varphi^*(c_L)$ but technology transfer reduces j's cost, no deviation in this range is profitable. This establishes part (a).

Part (b) then follows directly from (a) by noting that φ^* together with the quantities in (17) and (18) evaluated at $s = \varphi^*(c)$ and the (point) beliefs of $[\varphi^*]^{-1}(s)$ for $s \geq \varphi^*(c_L)$ and c_L for $s < \varphi^*(c_L)$ satisfy the definition of equilibrium.

We now show that the proposition describes the unique separating equilibrium [part (c)]. Let φ be the disclosure strategy in any separating equilibrium. First, we show φ must be strictly increasing and continuous. Consider two types where $c < c'$, and suppose that $\varphi(c) \geq \varphi(c')$. Then the disclosure $\varphi(c)$ is feasible for type c', and in equilibrium the incentive compatibility condition of $\pi_i^D(\varphi(c'), c') \geq \pi_i^D(\varphi(c), c')$ must hold. From (24), this reduces to $\bar{c}(\varphi(c')) \geq \bar{c}(\varphi(c)) + (c' - c)/2$. Then we have $\varphi(c') > \varphi(c)$, as $\bar{c}$ is strictly increasing, which contradicts the hypothesis.

For continuity, let $c < c'$. Since $\varphi(c')$ is feasible for c but $\varphi(c)$ is chosen in equilibrium, we have $\pi_i^D(\varphi(c), c) \geq \pi_i^D(\varphi(c'), c)$, which then implies that $(c' - c)/2 \geq \bar{c}(\varphi(c')) - \bar{c}(\varphi(c))$. Since each of $\bar{c}$ and φ is strictly increasing, the last term is nonnegative; letting $c' \downarrow c$, we see that φ is continuous from the right at c. Taking $c' < c$ and reversing the roles of c and c' shows that φ is continuous from the left at c.

Next, we claim that $\varphi(c) = c \; \forall c \in [c_L, c_H]$ cannot hold in a separating equilibrium. Consider $c < s^*$ where $F(s^*) = \frac{1}{2}$. From (24), we have

$$\pi_i^D(\varphi(c), c) \geq \pi_i^D(\varphi(c'), c) \quad \Leftrightarrow \quad \bar{c}(\varphi(c)) - \frac{c}{2} \geq \bar{c}(\varphi(c')) - \frac{c'}{2},$$

where we take $c < c' < s^*$. Noting that $\frac{d}{dx}[\bar{c}(x) - x/2] = \frac{1}{2} - F(x) > 0$, we see that type c can profitably deviate if $\varphi(c) = c$ and $\varphi(c') = c'$.

Thus, we must have $\varphi(c) > c$ for some type. As φ is continuous and strictly increasing, we must then have $\varphi(c) > c$ over some interval of types. Further, it is easy to show that φ must satisfy $1 = 2[1 - F(\varphi(c))]\varphi'(c)$ over any such interval. Let $c < c'$ be two types in such an interval. We know the disclosure $\varphi(c')$ is feasible for type c, and, since $\varphi(c) > c$, we know that the disclosure $\varphi(c)$ is feasible for c' sufficiently close to c. Then incentive compatibility between c and c' implies that $\bar{c}(\varphi(c')) - \bar{c}(\varphi(c)) = (c' - c)/2$, and the differential equation follows directly upon dividing by $c' - c$ and taking limits.

The next step is to identify where the differential equation applies and where the disclosure constraint is binding. We claim that $\varphi(c) = \mathrm{c}$ for $c \geq s^*$ and $\varphi(c) > c$ for $c < s^*$. For the first claim, suppose

$\varphi(c) > c$ for $c > s^*$. Then, as above, φ satisfies the differential equation over an interval that contains c; any solution is convex, and at a type $x > c > s^*$ we have $\varphi'(x) = \{2[1 - F(x)]\}^{-1} > 1$. Now, let $b \equiv \inf\{x | x \geq c,\ \varphi(x) = x\}$. We know $b \leq c_H$ as $\varphi(c_H) = c_H$. Then the differential equation holds over any subinterval of $[c, b]$, but this implies φ is discontinuous at b, by the above convexity and slope property. As a result, no such b exists; but this contradicts $\varphi(c_H) = c_H$. Thus, the disclosure constraint must bind for types above s^*.

For the second claim, consider $c < s^*$, and suppose $\varphi(c) = c$. Since the function $\bar{c}(x) - x/2$ is strictly increasing for $x < s^*$, we see that $\bar{c}(c) - c/2 < \bar{c}(s^*) - s^*/2$. This means that the type c can profitably deviate to the disclosure $\varphi(s^*) = s^*$. Thus, $\varphi(c) > c$, and the differential equation must hold for types below s^*.

Finally, the standard existence and uniqueness theorem for first-order differential equations (Davis, 1962, p. 85) can be applied. Hence, there is a unique solution to the differential equation on the interval $[c_L, s^*]$ that satisfies $\varphi(s^*) = s^*$, the necessary boundary condition in a separating equilibrium, and this is φ^* as given by (27) in the main text. Thus, the disclosure strategy in any separating equilibrium is given by φ^*. Since the quantity strategies are uniquely determined by the disclosure strategy, the separating equilibrium is unique (up to off-of-the-equilibrium-path beliefs and actions).

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