Economics

Working Papers

2023-04

# Share to Scare: Technology Sharing in the Absence of Strong Intellectual Property Rights

Jos Jansen

DEPARTMENT OF ECONOMICS
AND BUSINESS ECONOMICS
AARHUS UNIVERSITY

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Jos Jansen
*Aarhus University*†

May 2023

**Abstract**

I study the incentives of Cournot duopolists to share their technologies with their competitor in markets where intellectual property rights are absent and imitation is costless. The trade-off between a signaling effect and an expropriation effect determines the technology-sharing incentives. In equilibrium, there tends to be at most one firm that shares technologies. For similar technology distributions, there exists an equilibrium in which nobody shares. If the technology distributions are skewed towards efficient technologies, then there may exist equilibria in which one firm shares all technologies, only the best technologies, or only intermediate technologies. Further, I consider several extensions.

**Keywords:** Cournot duopoly, strategic disclosure, indivisibility, innovation, trade secret, open source, skewed distribution
**JEL Codes:** D82, L13, L17, O32, O34

*I thank Stefan Bechtold, Patrick Bolton, Jan Boone, Giacomo Calzolari, Ramon Faulí-Oller, David Gill, Maria Gil-Molto, Ela Glowicka, Georg von Graevenitz, Dietmar Harhoff, Martin Hellwig, Frédéric Koessler, Dan Kovenock, Johan Lagerlöf, Gerard Llobet, Thomas Mertens, Andras Niedermayer, Martin Peitz, Joel Sandonis, Oz Shy, Philipp Weinschenk, and audiences of numerous seminars and conferences for helpful discussions. I am grateful for the support of the WZB (Berlin) and EUI (Florence), where part of the research for this paper was done. All errors are mine.

†*Address:* Dept. of Economics and Business Economics, Aarhus University, Fuglesangs Allé 4 (Building 2632/L), DK-8210 Aarhus V, Denmark; *E-mail:* JJansen.Econ@gmail.com

# 1 Introduction

The paper studies the incentives of profit-maximizing firms to freely reveal their innovations to competitors. Upon disclosure the innovation is not protected by intellectual property rights, and the technology can be imitated at no cost. Such an analysis of disclosure incentives could be relevant in the context of less developed countries or transition economies, where institutions for the enforcement of intellectual property rights may be weak or missing.[1] This paper analyzes how firms should manage their intellectual property in such an environment.

An obvious strategy for a firm in an industry without intellectual property right protection would be to adopt secrecy. By adopting secrecy, a firm avoids imitation by its competitors, and maintains its potential technological lead. However, a secretive firm foregoes a potential benefit from sharing its technology. By sharing its technology, the firm persuades its competitors of the technology's efficiency, which may improve the firm's competitive position. The trade-off between the strategic gain from technology sharing and the loss from expropriation of the shared technology determines the incentive for technology sharing in my model.

The analysis could also provide insights in the strategic adoption of open source technology. Literature on open source technology (e.g., see Harhoff *et al.*, 2003, Lerner and Tirole, 2002, Maurer and Scotchmer, 2006, Von Hippel, 2005) identifies a number of important motives for the adoption of open source technologies by profit-maximizing firms. For example, firms may generate revenues from activities that are complementary to the open source technology, they may adopt an open source technology to improve their market position through network externalities, or they may use an open source technology to signal their productivity. In this paper, I explore some implications of the signaling motive for profit-maximizing firms. Also Blatter and Niedermayer (2015), Leppämäki and Mustonen (2009), and Spiegel (2009) analyze signaling motives for the adoption of open source projects. These papers focus on workers' signals to the labor market, whereas I analyze firms' signals to a competitor in the product market. That is, I analyze a model where firms strategically manage their competitor's expectations by freely revealing their technology or keeping it secret.[2]

[1] Recent surveys in the US and EU suggest that, also in developed countries, patents are considerd to be less effective as a mechanism for appropriating the value of process innovations in comparison with secrecy (Levin *et al.*, 1987, Cohen *et al.*, 2000, and Arundel, 2001). My analysis can be seen as a limiting case in which patents are completely ineffective for the appropriation of value.

[2] In a recent survey, Henkel and Tins (2004) identify some motives that play a role in the decision

Allen (1983) describes the case of technology sharing in the UK and US iron and steel industry of the 19th century. Firms in this industry acquired process innovations, through changes in the height and temperature of their blast furnaces, as a by-product of installing new production capacity. These productivity improvements were not patentable. In spite of the absence of intellectual property right protection, firms freely revealed process innovations by publications in engineering journals or through informal channels. Subsequently, the revealed innovations were adopted by competing firms. Finally, firms appear to be capacity-constrained and engaged in advancing size or output. The assumptions of my model (i.e., exogenous process innovations, no intellectual property protection, imitation of revealed technologies, and Cournot competition) seem to be consistent with the essential features of this case.[3] I find conditions under which free revealing of technology can be an equilibrium strategy.

Currently, firms appear to publish in scientific journals too. For example, Arora *et al.* (2021) find that 70% of the sampled innovative manufacturing firms in North America have published at least one scientific article between 1980 and 2015. The publishing firms have on average 19 publications per year. Baruffaldi *et al.* (in press) identify some advantages and a possible disadvantage associated with publication in scientific journals. Publication appears to be a relatively fast and cheap way of communicating new R&D information for firms. The peer review of an article tends to certify the revealed information. A journal's reputation may contribute to the publishing firm's research reputation. Although scientific publications may improve a firm's research reputation, firms tend to be concerned about revealing proprietary R&D information. My paper considers the basic trade-off between these advantages and disadvantage, and it characterizes publication strategies of profit-maximizing firms resulting from the trade-off.

First, I find that the technology-sharing strategies are strategic substitutes. If one firm adopts a strategy in which some of the firm's technologies are shared, then the competitor adopts full secrecy in equilibrium. In other words, at most one firm shares some of its technology range. This result can be easily understood in the extreme

to freely reveal embedded Linux code by profit-maximizing firms. They report that 80% (respectively, 75%) of the embedded Linux hardware (software) companies, participating in the survey, find the perception that "[c]ompeting companies use the code or learn from it, so there is a loss of competitive advantage" at least a somewhat important reason for not making their code public. This captures the loss from imitation. Moreover, Henkel and Tins find that 45.4% (respectively, 60.3%) of the embedded Linux hardware (software) companies, participating in the survey, agreed that their company reveals code because "revealing good code improves [the] company's technical reputation," while 19.2% (8.6%) disagreed. This is consistent with the signaling motive.

[3] The incremental nature of innovations could be captured by a narrow technology space.

situation in which a firm's competitor shares all technologies. In this case, the firm prefers to keep any technology secret, since the technology is either worse than the competitor's technology, or it would be expropriated with certainty if it were shared. In the former case, the firm finds itself in a strategically disadvantageous position. For technologies that are more efficient than the competitor's technology, technology sharing would yield imitation, and the loss from certain expropriation would outweigh any potential gain from signaling.

Second, I find that the incentive to share a technology is strongest for intermediate cost values, i.e., the marginal profit from disclosure is hump-shaped. An increase of the efficiency level of a firm's technology increases the signaling gain at a constant rate, while the expropriation risk increases at an increasing rate. This gives an incentive to conceal "dramatic" news (i.e., extremely low and high costs), while sharing "anticipated" news. Recently, a few other papers analyze different economic problems with non-monotonic disclosure incentives (e.g., Board, 2009, Sun, 2011, and Jansen, 2023). Board (2009) and Sun (2011) study the incentives of firms to disclose information about their product characteristics to consumers. By contrast, I analyze a model in which firms disclose information about their technology to each other, not to a third party. Moreover, Board and Sun study symmetric distributions, whereas I also have results for skewed distributions. In fact, the skewness of technology distributions plays a big role in my analysis. Jansen (2023) analyzes a model in which contestants try to influence the investment choices of a rival by disclosing information. Again, this economic model differs substantially from the model at hand.

These observations yield the following technology-sharing strategies in equilibrium. First, if the cost distributions are identical or similar, an equilibrium exists in which both firms conceal their technologies. By contrast, if distributions are sufficiently dissimilar, then such an equilibrium may not exist. Second, if the cost distribution of a firm's competitor is skewed towards efficient technologies, then the firm has an incentive to unilaterally share some technologies. Skewness limits the expected loss of expropriation, while the signaling gain remains. In this case, there always exists an equilibrium in which the firm shares all its technologies. Moreover, there may also exist an equilibrium in which one firm only shares its best technologies. Finally, an equilibrium may exist where one firm only shares intermediate technologies, while extreme technologies (and the rival's technology) are kept secret.

Endogenously, market structures may emerge where profit-maximizing firms adopt different technology-sharing strategies. For example, firms with proprietary and open source technologies coexist in equilibrium despite the absence of intellectual property protection. Such an asymmetric equilibrium can emerge in a symmetric model as long as the technology distribution is not skewed towards inefficient technologies. In practice, there are examples of high-technology markets where freely revealing firms compete with concealing firms (see e.g. Moody, 2001). Llanes and De Elejalde (2013) also obtain the coexistence of proprietary and open source standards in equilibrium for profit-maximizing firms. Their focus on investment spillovers and complementarities is complementary to mine.

The paper contributes to the literature on strategic disclosure of verifiable information. Milgrom and Roberts (1986), and Okuno-Fujiwara *et al.* (1990) obtain an important "unraveling result."[4] In the present paper, disclosure is costly, since a competitor may imitate the technology, and become a more aggressive competitor. Consequently, the unraveling result may fail to hold. Also Anton and Yao (2003, 2004), Encaoua and Lefouili (2005), Gill (2008), and Jansen (2006, 2011) study the strategic disclosure incentives of competing, innovative firms in the presence of knowledge spillovers. Anton and Yao, and Jansen study problems of one-sided asymmetric information where the identity of the disclosing firm is exogenously given. By contrast, Gill and the present paper analyze problems of two-sided asymmetric information. Although Gill analyzes a related model with two-sided asymmetric information, the identity of the disclosing firm is exogenous (i.e., the leader). In the present paper, both firms choose technology-sharing strategies simultaneously, and the identity of the disclosing firm is thereby determined endogenously.[5] Further, with two-sided asymmetric information there remains uncertainty about the size of the knowledge spillover, which affects the technology-sharing incentives in an interesting way.[6] In particular, there does not ex-

[4]If it is known that the sender of information is informed, information is verifiable, and there are no costs of disclosure, then the sender often cannot do better than disclose his information, given skeptical equilibrium beliefs of the receiver.

[5]The present paper differs in other important ways from Gill (2008) too. Whereas Gill identifies conditions under which entry may be deterred by strategic disclosure, I characterize conditions under which accommodating firms disclose. Second, Gill's model is tailored to competition in research and development, while I adopt a standard IO model of Cournot competition (although my model can also be interpreted as a static model of R&D investment). Finally, the types in Gill's model are drawn from uniform distributions, while I do not impose such a restriction on the distributions of types. In fact, I show that the skewness of the technology distributions has important implications for a firm's incentives to share its technology.

[6]The present analysis differs in a second respect from Anton and Yao. They assume that innovations are infinitely divisible, and firms can choose to disclose only part of their technology. Encaoua and Lefouili, Jansen, and the present paper study indivisible innovations (see Jansen, 2011, for an extensive comparison). In contrast to Anton and Yao, I obtain equilibria that need not be fully revealing to firms.

ist an equilibrium in which only technologies of intermediate productivity are shared in a model with one-sided asymmetric information (Jansen, 2011), whereas such an equilibrium may exist with two-sided asymmetric information.

The paper is organized as follows. Section 2 describes the model. Section 3 discusses the equilibrium output levels of firms for different technology-sharing choices. Section 4 derives the equilibrium technology-sharing strategies of identical firms. Section 5 extends the analysis by considering non-identical firms, intellectual property right protection, the incentives to precommit to share technologies, and Bertrand competition. Finally, Section 6 concludes the paper. The Appendix contains the proofs of the main propositions. I relegate proofs for the extension with intellectual property right protection to an online Supplementary Appendix.

# 2 The Model

Two risk-neutral firms produce substitutable goods. The firms have private information about their costs of production, $\theta_i$ for firm $i$, with $i = 1, 2$. Firm $i$ obtains a process innovation and has production cost $\theta_i \in \Theta$, which is a random draw from the technology space $\Theta \equiv [\underline{\theta}, \overline{\theta}]$ for $0 \leq \underline{\theta} < \overline{\theta}$, with p.d.f. $f_i : \Theta \to \mathbb{R}_+$ (and corresponding c.d.f. $F_i : \Theta \to [0, 1]$) for $i = 1, 2$. There is full support, i.e. $f_i(\theta) > 0$ for all $\theta \in \Theta$. The two firms' costs are independently distributed.

After each firm learns its cost, the firms make simultaneous technology-sharing choices. For $i = 1, 2$, firm $i$ with cost $\theta_i$ chooses whether to reveal its technology truthfully, $s_i(\theta_i) = \theta_i$, or to keep its technology secret and send uninformative message $s_i(\theta_i) = \varnothing$. The technology-sharing strategy of firm $i$ defines a partition $\{\mathcal{O}_i, \mathcal{S}_i\}$ of the technology space $\Theta$ (i.e., $\mathcal{O}_i, \mathcal{S}_i \subseteq \Theta$, with $\mathcal{O}_i \cap \mathcal{S}_i = \emptyset$ and $\mathcal{O}_i \cup \mathcal{S}_i = \Theta$) such that:

$$s_i(\theta_i) = \begin{cases} \theta_i, & \text{if } \theta_i \in \mathcal{O}_i \\ \varnothing, & \text{if } \theta_i \in \mathcal{S}_i. \end{cases} \tag{2.1}$$

In other words, the set $\mathcal{O}_i$ contains technologies that firm $i$ shares (i.e., technologies with an "open standard"), and $\mathcal{S}_i$ contains those technologies that firm $i$ keeps secret. Often, I focus on shared technologies from a single interval, i.e., $\mathcal{O}_i = [l_i, h_i]$ with $\underline{\theta} \leq l_i \leq h_i \leq \overline{\theta}$ for $i = 1, 2$.

Intellectual property rights for a shared technology do not exist. A firm's competitor can adopt a shared technology at no cost. Consequently, the competitor adopts the shared technology, if this technology enables the competitor to produce at a lower cost than his own technology. Therefore, firm $i$ has the following cost of production after technology sharing and adoption (for $i, j \in \{1, 2\}$ with $i \neq j$):

$$c_i(\theta_i, s_j) = \begin{cases} \min\{\theta_i, \theta_j\}, & \text{if } s_j = \theta_j \\ \theta_i, & \text{if } s_j = \varnothing. \end{cases} \tag{2.2}$$

The inverse demand for the good of firm $i$ is linear, i.e. $P_i(x_i, x_j) = \alpha - x_i - \beta x_j$, where $(x_i, x_j)$ is the bundle of outputs of firms $i$ and $j$, respectively, and $i, j \in \{1, 2\}$ with $i \neq j$. I assume that the intercept $\alpha$ is sufficiently high to obtain interior solutions in the product market. Parameter $\beta$ represents the degree of product differentiation, with $0 < \beta \leq 1$.[7] After technologies are adopted, firms simultaneously choose their output levels, $x_i \geq 0$ for firm $i$ with $i = 1, 2$ (Cournot competition). The profit of firm $i$ with cost $c_i$ is (for $i, j \in \{1, 2\}$ with $i \neq j$):[8]

$$\pi_i(x_i, x_j; c_i) = (\alpha - c_i - x_i - \beta x_j)x_i. \tag{2.3}$$

Although I formulate the model for a process innovation, it can be reinterpreted as a model of product innovations too. In the alternative interpretation, the random variable $\theta_i$ would determine the demand intercept of good $i$'s inverse demand $P_i(x_i, x_j; \theta_i) = \alpha - c_i(\theta_i, s_j) - x_i - \beta x_j$, and firm $i$'s cost would be normalized to zero. Then, a high value of $\theta_i$ yields a low demand intercept, which corresponds to a small product innovation.

I solve the game backwards in perfect Bayesian equilibria with pure strategies.

# 3 Product Market Competition

Three cases may emerge. First, I consider the situation where firms have complete information about their marginal costs of production. This situation emerges when both firms share their technologies: $(s_i, s_j) = (\theta_i, \theta_j)$. If the firms share marginal costs $(\theta_i, \theta_j)$, imitation gives each firm the efficient technology $\min\{\theta_i, \theta_j\}$. Consequently,

[7] That is, I analyze a market for substitutable goods. If the goods were complementary (i.e., $\beta < 0$), then the expropriation of a firm's technology would have a positive effect on the firm's profit. Consequently, there would be stronger incentives to share technologies.

[8] The model can also be interpreted as a static model of winner-take-all R&D competition in which firms choose whether to share their research designs (e.g., Anton and Yao, 2002, and Gill, 2008). The investment level of firm $i$, $x_i \in [0, 1]$, determines the probability with which it makes an innovation. Firm $i$'s cost of investment is $k \cdot (\theta_i x_i + x_i^2)$. If both firms innovate, each receives prize $T$. If only one firm innovates, the innovator receives prize $W$, with $0 \leq 2T \leq W \leq k$. An unsuccessful firm receives no prize. Hence, firm $i$'s expected profit is: $\pi_i(\mathbf{x}; \theta_i) = [W - k\theta_i - kx_i - (W - T)x_j]\, x_i$. Normalization, i.e. $k = 1$, and defining $W = \alpha$ and $W - T = \beta$, gives the profit function (2.3).

firm $i$ supplies the following output in equilibrium (for $i, j \in \{1, 2\}$ and $i \neq j$):[9]

$$x_i^{oo}(\theta_i, \theta_j) = \frac{1}{2+\beta}\left(\alpha - \min\{\theta_i, \theta_j\}\right). \tag{3.1}$$

Second, if firm $i$ shares $\theta_i$ and firm $j$ conceals, and firm $i$ has beliefs consistent with sharing strategy (2.1), then the first-order conditions of firms $i$ and $j$ are as follows (for $i, j \in \{1, 2\}$ and $i \neq j$):

$$2x_i(\theta_i) = \alpha - \theta_i - \beta\left(\int_{\underline{\theta}}^{\theta_i} f_j(\theta|\theta_j \in \mathcal{S}_j)x_j(\theta)d\theta + [1 - F_j(\theta_i|\theta_j \in \mathcal{S}_j)]\, x_j(\theta_i)\right) \tag{3.2}$$

and

$$2x_j(\theta_j) = \alpha - \min\{\theta_i, \theta_j\} - \beta x_i(\theta_i), \tag{3.3}$$

where $f_j(\cdot|\theta_j \in \mathcal{S}_j)$ and $F_j(\cdot|\theta_j \in \mathcal{S}_j)$ are respectively the posterior p.d.f. and c.d.f. for firm $j$ after concealment by this firm. These first-order conditions give the following equilibrium outputs (for $i, j \in \{1, 2\}$ and $i \neq j$):

$$x_i^{os}(\theta_i; \mathcal{S}_j) = \frac{1}{4-\beta^2}\left((2-\beta)\alpha - 2\theta_i + \beta E_j\left(\min\{\theta_i, \theta_j\}|\theta_j \in \mathcal{S}_j\right)\right), \tag{3.4}$$

$$\begin{aligned} x_i^{so}(\theta_i, \theta_i; \mathcal{S}_j) = \frac{1}{4-\beta^2}\Bigg( & (2-\beta)\alpha - 2\min\{\theta_i, \theta_j\} + \beta\theta_j \\ & + \frac{\beta^2}{2}\left[\min\{\theta_i, \theta_j\} - E_i\left(\min\{\theta_i, \theta_j\}|\theta_i \in \mathcal{S}_i\right)\right]\Bigg), \end{aligned} \tag{3.5}$$

where

$$E_i\left(\min\{\theta_i, \theta_j\}|\theta_i \in \mathcal{S}_i\right) = F_i(\theta_j|\theta_i \in \mathcal{S}_i)E\{\theta_i|\theta_i \leq \theta_j, \theta_i \in \mathcal{S}_i\} + [1 - F_i(\theta_j|\theta_i \in \mathcal{S}_i)]\theta_j$$

and

$$E\{\theta_i|\theta_i \leq \theta_j, \theta_i \in \mathcal{S}_i\} = \int_{\underline{\theta}}^{\theta_j} \frac{f_i(\theta|\theta_i \in \mathcal{S}_i)}{F_i(\theta_j|\theta_i \in \mathcal{S}_i)}\theta d\theta.$$

Finally, in the remaining case, where both firms choose secrecy, $(s_i, s_j) = (\varnothing, \varnothing)$, profit maximization gives the following first-order condition for firm $i$:

$$2x_i(\theta_i) = \alpha - \theta_i - \beta E\left\{x_j(\theta_j)|\theta_j \in \mathcal{S}_j\right\}, \tag{3.6}$$

[9] In $x_i^{kl}(\cdot)$ the superscript $k \in \{o, s\}$ denotes whether firm $i$ adopted an open standard ($k = o$) or adopted secrecy ($k = s$). Similarly, superscript $l$ denotes whether firm $i$'s competitor works under openess ($l = o$) or secrecy ($l = s$).

where $E\{\theta_j|\theta_j \in \mathcal{S}_j\}$ is firm $j$'s expected cost conditional on concealment by firm $j$. Solving for the equilibrium gives the following output level for firm $i$ ($i, j \in \{1, 2\}$ and $i \neq j$):

$$x_i^{ss}(\theta_i; \mathcal{S}_i, \mathcal{S}_j) = \frac{1}{4-\beta^2}\left((2-\beta)\alpha - 2\theta_i + \beta E\{\theta_j|\theta_j \in \mathcal{S}_j\} + \frac{\beta^2}{2}\left[\theta_i - E\{\theta_i|\theta_i \in \mathcal{S}_i\}\right]\right). \tag{3.7}$$

In any situation the expected equilibrium product market profit is: $\pi_i^{kl}(\cdot) = x_i^{kl}(\cdot)^2$ with $k, l \in \{o, s\}$ and $i = 1, 2$.

# 4 Technology Sharing Strategies

In this section, I characterize the firms' incentives to strategically share technologies.

## 4.1 Basic Properties of Equilibrium Strategies

A firm's technology-sharing strategy follows from comparing the firm's expected profit from sharing with the expected profit from secrecy. Suppose firm $i$'s beliefs about its competitor's technology-sharing strategy are consistent with the partition $\{\mathcal{O}_j, \mathcal{S}_j\}$ for $i, j \in \{1, 2\}$ with $i \neq j$, and firm $j$'s technology-sharing strategy gives the partition $\{\mathcal{O}_j, \mathcal{S}_j\}$ of the set $\Theta$. Given these assumptions, firm $i$'s expected profit from technology-sharing and secrecy are, respectively:

$$\Pi_i^o(\theta_i; \mathcal{S}_j) \equiv \int_{\theta_j \in \mathcal{O}_j} \pi_i^{oo}(\theta_i, \theta_j) dF_j(\theta_j) + \int_{\theta_j \in \mathcal{S}_j} \pi_i^{os}(\theta_i; \mathcal{S}_j) dF_j(\theta_j) \tag{4.1}$$

$$\Pi_i^s(\theta_i; \mathcal{S}_i, \mathcal{S}_j) \equiv \int_{\theta_j \in \mathcal{O}_j} \pi_i^{so}(\theta_i, \theta_j; \mathcal{S}_i) dF_j(\theta_j) + \int_{\theta_j \in \mathcal{S}_j} \pi_i^{ss}(\theta_i; \mathcal{S}_i, \mathcal{S}_j) dF_j(\theta_j). \tag{4.2}$$

Hence, the difference of the expected profit from technology sharing and secrecy is:

$$\begin{aligned}\Psi_i(\theta_i; \mathcal{S}_i, \mathcal{S}_j) &\equiv \Pi_i^o(\theta_i; \mathcal{S}_i) - \Pi_i^s(\theta_i; \mathcal{S}_i, \mathcal{S}_j) \\ &= \int_{\theta_j \in \mathcal{O}_j} \left[x_i^{oo}(\theta_i, \theta_j)^2 - x_i^{so}(\theta_i, \theta_j; \mathcal{S}_i)^2\right] dF_j(\theta_j) \\ &\qquad + \Pr[\theta_j \in \mathcal{S}_j]\left[x_i^{os}(\theta_i; \mathcal{S}_j)^2 - x_i^{ss}(\theta_i; \mathcal{S}_i, \mathcal{S}_j)^2\right]. \end{aligned} \tag{4.3}$$

The comparison between $x_i^{oo}(\theta_i, \theta_j)$ and $x_i^{so}(\theta_i, \theta_j; \mathcal{S}_i)$ gives the following trade-off. On the one hand, sharing the technology $\theta_i$ enables the firm's competitor to imitate the technology and become a more "aggressive" output-setter, whereas secrecy gives no expropriation. That is, after technology sharing the competitor gets marginal cost $\min\{\theta_i, \theta_j\}$ instead of $\theta_j$. On the other hand, by sharing technology $\theta_i$, firm $i$ informs its competitor about firm $i$'s actual marginal cost (i.e., $\min\{\theta_i, \theta_j\}$), which enables the competitor to adjust his output levels accordingly. By contrast, secrecy forces the competitor to set an output level as a best response against firm $i$ with an average marginal cost (i.e., $E_i\left(\min\{\theta_i, \theta_j\} | \theta_i \in \mathcal{S}_i\right)$). This explains the last term of $x_i^{so}(\theta_i, \theta_j; \mathcal{S}_i)$ in equation (3.5), which gives a signaling effect. Comparing $x_i^{os}(\theta_i; \mathcal{S}_j)$ with $x_i^{ss}(\theta_i; \mathcal{S}_i, \mathcal{S}_j)$ gives a similar trade-off.

A firm with a sufficiently inefficient technology has a disincentive to share its technology since the signaling and expropriation effects reinforce each other. A firm that would share an inefficient technology risks expropriation by its competitor, and signals to its competitor that it will be a "friendly" competitor in the product market. Both effects make the competitor an "aggressive" output-setter (strategic substitutes), which lowers the profit of the firm. This observation gives the following negative result.

**Proposition 1** *For any $i = 1, 2$, and $\underline{\theta} < l < \overline{\theta}$, there exists no equilibrium in which firm $i$ chooses technology-sharing strategy $s_i$ with $\mathcal{O}_i = [l, \overline{\theta}]$.*

A firm with an efficient technology faces a trade-off between two conflicting effects. On the one hand, the firm's competitor may imitate the disclosed technology and thereby become a more "aggressive" competitor in the product market. This expropriation effect gives the firm a disincentive to share the technology. On the other hand, the firm demonstrates it will be an "aggressive" competitor in the product market which reduces the output supplied by its competitor (strategic substitutes). This signaling effect gives the firm an incentive to share the technology.

The incentive to share a technology also depends on the competitor's technology-sharing strategy. The following proposition suggests that the technology-sharing strategies are strategic substitutes.

**Proposition 2** *For $i, j = 1, 2$ with $i \neq j$, if firm $i$ chooses to share technologies from the interval $[l_i, h_i]$ with $\underline{\theta} \leq l_i < h_i \leq \overline{\theta}$ (i.e., $\mathcal{O}_i = [l_i, h_i]$ in equation (2.1)) in equilibrium, then firm $j$ chooses to share no technology (i.e., $\mathcal{O}_j = \emptyset$) in equilibrium.*

First, in those instances where firm $i$ shares its technology (i.e., for $\theta_i \in \mathcal{O}_i$), firm $j$ has a disincentive to share. If firm $i$ shares its technology, $\theta_i$, then firm $i$ knows that its competitor has a technology which is at least as good as $\theta_i$. As a consequence, the competitor (firm $j$) has no incentive to share a technology which is less efficient than $\theta_i$, since firm $j$ would thereby signal that it is less efficient than expected (i.e., $\theta_i \geq E_j(\min\{\theta_i, \theta_j\}|\theta_j \in \mathcal{S}_j)$). Furthermore, if the competitor would share a technology which is more efficient than $\theta_i$, then the technology will be imitated with certainty. In this case, the direct effect of expropriation with certainty outweighs the indirect effect from signaling. This observation is consistent with previous results in models with one-sided asymmetric information (e.g., Anton and Yao, 2003-4, and Jansen, 2006, 2011), where the expropriation effect dominates the signaling effect in the absence of intellectual property rights.

Second, in those instances where firm $i$ does not share (i.e., for $\theta_i \in \mathcal{S}_i$ with $\mathcal{S}_i \neq \Theta$), the argument is a little more subtle. The fact that firm $i$ has an incentive to share some technologies implies that the competitor's posterior distribution must be relatively more skewed towards efficient technologies compared to firm $i$'s distribution. Only in this case does firm $i$'s sharing of an efficient technology give a relatively low risk of imitation (weak expropriation effect), and a drastic update of firm $j$'s beliefs after sharing the technology (strong signaling effect). Whereas this situation gives firm $i$ an incentive to share some technologies, it gives a disincentive to firm $i$'s competitor. It implies that the competitor is in a position where technology sharing yields a relatively strong expropriation effect and weak signaling effect. Proposition 2 shows that the competitor's expropriation effect outweighs the signaling effect in this situation.

## 4.2 Unilateral Technology-Sharing Incentives

This section discusses a firm's incentive to unilaterally share its technology, given full concealment by the firm's competitor (i.e., $\mathcal{S}_j = \Theta$). Proposition 2 shows that this restriction is consistent with equilibrium behavior if the firm shares technologies from a single interval.

Firm $i$ receives the profit of $x_i^{os}(\theta_i;\Theta)^2$ from sharing its technology $\theta_i$ when its competitor conceals all technologies.[10] The firm earns the profit $x_i^{ss}(\theta_i;\mathcal{S}_i,\Theta)^2$ if it conceals its cost and its competitor conceals all costs.[11] Firm $i$ has an incentive to share its technology $\theta_i$ if $x_i^{os}(\theta_i;\Theta) \geq x_i^{ss}(\theta_i;\mathcal{S}_i,\Theta)$, which reduces to $\psi_i(\theta_i;\mathcal{S}_i) \geq 0$, where:

$$\psi_i(\theta_i;\mathcal{S}_i) \equiv -[1-F_j(\theta_i)](E\{\theta_j|\theta_j \geq \theta_i\} - \theta_i) + \frac{\beta}{2}\left[E\{\theta_i|\theta_i \in \mathcal{S}_i\} - \theta_i\right]. \tag{4.4}$$

The two terms in function $\psi_i$ reflect the trade-off between an expropriation effect and a signaling effect.

[10] Output $x_i^{os}$ is defined in (3.4) with $E_j\left(\min\{\theta_i,\theta_j\}|\theta_j \in \Theta\right) = F_j(\theta_i)E\{\theta_j|\theta_j \leq \theta_i\} + [1-F_j(\theta_i)]\theta_i$.

[11] Here $x_i^{ss}$ is as in (3.7) with $E(\theta_j|\theta_j \in \mathcal{S}_j) = E(\theta_j)$ and $E(\theta_i|\theta_i \in \mathcal{S}_i)$ is consistent with firm $i$'s technology-sharing strategy.

The first term of $\psi_i$ represents the expropriation effect. This effect captures the effect of a firm's technology-sharing decision on its rival's marginal cost in the product market. Technology sharing has only an effect on the competitor's marginal cost if the competitor chooses to imitate the technology. Imitation only occurs if the competitor is less efficient, which happens with probability $1 - F_j(\theta_i)$. In that case, firm $i$'s competitor produces at unit cost $\theta_i$ after sharing by firm $i$. On the other hand, if firm $i$ conceals its technology to a less efficient competitor, then the expected cost of the competitor equals $E\{\theta_j|\theta_j \geq \theta_i\}$. Hence, the first term of equation (4.4) is the difference between the expected cost of a competitor after technology sharing with subsequent imitation, and concealment. Thereby, it captures the expected loss from expropriation.

The second term of $\psi_i$ gives the signaling effect of technology sharing. It captures the effect of firm $i$'s technology-sharing decision on its competitor's output through the competitor's perception of firm $i$'s cost. After firm $i$ shares technology $\theta_i$, the competitor knows that he competes with a firm with cost level $\theta_i$ instead of the average cost level $E\{\theta_i|\theta_i \in \mathcal{S}_i\}$. The effect of this update of beliefs on firm $j$'s output depends on the responsiveness of firm $j$'s best-response function towards firm $i$'s outputs (i.e., $\beta/2$).

The overall effect of a marginal increase of $\theta_i$ is as follows:

$$\psi_i'(\theta_i; \cdot) = [1 - F_j(\theta_i)] - \frac{\beta}{2}. \tag{4.5}$$

That is, an increase of $\theta_i$ makes both effects weaker. The expropriation effect becomes weaker since it becomes less likely that the competitor imitates the firm's technology (i.e., the first term of equation (4.4) is negative and increasing in $\theta_i$). The signaling effect also becomes weaker after a cost increase since the firm becomes a less "aggressive" output supplier in the product market, which enables it to steal a smaller share of the market from its competitor (i.e., the second term in equation (4.4) is initially positive but subsequently negative, and decreasing in firm $i$'s marginal cost).

The function $\psi_i$ is strictly concave in cost $\theta_i$, i.e., $\psi_i''(\theta_i; \cdot) = -f_j(\theta_i) < 0$ for all $\theta_i$. An increase of $\theta_i$ weakens the expropriation and signaling effects at different rates. The rate at which the expropriation effect becomes weaker is proportional to the probability of expropriation. This probability is decreasing in the cost level $\theta_i$. The signaling effect becomes weaker at a constant rate. This rate is initially smaller than the rate of change of expropriation, since the signaling effect is an indirect effect. Therefore, the incentive to share a technology is growing for low $\theta_i$. Eventually, the signaling effect becomes aligned with the expropriation effect and grows in $\theta_i$ at a constant rate. The expropriation effect weakens at a diminishing rate. This gives a growing disincentive to share technologies for high $\theta_i$. This implies the following.

**Proposition 3** *In any equilibrium with concealment of all technologies by firm $j$, there exist some bounds $l_i, h_i \in \Theta$, with $l_i \leq h_i$, such that firm $i$ chooses technology-sharing strategy $s_i$ in equation (2.1) with $\mathcal{O}_i = [l_i, h_i]$, for $i, j = 1, 2$ with $i \neq j$.*

The sign of $\psi_i'(\theta_i; \cdot)$ in equation (4.5) depends on the size of the cost $\theta_i$. In particular, $\psi_i'(\underline{\theta}; \cdot) = 1 - \frac{\beta}{2} > 0$ and $\psi_i'(\overline{\theta}; \cdot) = -\frac{\beta}{2} < 0$. The function $\psi_i$ reaches a maximum for the marginal cost:

$$\widehat{\theta}_i \equiv F_j^{-1}(1 - \beta/2). \tag{4.6}$$

For example, if goods are homogeneous (i.e., $\beta = 1$), then $\psi_i$ reaches a maximum when $\theta_i$ equals the median cost of firm $j$. Hence, firm $i$'s incentive to unilaterally share its technology is strongest for an intermediate cost level, i.e., $\theta_i = \widehat{\theta}_i$.

Propositions 2-3 imply that there exists an equilibrium where shared technologies have to form a single interval for one firm, whereas the other firm conceals all technologies.

## 4.3 Equilibrium Strategies for (*Ex Ante*) Identical Firms

The observations in Propositions 1-3 have immediate consequences for equilibrium technology-sharing strategies. They imply that there may exist four kinds of technology-sharing strategies in equilibrium: both firms share nothing, one firm unilaterally shares all technologies, one firm unilaterally shares only the best technologies, or one firm shares only intermediate technologies while the other firm shares nothing.

In the remainder of this section, I characterize the conditions under which these strategies may be used in an equilibrium of the symmetric model. That is, I restrict attention to *ex ante* identical firms here (i.e., $F_1 = F_2$). In Section 5, I relax this assumption by allowing firms to have different technology distributions.

### 4.3.1 Share Nothing

First, I characterize the conditions under which firms conceal all technologies in equilibrium. Suppose both firms conceal all their technologies (i.e., $\mathcal{S}_1 = \mathcal{S}_2 = \Theta$), and the firms have beliefs consistent with full concealment. Consequently, firm $i$'s competitor expects cost $E(\theta_i)$ of firm $i$ after concealment. Hence, firm $i$ has no incentive to deviate unilaterally from full concealment by sharing the technology $\theta_i$, if $\psi_i(\theta_i; \Theta) \leq 0$

for all $\theta_i \in \Theta$, with $\psi_i$ as in equation (4.4). A necessary and sufficient condition for the emergence of full concealment in equilibrium is therefore: $\psi_i(\widehat{\theta}_i; \Theta) \leq 0$ with $\widehat{\theta}_i$ as in equation (4.6) and $i = 1, 2$. This condition reduces to the following (for $i, j \in \{1, 2\}$ and $i \neq j$):

$$E\{\theta_j | \theta_j \geq \widehat{\theta}_i\} \geq E(\theta_i). \tag{C$_S$}$$

It is immediate that the condition is satisfied if the firms' cost distributions have equal means, i.e. $E(\theta_i) = E(\theta_j)$.[12] I summarize the analysis in the following proposition.

**Proposition 4** *If the firms' technology distributions are identical, then there exists an equilibrium where both firms conceal all technologies.*

For the intuition for this result, I consider the incentive of firm $i$ with $\theta_i = \widehat{\theta}_i$ as in equation (4.6) to unilaterally deviate from full secrecy by sharing its technology. On the one hand, such a unilateral deviation allows the firm's competitor to learn that $\theta_i = \widehat{\theta}_i$ instead of $E\{\theta_i\}$. This signaling effect is discounted at the rate $\frac{\beta}{2}$ as equation (4.4) illustrates. On the other hand, unilateral sharing of $\widehat{\theta}_i$ allows the firm's competitor to adopt technology $\widehat{\theta}_i$ instead of working with the expected technology $E\{\theta_j | \theta_j > \widehat{\theta}_i\}$. Expropriation occurs with probability $\frac{\beta}{2}$, as follows from definition (4.6). That is, expropriation has a bigger effect on the competitor's expected cost than signaling has on the expected value of the firm's own cost (i.e., $E\{\theta_j | \theta_j > \widehat{\theta}_i\} - \widehat{\theta}_i > E\{\theta_i\} - \widehat{\theta}_i$, since $E\{\theta_j | \theta_j > \widehat{\theta}_i\} > E\{\theta_j\} = E\{\theta_i\}$). Conveniently, the two effects from deviation are discounted at the same rate ($\frac{\beta}{2}$). Hence, the expropriation effect is stronger than the signaling effect for a deviating firm.

### 4.3.2 Share All Technologies

Now, I study firm $i$'s incentives to share all its cost information, i.e., $\mathcal{O}_i = \Theta$, given that firm $j$ conceals all. Again, I use function $\psi_i$ in (4.4) to analyze firm $i$'s technology-sharing incentives in equilibrium. The beliefs of firm $i$'s competitor that are consistent with full sharing by firm $i$ are skeptical beliefs, i.e., $E\{\theta_i | \theta_i \in \mathcal{S}_i\} = \overline{\theta}$ or $\mathcal{S}_i = \{\overline{\theta}\}$. Firm $i$ has no incentive to conceal information, given skeptical beliefs, if

$$E(\theta_j) \leq \left(1 - \frac{\beta}{2}\right) \underline{\theta} + \frac{\beta}{2} \overline{\theta}. \tag{C$_O$}$$

The following proposition states this result formally.

[12] In that case, the condition holds, since it reduces to $E\{\theta_j | \theta_j \geq \widehat{\theta}_i\} \geq E(\theta_j)$.

**Proposition 5** *There exists an equilibrium where firm $i$ shares all technologies while firm $j$ conceals all technologies (i.e., $\mathcal{S}_i = \{\overline{\theta}\}$ and $\mathcal{S}_j = \Theta$) if and only if condition ($C_O$) holds.*

Hence, firm $i$ has an incentive to share all technologies if firm $j$'s average cost is sufficiently low, and firm $j$ conceals its technologies. In this case, firm $i$ with the most efficient technology (i.e., $\theta_i = \underline{\theta}$) would create only a marginally more efficient competitor by sharing its technology. However, technology sharing changes the competitor's beliefs dramatically: from the least efficient technology (after concealment) to the most efficient (after sharing). This puts firm $i$ in an advantageous strategic position. Therefore, under condition ($C_O$) the signaling effect dominates for firm $i$.

Increasing the degree of product substitutability ($\beta$) increases the relative strength of the signaling effect, and gives a stronger incentive to share technologies. Therefore, condition ($C_O$) becomes weaker. For example, at the extreme where goods are homogeneous (i.e., $\beta = 1$) an equilibrium with full sharing can already emerge for technology distributions that are symmetric on the interval $\Theta$ (i.e., $E(\theta_j) = \frac{1}{2}(\underline{\theta}+\overline{\theta})$).

#### 4.3.3 Share Only The Best Technologies

So far, I presented equilibria in which firms choose strategies that do not depend on their technology draw. In this subsection, I discuss the incentives to share selectively. In particular, I give conditions for the existence of an equilibrium in which a firm shares its best technologies while all other technologies are kept secret. It is necessary and sufficient that there exist some $h$, with $\widehat{\theta}_i < h < \overline{\theta}$, such that:

$$\psi_i(h; [h, \overline{\theta}]) = 0 \text{ and } \psi_i(\underline{\theta}; [h, \overline{\theta}]) \geq 0. \tag{4.7}$$

Figure 1 illustrates these equilibrium conditions. The following proposition shows that no equilibrium exists in which a firm shares only its best technologies.

**Proposition 6** *If the firms' technology distributions are identical, then there exists no equilibrium with $\mathcal{S}_i = (h^*, \overline{\theta}]$ for any $\widehat{\theta}_i < h^* < \overline{\theta}$.*

Suppose that firm $i$ would share only technologies that are better than some technology $h$, and the firm's competitor has beliefs consistent with $\mathcal{S}_i = [h, \overline{\theta}]$. If this were the case, then firm $j$ would conceal all its technologies (Proposition 2). Then, for firm $i$ with technology $\theta_i = h$, the signaling effect should exactly offset the expropriation effect. From equation (4.4) it follows that sharing technology $\theta_i = h$ has the following

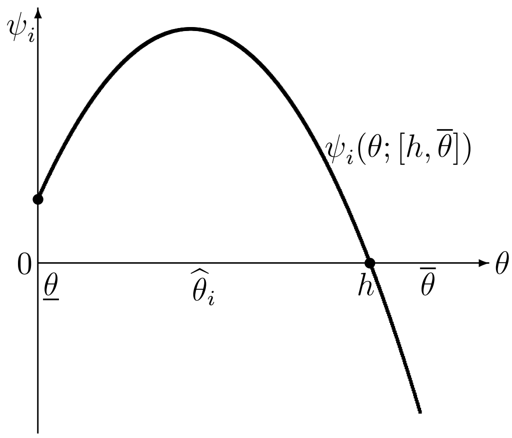


Figure 1: Sharing efficient technologies in equilibrium

effects. On the one hand, it gives a loss from expropriation of $E\{\theta_j|\theta_j > h\} - h$ with probability $1 - F_j(h)$. On the other hand, it gives a signaling gain of $E\{\theta_i|\theta_i > h\} - h$ discounted at $\frac{\beta}{2}$. With identical technology distributions, the two effects offset each other only if they have equal weighs, i.e., $1 - F_j(h) = \frac{\beta}{2}$, which implies that $h = \widehat{\theta}_i$. In other words, firm $i$ is indifferent between sharing and concealing $\widehat{\theta}_i$. However, this means that firm $i$ prefers to conceal all other technologies, since it has the strongest incentive to share technology $\theta_i = \widehat{\theta}$. Hence, it cannot be an equilibrium strategy for firm $i$ to share only its best technologies.

The proposition shows that an equilibrium in which one of the firms shares the best technologies can only emerge under special circumstances. It cannot emerge in a symmetric model. By contrast, full concealment and full unilateral technology sharing can emerge in equilibrium under symmetry (Propositions 4-5).

#### 4.3.4 Share Only Intermediate Technologies

In this subsection, I characterize conditions under which a firm shares technologies of intermediate efficiency, while it conceals very inefficient and very efficient technologies. That is, I analyze the sharing strategy $s_i$ with $\mathcal{O}_i = [l, h]$ and $\mathcal{S}_i = \Theta \backslash [l, h]$ for firm $i$, where $\underline{\theta} < l < \widehat{\theta}_i < h < \overline{\theta}$. By Proposition 2, firm $j$ conceals all technologies (i.e., $\mathcal{S}_j = \Theta$).

The equilibrium conditions for firm $i$ to share only technologies with $\theta_i \in [l, h]$, while firm $j$ conceals all information, are as follows:

$$\psi_i(y; \Theta \backslash [l, h]\}) = 0, \text{ for } y \in \{l, h\}, \tag{4.8}$$

where equation (4.4) defines $\psi_i$, and the posterior expected cost of the selectively sharing firm equals:

$$E\{\theta_i|\theta_i \notin [l,h]\} = \frac{F_i(l)}{F_i(l)+1-F_i(h)}E\{\theta_i|\theta_i \leq l\} + \frac{1-F_i(h)}{F_i(l)+1-F_i(h)}E\{\theta_i|\theta_i > h\}.$$

Solving this system of equations (4.8) yields equilibrium values for $l$ and $h$. Figure 2 illustrates the equilibrium conditions.

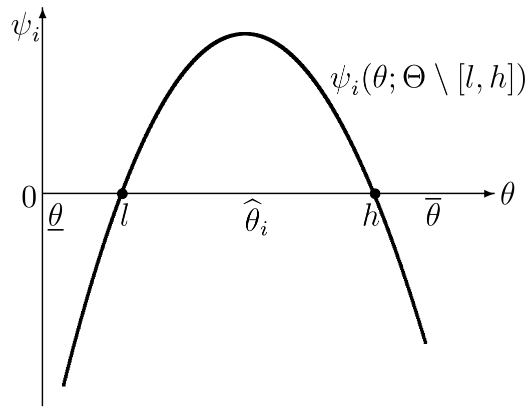


Figure 2: Sharing intermediate technologies in equilibrium

Below, I characterize a condition for the existence of such a selective sharing equilibrium when firms have identical technology distributions.

**Proposition 7** *Suppose that condition ($C_O$) holds with strict inequality, and the firms' technology distributions are identical. Then there are critical values $l^*$ and $h^*$, with $\underline{\theta} < l^* < \widehat{\theta}_i < h^* < \overline{\theta}$, such that for some $i, j = 1, 2$ with $i \neq j$ there exists an equilibrium with $\mathcal{S}_i = \Theta \backslash [l^*, h^*]$ and $\mathcal{S}_j = \Theta$.*

In other words, one of the firms has an incentive to share only intermediate technologies if the firms' technology distribution is skewed towards efficient technologies. In that case, the expropriation effect is relatively mild, and the signaling effect dominates for intermediate technologies.

Under the conditions of Proposition 7 there also exist equilibria with full concealment (Proposition 4), and full sharing by one of the firms (Proposition 5). However, Proposition 6 shows that in a symmetric model there exists no equilibrium in which one of the firms shares only its best technologies.

Finally, the results in this subsection are notably different from the existing results. For example, Jansen (2011) shows that in a model with one-sided asymmetric information, and an exogenous probability of imitation, there is no equilibrium in which the informed firm shares only intermediate technologies. This gives a contribution beyond endogenizing the identity of the firm that shares its technology. The introduction of two-sided asymmetric information generates a new equilibrium strategy.

# 5 Extensions

In this section, I extend the basic analysis by allowing firms to have non-identical technology distributions, by introducing weak protection of intellectual property, by allowing firms to precommit to technology-sharing rules, and by considering competition in prices instead of quantities.

## 5.1 Asymmetry

The previous equilibrium analysis was based on a model with identical firms. Here, I illustrate how the previous results rely on this assumption.

### 5.1.1 Non-existence of Equilibrium with Full Secrecy

First, an equilibrium without technology sharing may fail to exist if firms are sufficiently dissimilar, as the following proposition shows.

**Proposition 8** *There exists an equilibrium where both firms conceal all technologies (i.e., $\mathcal{S}_1 = \mathcal{S}_2 = \Theta$) if and only if condition ($C_S$) holds for $i, j \in \{1, 2\}$ and $i \neq j$, with $\widehat{\theta}_i$ as defined in equation (4.6).*

Although condition ($\mathrm{C}_S$) cannot be violated for more than one of the firms, it is violated whenever the firms' technology distributions are sufficiently dissimilar. For example, this happens if the distribution of firm $i$'s technology parameters is skewed towards inefficient technologies, while firm $j$'s distribution is non-skewed or skewed towards efficient technologies. In such a situation firm $i$ with technology $\widehat{\theta}_i$ has an incentive to unilaterally share its technology. Sharing the technology $\widehat{\theta}_i$ has only a limited expropriation effect, since the average efficiency of the competitor's technology does not differ much from $\widehat{\theta}_i$. However, technology sharing has a substantial signaling effect. Technology $\widehat{\theta}_i$ is far more efficient than firm $i$'s average technology if firm $i$'s prior distribution is skewed towards inefficient technologies. Therefore, sharing technology $\widehat{\theta}_i$ yields a drastic update of firm $j$'s beliefs about firm $i$'s efficiency, and a downward adjustment of firm $j$'s average output level.

An increase of the product substitutability, $\beta$, strengthens the signaling effect, which weakens a firm's incentive to keep its technology secret. This is reflected by the fact that condition ($C_S$) becomes more stringent after an increase of $\beta$, since $\widehat{\theta}_i$ is decreasing in $\beta$.

### 5.1.2 Existence of Equilibrium with Unilateral Full Sharing

Second, condition ($C_O$) does not require symmetry between firms, since it can hold in an asymmetric model. The condition only requires that a competitor's technology distribution is not skewed towards inefficient technologies. Hence, Proposition 5 does not rely on symmetry between the firms and holds for asymmetric firms too.

### 5.1.3 Existence of Equilibrium with Sharing of Intermediate Technologies

Third, I consider the situation where firms supply homogeneous goods (i.e., $\beta = 1$), and $\theta_j$ has a symmetric distribution on the interval $\Theta$, i.e., $E(\theta_j) = \widehat{\theta}_i = \frac{1}{2}(\underline{\theta} + \overline{\theta})$, and $f_j(\widehat{\theta}_i - \varepsilon) = f_j(\widehat{\theta}_i + \varepsilon)$ for any $\varepsilon \in [0, \frac{1}{2}(\overline{\theta} - \underline{\theta})]$. In this case the curve of $\psi_i$ is symmetric around $\theta_i = \widehat{\theta}_i$. Consequently, if an equilibrium exists in which firm $i$ shares selectively, then the interval of shared technologies is symmetric around $\widehat{\theta}_i$, i.e., $\mathcal{O}_i = [\widehat{\theta}_i - \varepsilon, \widehat{\theta}_i + \varepsilon]$ for some $\varepsilon \in [0, \frac{1}{2}(\overline{\theta} - \underline{\theta})]$. This observation simplifies the analysis of the technology-sharing incentives considerably.

**Proposition 9** *Suppose goods are homogeneous ($\beta = 1$), the distribution of $\theta_j$ is symmetric on $\Theta$, and condition ($C_S$) does not hold. Then there is a value $\varepsilon^*$, with $0 < \varepsilon^* < \frac{1}{2}(\overline{\theta} - \underline{\theta})$, such that there exists an equilibrium with $\mathcal{S}_i = \Theta \backslash [\widehat{\theta}_i - \varepsilon^*, \widehat{\theta}_i + \varepsilon^*]$ and $\mathcal{S}_j = \Theta$ for $i, j = 1, 2$ and $i \neq j$.*

In other words, if firm $i$'s cost distribution is sufficiently skewed towards inefficient technologies, while its rival's distribution is non-skewed, then firm $i$ has an incentive to share only intermediately efficient technologies in equilibrium. The intuition for the technology sharing incentives of intermediate types is similar to the intuition for the incentive to deviate from full secrecy (see subsection 5.1.1). Extreme types, e.g., $\theta_i \in \{\underline{\theta}, \overline{\theta}\}$, have an incentive to keep their technologies secret. First, firm $i$ with the least efficient technology, $\overline{\theta}$, has an incentive for secrecy, since technology sharing would yield a strategic loss (while expropriation is irrelevant). Second, the firm with the most efficient technology, $\underline{\theta}$, also has no incentive to share this technology. As shown in Proposition 5 with condition ($C_O$) binding, the signaling effect exactly offsets the expropriation effect for firm $i$ if firm $j$ would believe that a secretive firm $i$ has the least efficient technology, $\overline{\theta}$. Such an extreme belief is, however, inconsistent with selective technology sharing. Since the p.d.f. $f_i$ has full support on technology space $\Theta$, consistent beliefs would give a lower expected cost, i.e., $E\{\theta_i|\theta_i \notin [\widehat{\theta}_i - \varepsilon^*, \widehat{\theta}_i + \varepsilon^*]\} < \overline{\theta}$. Consequently, the equilibrium beliefs are such that the expropriation effect outweighs the signaling effect for firm $i$ with the most efficient technology.

Notice that under the assumptions of Proposition 9 there does not exist an equilibrium with full concealment, since the condition ($C_S$) is violated (see Proposition 8). On the other hand, for a symmetric distribution of $\theta_j$ and homogeneous goods ($\beta = 1$), the condition ($C_O$) is satisfied and binding. Therefore, there also exists an equilibrium with full sharing by firm $i$ (see Proposition 5).

#### 5.1.4 Existence of Equilibrium with Sharing of Best Technologies

Finally, I characterize conditions for the existence of an equilibrium in which a firm shares only its best technologies. Proposition 6 already shows that asymmetry is a necessary condition for the existence of such an equilibrium. The following lemma gives an additional necessary condition for existence.

**Lemma 1** *If there exists an equilibrium with $\mathcal{S}_i = (h^*, \overline{\theta}]$ and $\mathcal{S}_j = \Theta$ for some $\widehat{\theta}_i < h^* < \overline{\theta}$, then condition ($C_O$) holds.*

Hence, condition ($C_O$) is a necessary condition for the existence of such an equilibrium. Under this condition the expropriation effect is weak enough, and it may make the sharing of efficient technologies profitable. That is, whenever there is an equilibrium in which firm $i$ shares only its best technology draws, there also exists an equilibrium in which firm $i$ shares all technologies.

Finally, Proposition 10 gives specific, sufficient conditions for the existence of an equilibrium with sharing of only the best technologies by firm $i$.

**Proposition 10** *Suppose that condition ($C_O$) holds with strict inequality. Consider the critical value $\widetilde{\theta}$, with $\widehat{\theta}_i < \widetilde{\theta} < \overline{\theta}$, such that $\psi_i(\widetilde{\theta}; \mathcal{S}_i) = \psi_i(\underline{\theta}; \mathcal{S}_i)$, and a distribution $\widetilde{F}_i$ such that $\psi_i(\widetilde{\theta}; [\widetilde{\theta}, \overline{\theta}]) = 0$. Then for any distribution $G_i$ with $E_{G_i}\{\theta_i|\theta_i > \widetilde{\theta}\} \leq E_{\widetilde{F}_i}\{\theta_i|\theta_i > \widetilde{\theta}\}$, there is a critical value $h^*$, with $\widetilde{\theta} \leq h^* < \overline{\theta}$, such that there exists an equilibrium with $\mathcal{S}_i = (h^*, \overline{\theta}]$ and $\mathcal{S}_j = \Theta$.*

As before, condition ($C_O$) ensures that the expropriation effect is sufficiently weak. The restriction on the technology distribution $G_i$ simplifies as follows for an exponentially distributed technology. Suppose that firm $i$ draws its technology from $\Theta = [0, 1]$ by the truncated exponential distribution $F(\theta; \lambda_i) \equiv \left(1 - e^{-\lambda_i \theta}\right) / \left(1 - e^{-\lambda_i}\right)$ for $\lambda_i > 0$. The inverse hazard rate parameter, $\lambda_i$, measures the skewness of firm $i$'s distribution towards efficient technologies. Then the critical parameter value $\widetilde{\lambda}_i$ exists, with $0 < \widetilde{\lambda}_i < \infty$, such that $\psi_i(\widetilde{\theta}; [\widetilde{\theta}, \overline{\theta}]) = 0$ for $\lambda_i = \widetilde{\lambda}_i$. If $\lambda_i > \widetilde{\lambda}_i$, then the condition $E_{\lambda_i}\{\theta_i|\theta_i > h\} \leq E_{\widetilde{\lambda}_i}\{\theta_i|\theta_i > h\}$ is satisfied for all $h$.[13] In other words, for exponential distributions that are sufficiently skewed towards efficient technologies, the equilibrium condition on firm $i$'s distribution is satisfied.

#### 5.1.5 An Example

In this subsection, I illustrate the technology-sharing strategies for exponentially distributed cost parameters. I assume that the technology space is simply $\Theta = [0, 1]$, and goods are homogeneous (i.e., $\beta = 1$). The truncated exponential distribution function is $F(\theta; \lambda_i) \equiv \left(1 - e^{-\lambda_i \theta}\right) / \left(1 - e^{-\lambda_i}\right)$, and the corresponding density function is $f(\theta; \lambda_i) \equiv \lambda_i e^{-\lambda_i \theta} / \left(1 - e^{-\lambda_i}\right)$ for $\lambda_i > 0$, $\theta \in [0, 1]$, and $i = 1, 2$. The parameter $\lambda_i$ is a measure of the skewness of the distribution. For $\lambda_i \rightarrow 0$ this distribution converges to the uniform distribution, while an increase of $\lambda_i$ skews the distribution towards efficient technologies.

Figure 3 sketches regions which satisfy the equilibrium conditions of Propositions 8-10 for truncated exponential distributions. For the entire parameter space $(0, \infty)^2$ there always exists an equilibrium in which one of the firms shares all technologies. This follows from the fact that the strength of the expropriation effect is moderate, since the exponential distribution is skewed towards efficient technologies. The area N contains those parameter values for which both firms conceal all technologies in equilibrium. In this area the parameters $\lambda_i$ and $\lambda_j$ are of similar size. In area $\mathrm{B}_i$ there exists an equilibrium in which firm $i$ shares only its best technologies, for $i = 1, 2$. Here, the technology distribution of firm $i$ has relatively greater skewness towards efficient technologies. These parameter combinations correspond to asymmetric models, as Proposition 10 shows. Finally, numerical examples suggest that for parameter values in the areas $\mathrm{I}_i$ and N there exist equilibria in which firm $i$ shares only intermediate technologies, for $i = 1, 2$. Proposition 7 shows that such an equilibrium exists along the 45° line (i.e., for $\lambda_i = \lambda_j$ in area N). In addition, Proposition 9 shows that this equilibrium exists along the axis with $\lambda_j = 0$ (i.e., in area $\mathrm{I}_i$) for $j \neq i$. The example illustrates that there are many other situations where the strategy may be chosen in equilibrium.

[13] This follows from the fact that $E\{\theta_i|\theta_i > h\}$ is decreasing in $\lambda_i$ for any $h$, as can be easily shown.

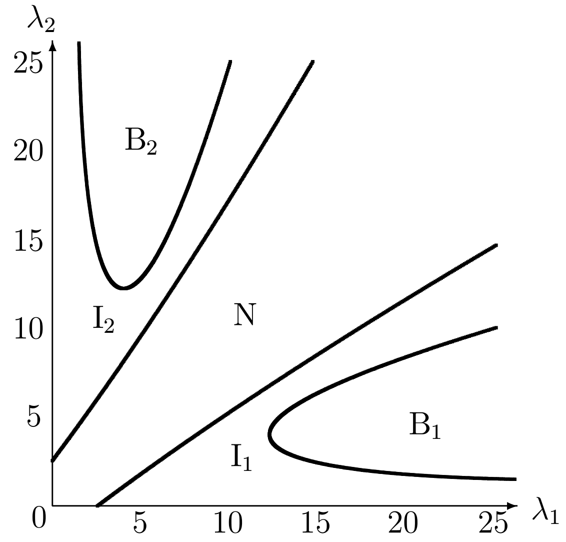


Figure 3: Strategic technology sharing (truncated exponential distributions)

## 5.2 Protection of Intellectual Property Rights

The analysis above assumes that there is no protection of intellectual property and imitation is costless. This is an extreme assumption which can be relaxed. The same qualitative results emerge in a model with sufficiently weak protection of intellectual property rights. However, for sufficiently strong intellectual property rights, the results are unlikely to hold.

Although there are many different ways to introduce imperfect protection of intellectual property rights, I adopt a very simple extension of the model to illustrate these claims. Firms interact in the following way. First, firms privately learn their technologies and simultaneously choose between sharing their technology or keeping it secret. Subsequently, a random draw determines the level of intellectual property protection. With probability $\gamma$, there is perfect protection of shared technologies, whereas there is no protection with probability $1-\gamma$, where $0 \leq \gamma \leq 1$. Thereby, the probability $\gamma$ stands for the strength of intellectual property protection. For $\gamma = 0$, there is no protection, and the previous analysis applies. Conversely, for $\gamma = 1$, there is perfect protection of intellectual property, which means that a competitor does not imitate a shared technology. Finally, firms simultaneously choose their output levels. To keep the analysis simple, I restrict attention to equilibria with extreme technology-sharing strategies. Either a firm shares all technologies or it shares nothing.

So far, I analyzed an extreme model in which intellectual property rights are absent (i.e., $\gamma = 0$). Now, I illustrate how a relaxation of this assumption affects the results (i.e., $\gamma > 0$). The protection of intellectual property rights weakens the expropriation effect, but it leaves the signaling effect unchanged.

First, I show that the results from Propositions 4 and 5 (as well as Proposition 8) extend to markets with weak protection of intellectual property rights.[14]

**Proposition 11** *There exists a critical probability $\gamma_0$ with $0 < \gamma_0 < 1$, such that for all $0 \leq \gamma \leq \gamma_0$:* ***(a)*** *there exists an equilibrium in which both firms conceal all technologies, if condition ($C_S$) holds with strict inequality for $i, j \in \{1, 2\}$ and $i \neq j$, with $\widehat{\theta}_i$ as defined in equation (4.6), and* ***(b)*** *there exists an equilibrium in which firm $i$ shares all technologies whereas firm $j$ conceals all technologies, if condition ($C_O$) holds.*

Second, if protection is sufficiently strong, then the equilibria from Proposition 11 no longer exist. A secretive firm has the incentive to unilaterally deviate by sharing some technologies. With strong protection, both firms share their technologies in equilibrium, as I show below.

**Proposition 12** *There exists a critical probability $\gamma_1$ with $0 < \gamma_1 < 1$, such that for all $\gamma_1 \leq \gamma \leq 1$ there exists an equilibrium in which both firms share all technologies.*

If intellectual property rights give perfect protection against imitation (i.e., $\gamma = 1$), then firms have an incentive to share all technologies (Okuno-Fujiwara *et al.*, 1990), since the expropriation effect disappears. Proposition 12 shows that the same equilibrium may emerge if intellectual property protection is sufficiently strong, but imperfect.

## 5.3 Precommitment to Share Technologies

So far, I assumed that a firm makes strategic technology-sharing decisions. This assumption is appropriate when the technology-sharing decision is a short-term decision (e.g., adopting a Berkeley open source license). However, there are cases in which long-term technology-sharing decision is more realistic (e.g., in case of adopting a GPL open source license). Therefore, I consider here the game in which the firms choose between technology sharing and secrecy before they learn the realization of their technologies.[15]

[14] An online Supplementary Appendix contains the proofs of Propositions 11-12.

[15] For example, Gal-Or (1986), and Shapiro (1986) also study models where firms precommit to disclose their technologies. These models can be interpreted as models with perfect protection of intellectual property (i.e., no imitation upon disclosure), whereas I study a model with no protection.

The proof of Proposition 2 has the following immediate implication.

**Corollary 1** *There exists no equilibrium in which both firms commit to share their technologies.*

**Proof.** If firm $j$ commits to share its technology, then $\Psi_i(\theta_i;\mathcal{S}_i,\emptyset) = E_j\{x_i^{oo}(\theta_i,\theta_j)^2 - x_i^{so}(\theta_i,\theta_j;\mathcal{S}_i)^2\}$, and equation (A.2) in the Appendix implies that firm $i$ prefers to commit to secrecy for any $i, j = 1, 2$ with $i \neq j$. ■

Given concealment by the competitor, firm $i$ expects the profit $E\{\Pi_i^o(\theta_i;\Theta)\}$ from committing to technology sharing, and $E\{\Pi_i^s(\theta_i;\Theta,\Theta)\}$ from committing to concealment, where $\Pi_i^o$ and $\Pi_i^s$ are defined in equations (4.1) and (4.2), respectively. Hence, firm $i$'s choice between committing to share or conceal its technologies depends on the sign of $E\{\Psi_i(\theta_i;\Theta,\Theta)\}$, with $\Psi_i$ as in equation (4.3). This gives the following immediate result.

**Corollary 2** *If condition ($C_S$) holds for all $i, j = 1, 2$ with $i \neq j$, then both firms commit to secrecy in the unique equilibrium.*

**Proof.** By Proposition 2, if firm $j$ commits to share its technology, then firm $i$ commits to secrecy, because $E\{\Psi_i(\theta_i;\Theta,\emptyset)\} < 0$. If firm $j$ commits to secrecy, then condition ($\mathrm{C}_S$) implies that $\Psi_i(\theta_i;\Theta,\Theta) \leq 0$ for all $\theta_i \in \Theta$, which gives $E\{\Psi_i(\theta_i;\Theta,\Theta)\} < 0$. Hence, under condition ($\mathrm{C}_S$), commitment to secrecy is the dominant strategy for a firm. ■

In other words, condition ($\mathrm{C}_S$) is a sufficient condition for the emergence of an equilibrium in which all technologies are kept secret. However, unlike the result in Proposition 8, the condition is not necessary for complete secrecy in equilibrium. A precommitting firm should be on average better off under technology concealment, whereas a strategic firm should prefer concealment for every possible technology realization. Clearly, the former requirement is weaker than the latter, which gives a greater incentives to precommit to technology concealment.

Figure 4 sketches the result of Corollary 2 for truncated exponential distributions (i.e., $F(\theta;\lambda_i) \equiv \left(1 - e^{-\lambda_i\theta}\right) / \left(1 - e^{-\lambda_i}\right)$ with $\lambda_i > 0$ and $\theta \in [0, 1]$ for $i = 1, 2$), a demand intercept of $\alpha = 4$, and homogeneous goods ($\beta = 1$). For parameter values in area $\mathrm{O}_i$, firm $i$ precommits to share its technologies while firm $j$ precommits to conceal in equilibrium for $i, j \in \{1, 2\}$ and $i \neq j$. For intermediate parameter values between the two bold lines (i.e., areas $\mathrm{N}_1^c$-N-$\mathrm{N}_2^c$), both firms commit to keep their technologies secret in equilibrium. As in Figure 3, only for parameter values between the thin lines (area N), there exists an equilibrium in which strategic firms conceal all technologies. Clearly, for the parameter values between the bold and thin lines (areas $N_1^c$ and $N_2^c$), precommitting firms conceal in equilibrium, but there exists no equilibrium in which two strategic firms conceal all technologies.

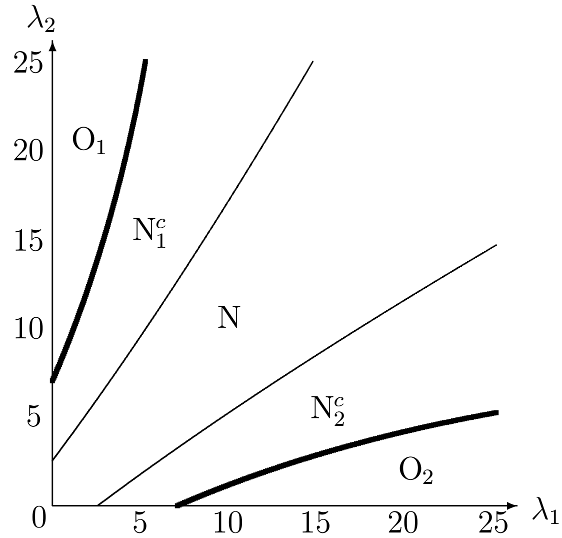


Figure 4: Commitment to share technologies (truncated exponential distributions)

In Figure 4, a precommitting firm does not share its technology in all the cases where a strategic firm would share. In the game with commitment, an equilibrium with technology sharing only exists for parameter values in the areas $O_i$ and $O_j$. By contrast, with strategic sharing, an equilibrium with technology sharing exists for all positive $(\lambda_i, \lambda_j)$. However, it is unclear whether this holds in general. On the one hand, precommitting firms could have weaker technology-sharing incentives, since unraveling does not occur with non-strategic choices (i.e., skeptical beliefs are inconsistent with precommitment strategies). On the other hand, precommitting firms could have stronger incentives to share all technologies, since they only need to be made better off on average, and not for all technology realizations.

## 5.4 Bertrand Competition

What role does the mode of product market competition play for the incentives to share technologies?

With Cournot competition, a firm with an efficient technology trades off a positive signaling effect against a negative expropriation effect. Although the signaling effect gives the firm an incentive to share its technology, the expropriation effect gives a disincentive to share. An improvement of a Cournot competitor's technology (i.e., a draw of a lower $\theta_i$ for firm $i$) makes both effects stronger. My paper shows that this may yield technology-sharing incentives which are non-monotonic in the technology's efficiency.

With Bertrand competition, firms base their technology-sharing choices on a trade-off between expropriation and signaling effects too. Expropriation has a similar effect on a Bertrand competitor as on a Cournot competitor. If a competitor imitates a firm's technology, this gives the competitor an incentive to choose a lower price and thereby become a more "aggressive" price competitor. This reduces the firm's profit. Yet, the signaling effect for a price competitor differs from the signaling effect for a quantity competitor. With Cournot competition, a firm would like to make its competitor believe that it is a tough competitor in the product market. By doing so, the competitor chooses a low output level, and this is profitable for the firm. By contrast, with Bertrand competition, a firm is better off if its competitor believes the firm is a friendly price competitor. In this way, the competitor sets a high price, which is beneficial for the firm.

For costs which are lower than expected, the signaling effect reinforces the expropriation effect for a Bertrand competitor. Therefore, a Bertrand competitor has no incentive to share a technology which is more efficient than expected. For less efficient technologies, there is a conflict between the signaling and expropriation effects. Expropriation makes it costly to share an inefficient technology, but signaling makes technology sharing beneficial. A less efficient technology (i.e., a higher draw of $\theta_i$) yields a weaker expropriation effect and a stronger signaling effect. This observation suggests that the incentive of a Bertrand competitor to share its technology is monotonic in the technology's efficiency. The higher is the cost $\theta_i$, the stronger is the incentive of firm $i$ to share this technology. This suggests that a Bertrand competitor has an incentive to share inefficient technologies but keep efficient technologies secret. Interestingly, firms do not choose such a strategy in equilibrium with Cournot competition (Proposition 1).

# 6 Conclusion

In this paper, I characterized the conditions under which firms share their technologies in the absence of intellectual property rights. The paper finds conditions on the technology distributions for the emergence of competition between an open and a proprietary technology standard. Coexistence between open and proprietary technologies may emerge endogenously in equilibrium of a symmetric model. Further, there may exist equilibria in which one of the firms shares selectively by sharing only intermediate technologies. These results cannot be obtained in models with one-sided asymmetric information. Herein lies the paper's contribution.

In particular, for firms with identical technology distributions, there exist three kinds of equilibrium strategies. First, there always exists an equilibrium in which both firms conceal their technologies. Second, if the distributions are sufficiently skewed towards efficient technologies, there also exist equilibria in which one firm shares all technologies. Finally, for such skewed distributions there exist also equilibria in which one firm shares intermediate technologies while all other technologies are kept secret. For firms with different technology distributions, an additional kind of strategy may be chosen in equilibrium. In such an equilibrium, one firm shares only its best technologies while all other technologies are concealed.

Firms in this paper choose their technology-sharing strategies simultaneously. In alternative settings, a firm may respond to its competitor's shared technology by choosing its technology-sharing strategy conditional on the shared technology. It could be interesting to compare the paper's equilibria with the equilibria that emerge in a model with sequential technology-sharing choices. The paper's analysis has an important implication for the equilibria of such a model. By applying the logic of Propositions 2-3, it is likely that at most one firm shares its technology along any equilibrium path. The best response of a follower to a shared technology of a leader may be to adopt secrecy. A more detailed characterization of equilibrium strategies awaits future research.

The paper considers perfectly substitutable technologies, as many other related papers do (e.g., Anton and Yao, 2003-4, Gill, 2008, Jansen, 2006, 2011). The introduction of slight imperfections in substitutability would not affect the qualitative results. However, in the absence of substitutability, the results are different. In the extreme, where technologies are perfect complements, firms can produce at the worst available efficiency level (not the best). For example, a firm with technology $\theta_i$ obtains technology $\max\{\theta_i, \theta_j\}$ if its competitor shares technology $\theta_j$, and it obtains $\overline{\theta}$ if the competitor conceals its technology. Firms with perfectly complementary technologies conceal all technologies in the unique equilibrium. First, if a firm's competitor shares its technology, then the firm faces a trade-off between expropriation and signaling.

As in the model with perfectly substitutable technologies, the expropriation effect dominates in this situation. Second, if the competitor keeps its technology secret, then technology sharing has no signaling effect. Unilateral technology sharing enables the competitor to improve its technology (from $\overline{\theta}$ to $\max\{\theta_i, \theta_j\}$), while the sharing firm remains with technology $\overline{\theta}$. By contrast, with perfectly substitutable technologies there is a trade-off between the two opposing effects in this case. It could be interesting to study the technology-sharing strategies between the extremes of perfect substitutability and perfect complementarity.

This analysis may have implications for the incentives of firms to invest in research and development (R&D). The technology distribution has been assumed to be exogenous. In practice, however, a firm may affect the technology distribution by investing in R&D. Suppose that a firm can change the skewness of the technology distribution through an investment in R&D. The more the firm invests, the more the distribution becomes skewed towards the efficient technology. In this case, a unilateral increase of the firm's investment does not only have the direct effect of increasing the firm's expected efficiency. It also may change the technology-sharing incentives of the firm's rival in the product market. In particular, an investment increase may give a greater incentive to the rival to share its technology. This indirect effect may interact in an interesting way with the direct effect of R&D investments. Further analysis of this interaction awaits future research.[16]

[16] For this and other extensions, it may be useful to consider the model with a discrete technology space (i.e., $\Theta = \{\theta^1, \theta^2, \theta^3\}$) and densities (i.e., $p_i^1, p_i^2, p_i^3$ for firm $i$). An online Supplementary Appendix characterizes the necessary and sufficient equilibrium conditions in such a discrete model. There, I discuss the conditions in detail for symmetric models (i.e., $p_1^m = p_2^m$ for all $m$), and for models in which one firm has uniformly distributed technologies (i.e., $p_j^m = \frac{1}{3}$ for all $m$).

# A Appendix

This Appendix provides proofs to the propositions.

## Proof of Proposition 1

Suppose there does exist an equilibrium with $\mathcal{S}_i = [\underline{\theta}, l]$ for some $\underline{\theta} < l < \overline{\theta}$. Then firm $i$ prefers to hide technologies close to $\overline{\theta}$, since evaluating $\Psi_i$ in (4.3) at $\theta_i = \overline{\theta}$ gives:

$$\begin{aligned}\Psi_i(\overline{\theta}; [\underline{\theta}, l], \mathcal{S}_j) \equiv & \int_{\theta_j \in \mathcal{O}_j} \left[x_i^{oo}(\overline{\theta}, \theta_j)^2 - x_i^{so}(\overline{\theta}, \theta_j; [\underline{\theta}, l])^2\right] dF_j(\theta_j) \\ & + \Pr[\theta_j \in \mathcal{S}_j] \left[x_i^{os}(\overline{\theta}; \mathcal{S}_j)^2 - x_i^{ss}(\overline{\theta}; [\underline{\theta}, l], \mathcal{S}_j)^2\right] < 0,\end{aligned}$$

since each term is negative. In particular,

$$x_i^{oo}(\overline{\theta}, \theta_j) - x_i^{so}(\overline{\theta}, \theta_j; [\underline{\theta}, l]) = -\frac{\beta^2}{2}[\theta_j - E(\min\{\theta_i, \theta_j\} | \theta_i \leq l, \theta_j)] \leq 0$$

with a strict inequality for any $\theta_j > \underline{\theta}$ and $\underline{\theta} < l < \overline{\theta}$, and

$$x_i^{os}(\overline{\theta}; \mathcal{S}_j) - x_i^{ss}(\overline{\theta}; [\underline{\theta}, l], \mathcal{S}_j) = \frac{-\beta^2 \left[\overline{\theta} - E\{\theta_i | \theta_i \leq l\}\right]}{2(4 - \beta^2)} < 0$$

for any $\underline{\theta} < l < \overline{\theta}$, and $\mathcal{S}_j \subseteq \Theta$. This gives a contradiction. □

## Proof of Proposition 2

The proof takes two steps. First, I find a necessary condition under which firm $i$ shares only the technologies $\theta_i \in [l, h]$ in equilibrium, with $\underline{\theta} \leq l < h \leq \overline{\theta}$.

**Lemma 2** *If firm $i$ has beliefs consistent with $s_j$ for some $\mathcal{S}_j \subseteq \Theta$, and it chooses $s_i$ with $\mathcal{O}_i = [l, h]$ in equilibrium, with $\underline{\theta} \leq l < h \leq \overline{\theta}$, then for all $\theta_i' \in [l, h]$:*

$$E_j \left(\min\{\theta_i', \theta_j\} | \theta_j \in \mathcal{S}_j\right) - E\{\theta_j | \theta_j \in \mathcal{S}_j\} + \frac{\beta}{2}\left[E\{\theta_i | \theta_i \notin [l, h]\} - \theta_i'\right] > 0. \qquad \text{(A.1)}$$

**Proof.** The expected profit gain for firm $i$ of sharing technology $\theta_i$, $\Psi_i(\theta_i; \mathcal{S}_i, \mathcal{S}_j)$ for any sets $\mathcal{S}_i, \mathcal{S}_j \subseteq \Theta$, is defined in equation (4.3). The first term of equation (4.3) is non-positive, since for any $\theta_i$ and $\theta_j$:

$$\begin{aligned}x_i^{oo}(\theta_i, \theta_j) - x_i^{so}(\theta_i, \theta_j; \mathcal{S}_i) = & \frac{-\beta}{4 - \beta^2}\Bigg(\theta_j - \min\{\theta_i, \theta_j\} \\ & - \frac{\beta}{2}\left[E_i \left(\min\{\theta_i, \theta_j\} | \theta_i \in \mathcal{S}_i\right) - \min\{\theta_i, \theta_j\}\right]\Bigg) \\ \leq & \frac{-\beta(1 - \frac{1}{2}\beta)}{4 - \beta^2}\Big(\theta_j - \min\{\theta_i, \theta_j\}\Big) \leq 0 \qquad \text{(A.2)}\end{aligned}$$

Therefore, any expected gain from sharing a technology is created by the second term of equation (4.3). A necessary condition for sharing technologies in $[l, h]$ by firm $i$, with beliefs consistent with secrecy of technologies in $\mathcal{S}_j \subseteq \Theta$, is that the second term of $\Psi_i(\theta_i; \Theta \backslash [l, h], \mathcal{S}_j)$ in equation (4.3) is positive for $\theta'_i \in [l, h]$. This necessary condition reduces to $x_i^{os}(\theta'_i; \mathcal{S}_j) > x_i^{ss}(\theta'_i; \Theta \backslash [l, h], \mathcal{S}_j)$, which is equivalent to equation (A.1). ■

Notice that (A.1) reduces to $\Upsilon_i(\theta'_i) > 0$ for $\theta'_i \in [l, h]$ with:

$$\Upsilon_i(\theta'_i) \equiv -[1 - F_j(\theta'_i|\theta_j \in \mathcal{S}_j)] \left(E\{\theta_j|\theta_j > \theta'_i, \theta_j \in \mathcal{S}_j\} - \theta'_i\right) + \frac{\beta}{2} \left[E\{\theta_i|\theta_i \notin [l, h]\} - \theta'_i\right] \tag{A.3}$$

Second, I show that the necessary condition (A.1) implies that firm $j$ has no incentive to share any technology.

**Lemma 3** *If condition (A.1) holds for $\theta'_i \in [l, h]$, and firm $j$ has beliefs consistent with $s_i$ for $\mathcal{O}_i = [l, h]$, then firm $j$ does not share any technology in equilibrium (i.e., $\mathcal{S}_j = \Theta$).*

**Proof.** The expected profit gain of firm $j$ from sharing the technology $\theta_j$ is $\Psi_j(\theta_j; \mathcal{S}_j, \Theta \backslash [l, h])$ as defined in equation (4.3). The firm can only have an incentive to share a technology $\theta_j$ if the second term of $\Psi_j(\theta_j; \mathcal{S}_j, \Theta \backslash [l, h])$ is positive. (The first term is negative due to (A.2) for firm $j$.) This second term is positive if $x_j^{os}(\theta_j; \Theta \backslash [l, h]) > x_j^{ss}(\theta_j; \mathcal{S}_j, \Theta \backslash [l, h])$, which reduces to $\Upsilon_j(\theta_j) > 0$, where:

$$\Upsilon_j(\theta_j) \equiv \frac{\beta}{2} \left[E\{\theta_j|\theta_j \in \mathcal{S}_j\} - \theta_j\right] - E_i\left(\theta_i - \min\{\theta_i, \theta_j\}|\, \theta_i \notin [l, h]\right) \tag{A.4}$$

with

$$E_i\left(\theta_i - \min\{\theta_i, \theta_j\}\,|\theta_i \notin [l, h]\right) = \begin{cases} \int_{\underline{\theta}_j}^{l} \frac{(\theta - \theta_j) f_i(\theta)}{F_i(l) + 1 - F_i(h)} d\theta + \int_h^{\overline{\theta}} \frac{(\theta - \theta_j) f_i(\theta)}{F_i(l) + 1 - F_i(h)} d\theta, & \text{if } \theta_j < l \\ \int_{\max\{\theta_j, h\}}^{\overline{\theta}} \frac{(\theta - \theta_j) f_i(\theta)}{F_i(l) + 1 - F_i(h)} d\theta, & \text{if } \theta_j \geq l \end{cases}$$

The function $\Upsilon_j(\theta_j)$ is continuous in $\theta_j$. Moreover, it is concave in $\theta_j$, since:

$$\frac{\partial}{\partial \theta_j} E_i\left(\theta_i - \min\{\theta_i, \theta_j\}\,|\theta_i \notin [l, h]\right) = \begin{cases} -\left(1 - \frac{F_i(\theta_j)}{F_i(l) + 1 - F_i(h)}\right), & \text{if } \theta_j < l \\ -\left(\frac{1 - F_i(\max\{\theta_j, h\})}{F_i(l) + 1 - F_i(h)}\right), & \text{if } \theta_j \geq l \end{cases}$$

and therefore $\frac{\partial^2}{\partial \theta_j^2} E_i\left(\theta_i - \min\{\theta_i, \theta_j\}\,|\theta_i \notin [l, h]\right) \geq 0$ for all $\theta_j$. The function reaches a global maximum for $\theta_j = \widetilde{\theta}$, with $\underline{\theta} < \widetilde{\theta} < \overline{\theta}$, since it is concave with $\Upsilon'_j(\underline{\theta}) = 1 - \frac{\beta}{2} > 0$ and $\Upsilon'_j(\overline{\theta}) = -\frac{\beta}{2} < 0$. I distinguish two cases.

**(a)** If $\frac{\beta}{2}F_i(l) \leq (1-\frac{\beta}{2})[1-F_i(h)]$, then $\Upsilon_j'(h) \geq 0$ and therefore $\widetilde{\theta} \geq h$ with $\frac{1-F_i(\widetilde{\theta})}{F_i(l)+1-F_i(h)} = \frac{\beta}{2}$. In that case, for any $\theta_i' \in [l,h]$ the following holds:

$$
\begin{aligned}
\Upsilon_j(\widetilde{\theta}) &= \frac{\beta}{2}\left[E\{\theta_j|\theta_j \in \mathcal{S}_j\} - \widetilde{\theta}\right] - \int_{\widetilde{\theta}}^{\overline{\theta}} \frac{(\theta-\widetilde{\theta})f_i(\theta)}{F_i(l)+1-F_i(h)}d\theta \\
&= \frac{\beta}{2}\left(\left[E\{\theta_j|\theta_j \in \mathcal{S}_j\} - \widetilde{\theta}\right] - \int_{\widetilde{\theta}}^{\overline{\theta}} \frac{(\theta-\widetilde{\theta})f_i(\theta)}{1-F_i(\widetilde{\theta})}d\theta\right) \\
&= \frac{\beta}{2}\left(E\{\theta_j|\theta_j \in \mathcal{S}_j\} - E\{\theta_i|\theta_i > \widetilde{\theta}\}\right) \\
&< \frac{\beta}{2}\left(E_j\left(\min\{\theta_i', \theta_j\}|\theta_j \in \mathcal{S}_j\right) + \frac{\beta}{2}\left[E\{\theta_i|\theta_i \notin [l,h]\} - \theta_i'\right] - E\{\theta_i|\theta_i > \widetilde{\theta}\}\right) \\
&\leq \frac{\beta}{2}\left(\frac{\beta}{2}E\{\theta_i|\theta_i \notin [l,h]\} + \left(1-\frac{\beta}{2}\right)\theta_i' - E\{\theta_i|\theta_i > \widetilde{\theta}\}\right) < 0.
\end{aligned}
$$

The first inequality follows from (A.1). The observation $E_j\left(\min\{\theta_i', \theta_j\}|\theta_j \in \mathcal{S}_j\right) \leq \theta_i'$ gives the second inequality. The last inequality follows from $E\{\theta_i|\theta_i \notin [l,h]\} = \frac{F_i(l)}{F_i(l)+1-F_i(h)}E\{\theta_i|\theta_i \leq l\} + \frac{1-F_i(h)}{F_i(l)+1-F_i(h)}E\{\theta_i|\theta_i > h\} \leq E\{\theta_i|\theta_i > h\} \leq E\{\theta_i|\theta_i > \widetilde{\theta}\}$ and $\theta_i' \leq h \leq \widetilde{\theta} < E\{\theta_i|\theta_i > \widetilde{\theta}\}$.

**(b)** If $\frac{\beta}{2}F_i(l) > (1-\frac{\beta}{2})[1-F_i(h)]$, then $\Upsilon_j(l) < 0$ and therefore $\frac{F_i(\widetilde{\theta})}{F_i(l)+1-F_i(h)} = 1-\frac{\beta}{2}$ and $\widetilde{\theta} < l$. Then for any $\theta_i' \in [l,h]$ the following holds:

$$
\begin{aligned}
\Upsilon_j(\widetilde{\theta}) &= \frac{\beta}{2}\left[E\{\theta_j|\theta_j \in \mathcal{S}_j\} - \widetilde{\theta}\right] - \int_{\widetilde{\theta}}^{l} \frac{(\theta-\widetilde{\theta})f_i(\theta)}{F_i(l)+1-F_i(h)}d\theta - \int_{h}^{\overline{\theta}} \frac{(\theta-\widetilde{\theta})f_i(\theta)}{F_i(l)+1-F_i(h)}d\theta \\
&= \frac{\beta}{2}E\{\theta_j|\theta_j \in \mathcal{S}_j\} - \int_{\widetilde{\theta}}^{l} \frac{\theta f_i(\theta)}{F_i(l)+1-F_i(h)}d\theta - \int_{h}^{\overline{\theta}} \frac{\theta f_i(\theta)}{F_i(l)+1-F_i(h)}d\theta \\
&= \frac{\beta}{2}E\{\theta_j|\theta_j \in \mathcal{S}_j\} + \left(1-\frac{\beta}{2}\right)E\{\theta_i|\theta_i \leq \widetilde{\theta}\} - E\{\theta_i|\theta_i \notin [l,h]\} \\
&< \frac{\beta}{2}\left(E_j\left(\min\{\theta_i', \theta_j\}|\theta_j \in \mathcal{S}_j\right) + \frac{\beta}{2}\left[E\{\theta_i|\theta_i \notin [l,h]\} - \theta_i'\right]\right) \\
&\quad + \left(1-\tfrac{\beta}{2}\right)E\{\theta_i|\theta_i \leq \widetilde{\theta}\} - E\{\theta_i|\theta_i \notin [l,h]\} \\
&= \frac{\beta}{2}\left[E_j\left(\min\{\theta_i', \theta_j\}|\theta_j \in \mathcal{S}_j\right) - \theta_i'\right] + \left(1-\frac{\beta}{2}\right)\left[E\{\theta_i|\theta_i \leq \widetilde{\theta}\} - \theta_i'\right] \\
&\quad - \left[1-\left(\frac{\beta}{2}\right)^2\right]\left[E\{\theta_i|\theta_i \notin [l,h]\} - \theta_i'\right]
\end{aligned}
$$

$$
\begin{aligned}
&= \frac{\beta}{2} F_j(\theta_i'|\theta_j \in \mathcal{S}_j)\left[E\{\theta_j|\theta_j \le \theta_i', \theta_j \in \mathcal{S}_j\} - \theta_i'\right] + \left(1 - \frac{\beta}{2}\right)\left[E\{\theta_i|\theta_i \le \widetilde{\theta}\} - \theta_i'\right] \\
&\quad - \left[1 - \left(\frac{\beta}{2}\right)^2\right]\left[E\{\theta_i|\theta_i \notin [l,h]\} - \theta_i'\right] \\
&< 0.
\end{aligned}
$$

The first inequality follows from the necessary condition (A.1). The last inequality follows from the facts that $E\{\theta_j|\theta_j \le \theta_i', \theta_j \in \mathcal{S}_j\} \le \theta_i'$, from $E\{\theta_i|\theta_i \le \widetilde{\theta}\} < \widetilde{\theta} < l \le \theta_i'$, and from the observation that $\Upsilon_i(\theta_i') > 0$ in (A.3) implies $E\{\theta_i|\theta_i \notin [l,h]\} \ge \theta_i'$, since $E\{\theta_j|\theta_j > \theta_i', \theta_j \in \mathcal{S}_j\} \ge \theta_i'$ and $F_j(\theta_i'|\theta_j \in \mathcal{S}_j) \le 1$.

Cases **(a)** and **(b)** imply that there exists no technology which firm $j$ wants to share, since $\Upsilon_j(\theta_j) \le \Upsilon_j(\widetilde{\theta}) < 0$ for all $\theta_j$, and any $[l,h]$ and $\mathcal{S}_j$. Hence, the only equilibrium strategy that exists for firm $j$ is to conceal all technologies. ■

## Proof of Proposition 3

If firm $j$ keeps any technology secret (i.e., $\mathcal{S}_j = \Theta$), then $\Psi_i(\theta_i; \mathcal{S}_i, \Theta) = x_i^{os}(\theta_i; \mathcal{S}_j)^2 - x_i^{ss}(\theta_i; \mathcal{S}_i, \mathcal{S}_j)^2$. The sign of $\Psi_i(\theta_i; \mathcal{S}_i, \Theta)$ is equal to the sign of:

$$
\begin{aligned}
x_i^{os}(\theta_i; \mathcal{S}_j) - x_i^{ss}(\theta_i; \mathcal{S}_i, \Theta) &= \frac{\beta}{4-\beta^2}\left(E_j\left(\min\{\theta_i, \theta_j\}\right) - E\{\theta_j\} + \frac{\beta}{2}\left[E\{\theta_i|\theta_i \in \mathcal{S}_i\} - \theta_i\right]\right) \\
&= \frac{\beta}{4-\beta^2}\psi_i(\theta_i, \mathcal{S}_i),
\end{aligned}
$$

where equation (4.4) defines the function $\psi_i$. As $\psi_i$ is concave in $\theta_i$ for any $\mathcal{S}_i$, there exist bounds $l_i$ and $h_i$, with $\underline{\theta} \le l_i \le h_i \le \overline{\theta}$, such that firm $i$ shares technologies in $[l_i, h_i]$ whereas it conceals technologies $\Theta \backslash [l_i, h_i]$ in equilibrium. □

## Proof of Proposition 4

The proof is omitted, since it follows immediately from the argument in the text.

## Proof of Proposition 5

Suppose firm $j$ has skeptical beliefs, i.e., $E(\theta_i|\theta_i \in \mathcal{S}_i) = \overline{\theta}$ or $\mathcal{S}_i = \{\overline{\theta}\}$. Firm $i$ has no incentive to conceal information, given skeptical beliefs, if $\psi_i(\theta_i; \{\overline{\theta}\}) \ge 0$ for all $\theta_i$, where $\psi_i$ is defined in equation (4.4). Concavity of $\psi_i$ in $\theta_i$ reduces the equilibrium condition to $\min\{\psi_i(\underline{\theta}; \{\overline{\theta}\}), \psi_i(\overline{\theta}; \{\overline{\theta}\})\} \ge 0$. This inequality is satisfied if and only if ($\mathrm{C}_O$) holds, since $\psi_i(\underline{\theta}; \{\overline{\theta}\}) = -(E\{\theta_j\} - \underline{\theta}) + \frac{\beta}{2}\left(\overline{\theta} - \underline{\theta}\right)$ and $\psi_i(\overline{\theta}; \{\overline{\theta}\}) = 0$. Finally, Proposition 2 shows that firm $j$ conceals all $\theta_j$ in equilibrium. □

## Proof of Proposition 6

Take any $h^*$ in the interior of $\Theta$, and suppose that firms have identical distributions (i.e., $F_i(\theta) = F(\theta)$ for all $i$). If there would exist an equilibrium with $\mathcal{S}_i = [h^*, \overline{\theta}]$, then Proposition 2 implies that firm $j$ conceals all technologies (i.e., $\mathcal{S}_j = \Theta$) in equilibrium. Hence, the following conditions would be necessary for the existence of the equilibrium. **(i)** $\psi_i(h^*; [h^*, \overline{\theta}]) = 0$, and **(ii)** $\psi_i(\underline{\theta}; [h^*, \overline{\theta}]) \geq 0$. Using symmetry, condition **(i)** gives:

$$\begin{aligned} \psi_i(h^*; [h^*, \overline{\theta}]) &= \frac{\beta}{2}\left[E\{\theta_i|\theta_i > h^*\} - h^*\right] - [1 - F_j(h^*)](E\{\theta_j|\theta_j > h^*\} - h^*) \\ &= \left(\frac{\beta}{2} - [1 - F(h^*)]\right)\left[E\{\theta|\theta > h^*\} - h^*\right] = 0 \end{aligned}$$

This equality can only hold for $h^* = \widehat{\theta}_i$ $(\equiv F^{-1}(1 - \frac{\beta}{2}))$. However, $\psi_i(\widehat{\theta}_i; [\widehat{\theta}_i, \overline{\theta}]) = 0$ implies $\psi_i(\theta; [\widehat{\theta}_i, \overline{\theta}]) < 0$ for all $\theta \neq \widehat{\theta}_i$, since $\psi_i(\theta_i; \cdot)$ reaches the global maximum at $\widehat{\theta}_i$, which means that condition **(ii)** cannot be satisfied. □

## Proof of Proposition 7

Under the proposition's conditions there should exist values $l^*$ and $h^*$, with $\underline{\theta} < l^* < \widehat{\theta}_i < h^* < \overline{\theta}$, such that (i) $\psi_i(l^*; \Theta \backslash [l^*, h^*]) = \psi_i(h^*; \Theta \backslash [l^*, h^*])$ and (ii) $\psi_i(h^*; \Theta \backslash [l^*, h^*]) = 0$. Now, if condition ($\mathrm{C}_O$) holds strictly, then $\psi_i(\underline{\theta}; \mathcal{S}_i) > \psi_i(\overline{\theta}; \mathcal{S}_i)$ for any $\mathcal{S}_i$. The properties of $\psi_i$ imply the existence of $\widetilde{\theta} \in (\widehat{\theta}_i, \overline{\theta})$ such that $\psi_i(\underline{\theta}; \cdot) = \psi_i(\widetilde{\theta}; \cdot)$.

First, condition (i) implicitly defines a decreasing, continuous function $\widetilde{l} : [\widehat{\theta}_i, \widetilde{\theta}] \rightarrow [\underline{\theta}, \widehat{\theta}_i]$ with $\widetilde{l}(\widehat{\theta}_i) = \widehat{\theta}_i$ and $\widetilde{l}(\widetilde{\theta}) = \underline{\theta}$.

Second, condition (ii) implicitly defines the continuous function $\widehat{l} : [\widehat{\theta}_i, \widetilde{\theta}] \rightarrow [\underline{\theta}, \widehat{\theta}_i]$. This follows from observing that (under symmetry) for any $h \in [\widehat{\theta}_i, \widetilde{\theta}]$:

$$\psi_i(h; \Theta \backslash [\widehat{\theta}_i, h]) \leq 0 \leq \psi_i(h; \Theta \backslash [\underline{\theta}, h]),$$

where the first inequality follows from:

$$
\begin{aligned}
\psi_i(h;\Theta\backslash[\widehat{\theta}_i,h]) &= \frac{\beta}{2}\left[E\{\theta_i|\theta_i\notin[\widehat{\theta}_i,h]\}-h\right]-[1-F_j(h)](E\{\theta_j|\theta_j>h\}-h)\\
&= \frac{\beta}{2}\cdot\frac{F(\widehat{\theta})}{F(\widehat{\theta})+1-F(h)}\left(E\{\theta|\theta\leq\widehat{\theta}\}-h\right)\\
&\quad +[1-F(h)]\left(\frac{\beta/2}{F(\widehat{\theta})+1-F(h)}-1\right)(E\{\theta|\theta>h\}-h)\\
&= \frac{\beta}{2}\cdot\frac{-F(\widehat{\theta})}{F(\widehat{\theta})+1-F(h)}\left(h-E\{\theta|\theta\leq\widehat{\theta}\}\right)\\
&\quad -[1-F(h)]\frac{1-\beta+1-F(h)}{F(\widehat{\theta})+1-F(h)}(E\{\theta|\theta>h\}-h)\leq 0,
\end{aligned}
$$

and the second inequality follows from:

$$
\begin{aligned}
\psi_i(h;\Theta\backslash[\underline{\theta},h]) &= \frac{\beta}{2}[E\{\theta_i|\theta_i>h]\}-h]-[1-F_j(h)](E\{\theta_j|\theta_j>h\}-h)\\
&= \left[F(h)-\left(1-\frac{\beta}{2}\right)\right](E\{\theta|\theta>h]\}-h)\geq 0.
\end{aligned}
$$

Application of the intermediate value theorem gives the existence of $\widehat{l}(h)\in[\underline{\theta},\widehat{\theta}_i]$ such that $\psi_i(h;\Theta\backslash[\widehat{l}(h),h])=0$. In particular, the function $\widehat{l}$ has the extreme values: $\widehat{l}(\widehat{\theta}_i)=\underline{\theta}$ and $\underline{\theta}<\widehat{l}(\widetilde{\theta})<\widehat{\theta}_i$.

In summary, conditions (i) and (ii) define the continuous functions $\widetilde{l},\widehat{l}:[\widehat{\theta}_i,\widetilde{\theta}]\rightarrow[\underline{\theta},\widehat{\theta}_i]$, with $\widetilde{l}(\widehat{\theta}_i)>\widehat{l}(\widehat{\theta}_i)$ and $\widetilde{l}(\widetilde{\theta})<\widehat{l}(\widetilde{\theta})$. Hence, the intermediate value theorem implies that there exists a $h^*$, with $\widehat{\theta}_i<h^*<\widetilde{\theta}$, such that $\widetilde{l}(h^*)=\widehat{l}(h^*)$. After defining $l^*\equiv\widetilde{l}(h^*)$, it follows that: $\psi_i(l^*;\Theta\backslash[l^*,h^*])=\psi_i(h^*;\Theta\backslash[l^*,h^*])=0$.

Finally, Proposition 2 shows that firm $j$ keeps all $\theta_j\in\Theta$ secret in equilibrium. □

## Proof of Proposition 8

Assume that firm $j$ conceals all technologies, i.e., $\mathcal{S}_j=\Theta$, and firm $j$ has beliefs consistent with full concealment by firm $i$, i.e., $\mathcal{S}_i=\Theta$, for $i,j=1,2$ with $i\neq j$. Then, firm $i$ keeps all technologies secret if and only if $\psi_i(\theta_i;\Theta)\leq 0$ for all $\theta_i$, where $\psi_i$ is defined in equation (4.4). As $\psi_i$ reaches a global maximum at $\theta_i=\widehat{\theta}_i$ as defined in equation (4.6), the equilibrium condition is met for all $\theta_i$ if and only if $\psi_i(\widehat{\theta}_i;\Theta)\leq 0$. By equations (4.4) and (4.6), this condition yields condition ($C_S$). □

## Proof of Proposition 9

Suppose that firms hold beliefs consistent with the technology-sharing strategy in the proposition, i.e., $\mathcal{S}_i = [\underline{\theta}, \widehat{\theta}_i - \varepsilon) \cup (\widehat{\theta}_i + \varepsilon, \overline{\theta}]$, and $\mathcal{S}_j = \Theta$ with $E(\theta_j) = \widehat{\theta}_i$. The perfect substitutability of goods and symmetry of firm $j$'s technology distribution imply symmetry of $\psi_i$ around $\theta_i = \widehat{\theta}_i$, i.e., $\psi_i(\widehat{\theta}_i - \varepsilon; \mathcal{S}_i) = \psi_i(\widehat{\theta}_i + \varepsilon; \mathcal{S}_i)$ for all $\varepsilon \in [0, \frac{1}{2}(\overline{\theta} - \underline{\theta})]$ and any $\mathcal{S}_i$.

Define the continuous function $\widehat{\psi} : [0, \frac{1}{2}(\overline{\theta} - \underline{\theta})] \to \mathbb{R}$ as follows:

$$\widehat{\psi}(\varepsilon) \equiv \psi_i(\widehat{\theta}_i + \varepsilon; \Theta \backslash [\widehat{\theta}_i - \varepsilon, \widehat{\theta}_i + \varepsilon]).$$

Notice that an equilibrium condition for selective technology sharing by firm $i$ is: $\widehat{\psi}(\varepsilon^*) = 0$ for $0 < \varepsilon^* < \frac{1}{2}(\overline{\theta} - \underline{\theta})$. The violation of condition (C$_S$) implies that $\widehat{\psi}(0) > 0$. Application of the De L'Hospital rule gives:

$$\begin{aligned}
\lim_{\varepsilon \uparrow \frac{1}{2}(\overline{\theta} - \underline{\theta})} E\{\theta_i | \theta_i \notin [\widehat{\theta}_i - \varepsilon, \widehat{\theta}_i + \varepsilon]\} &= \lim_{\varepsilon \uparrow \frac{1}{2}(\overline{\theta} - \underline{\theta})} \frac{\int_{\underline{\theta}}^{\widehat{\theta}_i - \varepsilon} f_i(\theta)\theta d\theta + \int_{\widehat{\theta}_i + \varepsilon}^{\overline{\theta}} f_i(\theta)\theta d\theta}{F_i(\widehat{\theta}_i - \varepsilon) + 1 - F_i(\widehat{\theta}_i + \varepsilon)} \\
&= \lim_{\varepsilon \uparrow \frac{1}{2}(\overline{\theta} - \underline{\theta})} \frac{-f_i(\widehat{\theta}_i - \varepsilon)(\widehat{\theta}_i - \varepsilon) - f_i(\widehat{\theta}_i + \varepsilon)(\widehat{\theta}_i + \varepsilon)}{-f_i(\widehat{\theta}_i - \varepsilon) - f_i(\widehat{\theta}_i + \varepsilon)} \\
&= \frac{f_i(\underline{\theta})}{f_i(\underline{\theta}) + f_i(\overline{\theta})}\underline{\theta} + \frac{f_i(\overline{\theta})}{f_i(\underline{\theta}) + f_i(\overline{\theta})}\overline{\theta} < \overline{\theta}.
\end{aligned}$$

Hence, $\lim_{\varepsilon \uparrow \frac{1}{2}(\overline{\theta} - \underline{\theta})} \widehat{\psi}(\varepsilon) < 0$. The intermediate value theorem implies that there exists an $\varepsilon^*$, with $0 < \varepsilon^* < \frac{1}{2}(\overline{\theta} - \underline{\theta})$, such that $\widehat{\psi}(\varepsilon^*) = 0$.

Finally, Proposition 2 shows that firm $j$ keeps all $\theta_j \in \Theta$ secret in equilibrium. □

## Proof of Lemma 1

For any $h^*$, with $\widehat{\theta}_i < h^* < \overline{\theta}$, a necessary condition for the existence of an equilibrium with $\mathcal{S}_i = [h^*, \overline{\theta}]$ and $\mathcal{S}_j = \Theta$ is that $\psi_i(\underline{\theta}; [h^*, \overline{\theta}]) \geq 0 > \psi_i(\overline{\theta}; [h^*, \overline{\theta}])$, where $\psi_i$ is defined in equation (4.4). If (C$_O$) is violated, then $\psi_i(\underline{\theta}; \mathcal{S}_i) < \psi_i(\overline{\theta}; \mathcal{S}_i)$ for any $\mathcal{S}_i$, and the equilibrium condition cannot be satisfied. □

## Proof of Proposition 10

For some $h^*$, with $\widehat{\theta}_i < h^* < \overline{\theta}$, there exists an equilibrium with $\mathcal{S}_i = [h^*, \overline{\theta}]$ and $\mathcal{S}_j = \Theta$, if (4.7) holds for $h = h^*$. The conditions in (4.7) can be written as $\widetilde{\psi}(h^*; F_i) = 0$ and $\underline{\psi}(h^*; F_i) \geq 0$ for the following continuous functions:

$$\widetilde{\psi}(x; F_i) \equiv \psi_i(x; [x, \overline{\theta}]) = \frac{\beta}{2}\left[E\{\theta_i | \theta_i > x\} - x\right] - [1 - F_j(x)](E\{\theta_j | \theta_j > x\} - x)$$

$$\underline{\psi}(x;F_i) \equiv \psi_i(\underline{\theta};[x,\overline{\theta}]) = \frac{\beta}{2}E\{\theta_i|\theta_i > x\} + \left(1-\frac{\beta}{2}\right)\underline{\theta} - E\{\theta_j\}$$

Notice that if ($\mathrm{C}_O$) holds strictly, then $\psi_i(\underline{\theta};\mathcal{S}_i) > \psi_i(\overline{\theta};\mathcal{S}_i)$ for any $\mathcal{S}_i$. Hence, there exists a $\widetilde{\theta}$, with $\widehat{\theta}_i < \widetilde{\theta} < \overline{\theta}$, such that $\psi_i(\widetilde{\theta};\mathcal{S}_i) = \psi_i(\underline{\theta};\mathcal{S}_i)$ for any $\mathcal{S}_i$. Take a distribution $\widetilde{F}_i$ such that $\psi_i(\widetilde{\theta};[\widetilde{\theta},\overline{\theta}]) = 0$.[17] Clearly, for distributions $\widetilde{F}_i$ and $F_j$ there exists an equilibrium with $\mathcal{S}_i = [\widetilde{\theta},\overline{\theta}]$ and $\mathcal{S}_j = \Theta$, since $\underline{\psi}(\widetilde{\theta};\widetilde{F}_i) = \widetilde{\psi}(\widetilde{\theta};\widetilde{F}_i) = 0$.

Now take any distribution function $G_i$, with $E_{G_i}\{\theta_i|\theta_i > \widetilde{\theta}\} \leq E_{\widetilde{F}_i}\{\theta_i|\theta_i > \widetilde{\theta}\}$. For this distribution $\underline{\psi}(\widetilde{\theta};G_i) \leq 0 < \underline{\psi}(\overline{\theta};G_i)$, where the first inequality follows from $\underline{\psi}(\widetilde{\theta};G_i) \leq \underline{\psi}(\widetilde{\theta};\widetilde{F}_i) = 0$ and the second inequality follows from ($\mathrm{C}_O$). Hence, there exists some $\theta_o$, with $\widetilde{\theta} \leq \theta_o < \overline{\theta}$, such that $\underline{\psi}(\theta_o;G_i) = 0$ and $\underline{\psi}(\theta;G_i) > 0$ for all $\theta > \theta_o$. Further,

$$\begin{aligned}
\widetilde{\psi}(\theta_o;G_i) &= \underline{\psi}(\theta_o;G_i) + E\{\theta_j\} - \left(1-\frac{\beta}{2}\right)\underline{\theta} - \frac{\beta}{2}\theta_o - [1-F_j(\theta_o)](E\{\theta_j|\theta_j > \theta_o\} - \theta_o) \\
&= E\{\theta_j\} - \left(1-\frac{\beta}{2}\right)\underline{\theta} - \frac{\beta}{2}\theta_o - [1-F_j(\theta_o)](E\{\theta_j|\theta_j > \theta_o\} - \theta_o) \\
&\leq E\{\theta_j\} - \left(1-\frac{\beta}{2}\right)\underline{\theta} - \frac{\beta}{2}\widetilde{\theta} - [1-F_j(\widetilde{\theta})](E\{\theta_j|\theta_j > \widetilde{\theta}\} - \widetilde{\theta}) \\
&= \underline{\psi}(\widetilde{\theta};\widetilde{F}_i) + E\{\theta_j\} - \left(1-\frac{\beta}{2}\right)\underline{\theta} - \frac{\beta}{2}\widetilde{\theta} - [1-F_j(\widetilde{\theta})](E\{\theta_j|\theta_j > \widetilde{\theta}\} - \widetilde{\theta}) \\
&= \widetilde{\psi}(\widetilde{\theta};\widetilde{F}_i) = 0
\end{aligned}$$

where the inequality follows from the observation that the function $H(x) \equiv \frac{\beta}{2}x + [1 - F_j(x)](E\{\theta_j|\theta_j > x\} - x)$ is increasing in $x$ for all $x > \widehat{\theta}_i$ (since $H'(x) = F_j(x) - (1-\frac{\beta}{2})$), and the fact that $\theta_o \geq \widetilde{\theta}$.

Also notice that $\widetilde{\psi}(\overline{\theta};G_i) = 0$, and $\lim_{\theta\uparrow\overline{\theta}} d\widetilde{\psi}(\theta;G_i)/dx < 0$, since the first derivative of this function equals:

$$\begin{aligned}
\frac{d\widetilde{\psi}(x;G_i)}{dx} &= \frac{\beta}{2}\left(\frac{d}{dx}E\{\theta_i|\theta_i > x\} - 1\right) - \frac{d}{dx}\Big([1-F_j(x)](E\{\theta_j|\theta_j \geq x\} - x)\Big) \\
&= \frac{\beta}{2}\left(\frac{g_i(x)}{1-G_i(x)}\left[E\{\theta_i|\theta_i > x\} - x\right] - 1\right) + 1 - F_j(x)
\end{aligned}$$

and its limit for $x$ approaching $\overline{\theta}$ equals:

$$\lim_{x\uparrow\overline{\theta}} \frac{d\widetilde{\psi}(x;G_i)}{dx} = \frac{\beta}{2}\left(g_i(\overline{\theta})\lim_{x\uparrow\overline{\theta}}\frac{E\{\theta_i|\theta_i > x\} - x}{1-G_i(x)} - 1\right) = \frac{-\beta}{4}$$

[17] That is, $\widetilde{F}_i$ is such that: $\frac{\beta}{2}E_{\widetilde{F}_i}\{\theta_i|\theta_i > \widetilde{\theta}\} = \frac{\beta}{2}\widetilde{\theta} + [1-F_j(\widetilde{\theta})](E\{\theta_j|\theta_j > \widetilde{\theta}\} - \widetilde{\theta})$.

since (by applying De L'Hospital rule)

$$\begin{aligned}\lim_{x\uparrow\overline{\theta}}\frac{E\{\theta_i|\theta_i>x\}-x}{1-G_i(x)} &= \lim_{x\uparrow\overline{\theta}}\frac{g_i(x)\frac{E\{\theta_i|\theta_i>x\}-x}{1-G_i(x)}-1}{-g_i(x)}=\frac{1}{g_i(\overline{\theta})}-\lim_{x\uparrow\overline{\theta}}\frac{E\{\theta_i|\theta_i>x\}-x}{1-G_i(x)}\\ &\Rightarrow \lim_{x\uparrow\overline{\theta}}\frac{E\{\theta_i|\theta_i>x\}-x}{1-G_i(x)}=\frac{1}{2g_i(\overline{\theta})}.\end{aligned}$$

Hence, $\widetilde{\psi}(\theta_i;G_i)>0$ for technologies $\theta_i$ close to $\overline{\theta}$.

In summary, $\widetilde{\psi}(\theta_o;G_i)\le 0<\widetilde{\psi}(\overline{\theta}-\varepsilon;G_i)$ for small $\varepsilon>0$ and $\underline{\psi}(\theta;G_i)\ge 0$ for all $\theta\ge\theta_o$. The intermediate value theorem implies that there exists an $h^*$, with $\theta_o\le h^*<\overline{\theta}$, such that $\widetilde{\psi}(h^*;G_i)=0$. Hence, $h^*$ satisfies the equilibrium conditions. Finally, Proposition 2 shows that firm $j$ keeps all $\theta_j\in\Theta$ secret in equilibrium. □

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# Share to Scare: Technology Sharing in the Absence of Strong Intellectual Property Rights

Jos Jansen
Aarhus University

April 2023

# Supplementary Appendix: not for publication

## B Extension with random protection of IP

Here, I derive equilibrium output levels and technology-sharing choices in a market where there is full protection of intellectual property rights with probability $1-\gamma$ and no protection with probability $\gamma$. The equilibrium output levels in the market without protection are equations (3.1), (3.4), (3.5), and (3.7).

With full protection, each firm produces with its own technology (i.e., $\theta_i$ for firm $i$ with $i = 1, 2$), regardless of the technology-sharing choices. Then, technology sharing only results in sharing information about the technology's efficiency. The firms choose the following output levels. If both firms share their technologies, then the firms have complete information. In equilibrium, firm $i$ with technology $\theta_i$ chooses the following output level if its competitor has technology $\theta_j$ (for $i, j = 1, 2$ with $i \neq j$):[18]

$$x_i^{pp}(\theta_i, \theta_j) = \frac{(2-\beta)\alpha - 2\theta_i + \beta\theta_j}{4-\beta^2}. \tag{B.1}$$

If firm $i$ shares its technology, $\theta_i$, but firm $j$ keeps its technology $\theta_j$ secret (for $i, j = 1, 2$ with $i \neq j$), then they choose the following output levels in equilibrium:

$$x_i^{ps}(\theta_i; \mathcal{S}_j) = \frac{1}{4-\beta^2}\Bigg((2-\beta)\alpha - 2\theta_i + \beta E\{\theta_j | \theta_j \in \mathcal{S}_j\}\Bigg), \tag{B.2}$$

$$x_j^{sp}(\theta_j, \theta_i; \mathcal{S}_j) = \frac{(2-\beta)\alpha - 2\theta_j + \beta\theta_i}{4-\beta^2} + \frac{\beta^2}{2}\cdot\frac{\theta_j - E\{\theta_j | \theta_j \in \mathcal{S}_j\}}{4-\beta^2}. \tag{B.3}$$

Finally, firm $i$ chooses the equilibrium output level $x_i^{ss}(\theta_i; \mathcal{S}_i, \mathcal{S}_j)$ in equation (3.7) if both firms keep their technologies secret. These output levels determine the expected equilibrium profits in a market with perfect protection of intellectual property.

[18] Superscript $p$ indicates technology sharing with a perfectly protected technology. As before, superscript $s$ indicates a technology which is kept secret.

## Proof of Proposition 11

**(a)** Assume that both firms have prior beliefs about their competitor's technology if this technology is kept secret, i.e., $\mathcal{S}_1 = \mathcal{S}_2 = \Theta$. Given secrecy by competitor $j$, firm $i$'s expected equilibrium profit from keeping technology $\theta_i$ secret is (for $i, j = 1, 2$ with $i \neq j$): $\Pi_i^{ss}(\theta_i; \Theta, \Theta) = x_i^{ss}(\theta_i; \Theta, \Theta)^2$. The unilateral deviation from full secrecy by the firm yields the expected profit: $\Pi_i^{ps}(\theta_i; \Theta, \Theta) = \gamma x_i^{ps}(\theta_i; \Theta, \Theta)^2 + (1-\gamma) x_i^{os}(\theta_i; \Theta, \Theta)^2$. The firms adopt full secrecy in equilibrium if $\Pi_i^{ss}(\theta_i; \Theta, \Theta) \geq \Pi_i^{ps}(\theta_i; \Theta, \Theta)$ holds for all $\theta_i$ and $i = 1, 2$. The equilibrium condition can be written as follows:

$$\begin{aligned}
&\gamma \left[x_i^{ss}(\theta_i; \Theta, \Theta)^2 - x_i^{ps}(\theta_i; \Theta, \Theta)^2\right] + (1-\gamma) \left[x_i^{ss}(\theta_i; \Theta, \Theta)^2 - x_i^{os}(\theta_i; \Theta, \Theta)^2\right] \geq 0 \\
&\gamma \left[x_i^{ss}(\theta_i; \Theta, \Theta) - x_i^{ps}(\theta_i; \Theta, \Theta)\right]\left[x_i^{ss}(\theta_i; \Theta, \Theta) + x_i^{ps}(\theta_i; \Theta, \Theta)\right] \\
&\qquad + (1-\gamma) \left[x_i^{ss}(\theta_i; \Theta, \Theta) - x_i^{os}(\theta_i; \Theta, \Theta)\right]\left[x_i^{ss}(\theta_i; \Theta, \Theta) + x_i^{os}(\theta_i; \Theta, \Theta)\right] \geq 0
\end{aligned}$$

where

$$\begin{aligned}
x_i^{ss}(\theta_i; \Theta, \Theta) - x_i^{ps}(\theta_i; \Theta, \Theta) &= \frac{\beta^2}{2} \cdot \frac{\theta_i - E\{\theta_i\}}{4 - \beta^2} \\
x_i^{ss}(\theta_i; \Theta, \Theta) - x_i^{os}(\theta_i; \Theta, \Theta) &= \frac{-\beta}{4 - \beta^2} \psi_i(\theta_i, \Theta).
\end{aligned}$$

The equilibrium condition is linear in protection probability $\gamma$ for any technology $\theta_i$. In particular, if $\gamma = 1$, then the condition does not hold, because $x_i^{ss}(\theta_i; \Theta, \Theta) < x_i^{ps}(\theta_i; \Theta, \Theta)$ for all $\theta_i < E\{\theta_i\}$. Conversely, if $\gamma = 0$ and condition ($C_S$) holds with strict inequality, then $\Pi_i^{ss}(\theta_i; \Theta, \Theta) > \Pi_i^{ps}(\theta_i; \Theta, \Theta)$ for all $\theta_i$, because then $\psi_i(\theta_i, \Theta) < 0$ for all $\theta_i$. Due to continuity (linearity) in $\gamma$, there exists a critical probability $\gamma_0^a$ with $0 < \gamma_0^a < 1$ such that $\Pi_i^{ss}(\theta_i; \Theta, \Theta) \geq \Pi_i^{ps}(\theta_i; \Theta, \Theta)$ holds for all $\theta_i$, if $0 \leq \gamma \leq \gamma_0^a$.

**(b)** Take some $i, j = 1, 2$ with $i \neq j$. Assume that firm $i$ has prior beliefs about firm $j$'s technology, i.e., $\mathcal{S}_j = \Theta$, whereas firm $j$ has skeptical beliefs, i.e., $\mathcal{S}_i = \{\overline{\theta}\}$.

First, I consider the incentives of firm $i$ to unilaterally share its technology. Given secrecy by competitor $j$, sharing technology $\theta_i$ yields the expected equilibrium profit $\Pi_i^{ps}(\theta_i; \{\overline{\theta}\}, \Theta) = \gamma x_i^{ps}(\theta_i; \{\overline{\theta}\}, \Theta)^2 + (1-\gamma) x_i^{os}(\theta_i; \{\overline{\theta}\}, \Theta)^2$ for firm $i$. If firm i deviates unilaterally by keeping technology $\theta_i$ secret, it earns the expected profit: $\Pi_i^{ss}(\theta_i; \{\overline{\theta}\}, \Theta) = x_i^{ss}(\theta_i; \{\overline{\theta}\}, \Theta)^2$. The firm has no deviation incentive if $\Pi_i^{ps}(\theta_i; \{\overline{\theta}\}, \Theta) \geq \Pi_i^{ss}(\theta_i; \{\overline{\theta}\}, \Theta)$ holds for all $\theta_i$. The condition can be written as follows:

$$\gamma \left[x_i^{ps}(\theta_i; \{\overline{\theta}\}, \Theta)^2 - x_i^{ss}(\theta_i; \{\overline{\theta}\}, \Theta)^2\right] + (1-\gamma) \left[x_i^{os}(\theta_i; \{\overline{\theta}\}, \Theta)^2 - x_i^{ss}(\theta_i; \{\overline{\theta}\}, \Theta)^2\right] \geq 0$$

$$\Leftrightarrow \quad \gamma\frac{\beta^2}{2}\cdot\frac{\overline{\theta}-\theta_i}{4-\beta^2}\gamma\left[x_i^{ps}(\theta_i;\{\overline{\theta}\},\Theta)+x_i^{ss}(\theta_i;\{\overline{\theta}\},\Theta)\right]$$
$$+(1-\gamma)\beta\frac{\psi_i(\theta_i,\{\overline{\theta}\})}{4-\beta^2}\left[x_i^{os}(\theta_i;\{\overline{\theta}\},\Theta)+x_i^{ss}(\theta_i;\{\overline{\theta}\},\Theta)\right]\geq 0.$$

The condition holds if $\psi_i(\theta_i,\{\overline{\theta}\})\geq 0$ for all $\theta_i$, which is the case if condition ($C_O$) holds.

Second, I consider the incentives of firm $j$ to keep its technology secret, given firm $i$ shares all technologies. The firm expects to earn the profit $\Pi_j^{sp}(\theta_j;\Theta)=\gamma E_j\{x_j^{sp}(\theta_j,\theta_i;\Theta)^2\}+(1-\gamma)E_i\{x_j^{so}(\theta_j,\theta_i;\Theta)^2\}$ from keeping the technology $\theta_j$ secret, whereas it earns $\Pi_j^{pp}(\theta_j)=\gamma E_i\{x_j^{pp}(\theta_j,\theta_i)^2\}+(1-\gamma)E_i\{x_j^{oo}(\theta_j,\theta_i)^2\}$ from sharing its technology. Firm $j$ adopts full secrecy if $\Pi_j^{sp}(\theta_j;\Theta)\geq\Pi_j^{pp}(\theta_j)$ for all $\theta_j$, which yields:

$$\gamma E_i\{x_j^{sp}(\theta_j,\theta_i;\Theta)^2-x_j^{pp}(\theta_j,\theta_i)^2\}+(1-\gamma)E_i\{x_j^{so}(\theta_j,\theta_i;\Theta)^2-x_j^{oo}(\theta_j,\theta_i)^2\}\geq 0$$
$$\Leftrightarrow \quad \gamma E_i\left\{\left[x_j^{sp}(\theta_j,\theta_i;\Theta)-x_j^{pp}(\theta_j,\theta_i)\right]\left[x_j^{sp}(\theta_j,\theta_i;\Theta)+x_j^{pp}(\theta_j,\theta_i)\right]\right\}$$
$$+(1-\gamma)E_i\left\{\left[x_j^{so}(\theta_j,\theta_i;\Theta)-x_j^{oo}(\theta_j,\theta_i)\right]\left[x_j^{so}(\theta_j,\theta_i;\Theta)+x_j^{oo}(\theta_j,\theta_i)\right]\right\}\geq 0.$$

The left hand side of the inequality is continuous (linear) in $\gamma$. If $\gamma=1$, then the inequality does not hold for any $\theta_j<E\{\theta_j\}$, because:

$$x_j^{sp}(\theta_j,\theta_i;\Theta)-x_j^{pp}(\theta_j,\theta_i)=\frac{\beta^2}{2(4-\beta^2)}\left[\theta_j-E\{\theta_j\}\right].$$

If $\gamma=0$, then the inequality holds for all $\theta_j$, because $x_j^{so}(\theta_j,\theta_i;\Theta)\geq x_j^{oo}(\theta_j,\theta_i)$ by equation (A.2). If $0<\gamma<1$, then the inequality holds for all $\theta_j\geq E\{\theta_j\}$. Conversely, for all $\theta_j<E\{\theta_j\}$, $E_i\left\{\left[x_j^{sp}(\theta_j,\theta_i;\Theta)-x_j^{pp}(\theta_j,\theta_i)\right]\left[x_j^{sp}(\theta_j,\theta_i;\Theta)+x_j^{pp}(\theta_j,\theta_i)\right]\right\}<0$ and it is finite, whereas $E_i\left\{\left[x_j^{so}(\theta_j,\theta_i;\Theta)-x_j^{oo}(\theta_j,\theta_i)\right]\left[x_j^{so}(\theta_j,\theta_i;\Theta)+x_j^{oo}(\theta_j,\theta_i)\right]\right\}>0$ and it is finite. Hence, there exists a critical probability $\gamma_0^b$, with $0<\gamma_0^b<1$, such that $\Pi_j^{sp}(\theta_j;\Theta)\geq\Pi_j^{pp}(\theta_j)$ for all $\theta_j$ if $0\leq\gamma\leq\gamma_0^b$.

Finally, define $\gamma_0\equiv\min\{\gamma_0^a,\gamma_0^b\}$. This completes the proof. □

## Proof of Proposition 12

Assume that both firms have skeptical beliefs about their competitor's technology if it is kept secret, i.e., $\mathcal{S}_i=\{\overline{\theta}\}$ for $i=1,2$. For $i,j=1,2$ with $i\neq j$, if firm $j$ shares all technologies, firm $i$'s expected profit from sharing technology $\theta_i$ is as follows:

$$\Pi_i^{pp}(\theta_i)=\gamma E_j\{x_i^{pp}(\theta_i,\theta_j)^2\}+(1-\gamma)E_j\{x_i^{oo}(\theta_i,\theta_j)^2\}.$$

The expected profit from unilateral deviation by keeping the technology secret is as follows:

$$\Pi_i^{sp}(\theta_i;\{\overline{\theta}\}) = \gamma E_j\{x_i^{sp}(\theta_i,\theta_j;\{\overline{\theta}\})^2\} + (1-\gamma)E_j\{x_i^{so}(\theta_i,\theta_j;\{\overline{\theta}\})^2\}.$$

In equilibrium, both firms share all technologies if $\Pi_i^{pp}(\theta_i) - \Pi_i^{sp}(\theta_i;\{\overline{\theta}\}) \geq 0$ for all $\theta_i$ and $i = 1, 2$. The inequality can be written as follows:

$$\begin{aligned}
&\gamma E_j\{x_i^{pp}(\theta_i,\theta_j)^2 - x_i^{sp}(\theta_i,\theta_j;\{\overline{\theta}\})^2\} + (1-\gamma)E_j\{x_i^{oo}(\theta_i,\theta_j)^2 - x_i^{so}(\theta_i,\theta_j;\{\overline{\theta}\})^2\} \geq 0\\
&\gamma E_j\{\left[x_i^{pp}(\theta_i,\theta_j) - x_i^{sp}(\theta_i,\theta_j;\{\overline{\theta}\})\right]\left[x_i^{pp}(\theta_i,\theta_j) + x_i^{sp}(\theta_i,\theta_j;\{\overline{\theta}\})\right]\}\\
&\qquad + (1-\gamma)E_j\{\left[x_i^{oo}(\theta_i,\theta_j) - x_i^{so}(\theta_i,\theta_j;\{\overline{\theta}\})\right]\left[x_i^{oo}(\theta_i,\theta_j) + x_i^{so}(\theta_i,\theta_j;\{\overline{\theta}\})\right]\} \geq 0,
\end{aligned}$$

where for all $\theta_i, \theta_j \in \Theta$, the equilibrium output differences are

$$x_i^{pp}(\theta_i,\theta_j) - x_i^{sp}(\theta_i,\theta_j;\{\overline{\theta}\}) = \frac{\beta^2}{2}\cdot\frac{\overline{\theta}-\theta_i}{4-\beta^2} \geq 0, \text{ and} \tag{B.4}$$

$$x_i^{oo}(\theta_i,\theta_j) - x_i^{so}(\theta_i,\theta_j;\{\overline{\theta}\}) = -\beta\frac{\theta_j - \min\{\theta_i,\theta_j\}}{2(2+\beta)} \leq 0. \tag{B.5}$$

These inequalities imply that the expected equilibrium profit difference $\Pi_i^{pp}(\theta_i) - \Pi_i^{sp}(\theta_i;\{\overline{\theta}\})$ is increasing in $\gamma$ for all $\theta_i$. If $\gamma = 1$, then $\Pi_i^{pp}(\theta_i) - \Pi_i^{sp}(\theta_i;\{\overline{\theta}\}) \geq 0$ for all $\theta_i \in \Theta$. Although the term $E_j\{x_i^{oo}(\theta_i,\theta_j)^2 - x_i^{so}(\theta_i,\theta_j;\{\overline{\theta}\})^2\}$ is increasing in $\theta_i$, the term $E_j\{x_i^{pp}(\theta_i,\theta_j)^2 - x_i^{sp}(\theta_i,\theta_j;\{\overline{\theta}\})^2\}$ is decreasing in $\theta_i$. As the partial derivative of $E_j\{x_i^{oo}(\theta_i,\theta_j)^2 - x_i^{so}(\theta_i,\theta_j;\{\overline{\theta}\})^2\}$ with respect to $\theta_i$ is finite, there exists a critical value $0 < \gamma_1 < 1$ such that $\Pi_i^{pp}(\theta_i) - \Pi_i^{sp}(\theta_i;\{\overline{\theta}\})$ is decreasing in $\theta_i$ for all $\gamma_1 \leq \gamma \leq 1$. Finally, $\Pi_i^{pp}(\overline{\theta}) - \Pi_i^{sp}(\overline{\theta};\{\overline{\theta}\}) = 0$ for all probabilities $\gamma$, because equations (B.4) and (B.5) yield $x_i^{pp}(\overline{\theta},\theta_j) - x_i^{sp}(\overline{\theta},\theta_j;\{\overline{\theta}\}) = x_i^{oo}(\overline{\theta},\theta_j) - x_i^{so}(\overline{\theta},\theta_j;\{\overline{\theta}\}) = 0$. Hence, $\Pi_i^{pp}(\overline{\theta}) - \Pi_i^{sp}(\overline{\theta};\{\overline{\theta}\}) \geq 0$ for all $\gamma_1 \leq \gamma \leq 1$. This completes the proof. $\square$

# C Model with Discrete Types

Consider the model with three discrete types, i.e., $\theta_i \in \{\theta^1, \theta^2, \theta^3\}$ with $\theta^1 \geq 0$ and $\theta^k - \theta^{k-1} = \Delta > 0$ for $k = 2, 3$ and $i = 1, 2$. I define the probability $p_i^m \equiv \Pr[\theta_i = \theta^m]$, where $p_i^m > 0$ and $p_i^1 + p_i^2 + p_i^3 = 1$ for $m \in \{1, 2, 3\}$ and $i = 1, 2$. This is the simplest setting in which all the equilibria of the model with a continuum of types can emerge.

In this model the expected effect from expropriation of technology $\theta_i = \theta^m$ equals:

$$E\left(\theta_j - \min\{\theta^m,\theta_j\}\right) = \sum_{k=m}^{3}\Pr[\theta_j = \theta^k]\left(\theta^k - \theta^m\right)$$

for $m \in \{1, 2, 3\}$ and $j = 1, 2$. Consequently, the function $\psi_i(\theta; x)$, as defined in (4.4), for $\theta = \theta^m$ can be written as follows:

$$\psi_i^d(\theta^m; \mathcal{S}_i) \equiv \frac{\beta}{2} \left(E\{\theta_i | \theta_i \in \mathcal{S}_i\} - \theta^m\right) - \sum_{k=m}^{3} p_j^k \left(k - m\right) \Delta, \tag{C.1}$$

with $m \in \{1, 2, 3\}$ and $i, j = 1, 2$ (with $i \neq j$). Notice that firm $i$ with the worst technology does never strictly prefer to share its technology, i.e., $\psi_i^d(\theta^3; \mathcal{S}_i) \leq 0$ for any $\mathcal{S}_i$. Therefore, I restrict attention to the more efficient technologies $\theta^1$ and $\theta^2$ when I derive conditions for the existence of equilibria.

In particular, I illustrate the equilibrium conditions by looking into two specific cases. First, I consider the symmetric model with *ex ante* identical firms (i.e., $p_i^m = p^m$ for all $i$ and $m$). Second, I characterize the equilibria in the case where one of the firms has a uniform technology distribution (e.g., $p_2^m = \frac{1}{3}$ for all $m$).

**Share nothing:** For $\mathcal{S}_i = \{\theta^1, \theta^2, \theta^3\}$, the expected cost of firm $i$ can be written as $E(\theta_i) = p_i^1\theta^1 + (1 - p_i^1 - p_i^3)\theta^2 + p_i^3\theta^3 = \theta^2 + (p_i^3 - p_i^1)\Delta$. Firms have no incentive to share their technologies, iff $\psi_i^d(\theta^m; \{\theta^1, \theta^2, \theta^3\}) \leq 0$ for $m = 1, 2$ and all $i$, which gives:

$$\begin{aligned} \frac{\beta}{2}\left[2 - m + p_i^3 - p_i^1\right]\Delta \quad &\leq \quad \sum_{k=m}^{3} p_j^k \left(k - m\right)\Delta \text{ for } m = 1, 2 \\ \Leftrightarrow \quad &\frac{\beta}{2}\left(1 - p_i^1 + p_i^3\right) \leq \min\left\{1 - p_j^1, \frac{\beta}{2}\right\} + p_j^3 \end{aligned} \tag{C.2}$$

for $i, j = 1, 2$ and $i \neq j$. As before, if the firms' technology distributions do not differ dramatically, then there is an equilibrium in which both firms keep their technologies secret.

First, in the case where firms are identical (i.e., $p_i^m = p^m$ for all $i$ and all $m$), an equilibrium in which both firms share nothing always exists, since condition (C.2) is always satisfied in this case. Figure 5(a) illustrates the set of feasible parameter values for identical firms. For the entire set of parameters (i.e., $p^1, p^3 > 0$ and $p^1 + p^3 < 1$) there exists an equilibrium in which both firms conceal all technologies.

Second, I consider the case in which firm $j$'s technology distribution is uniform (i.e., $p_j^m = \frac{1}{3}$ for all $m$), and firms produce a homogeneous good ($\beta = 1$). In this case, a firm can have an incentive to deviate unilaterally from full concealment if firm $i$'s technology distribution is sufficiently skewed. In particular, if firm $i$'s technology distribution is sufficiently skewed towards the worst technology, then firm $i$ has an incentive to share the intermediate technology, $\theta_i = \theta^2$, given beliefs consistent with

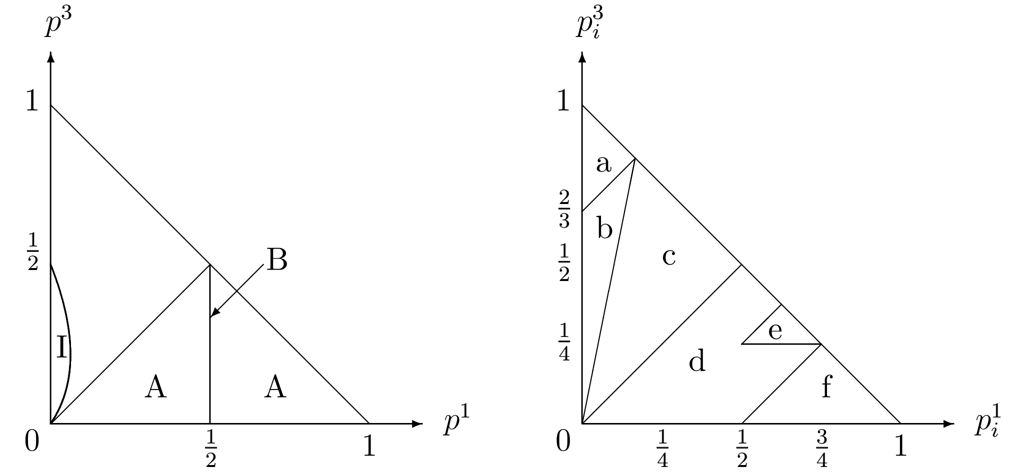


Fig. 5(a): Identical Firms

Fig. 5(b): Uniform Distribution $\theta_j$

Figure 5: Technology sharing with discrete distribution

full concealment. By sharing the intermediate technology, firm $i$ signals that it will be much tougher than expected, and create only a small reduction of the competitor's expected cost. Overall, technology sharing makes the expected competitor less "aggressive", which makes it profitable. Area (a) in Figure 5(b) contains all parameter values for which firm $i$ has an incentive to deviate (i.e., $p_i^3 > \frac{2}{3} + p_i^1$). Alternatively, if firm $i$'s distribution is skewed towards the most efficient technology, then firm $j$ has an incentive to unilaterally share the most efficient technology $\theta_j = \theta^1$, given prior beliefs. Here expropriation by firm $i$ is only a minor concern, whereas signaling has a substantial effect on the beliefs of firm $i$. For $p_i^1 > \frac{1}{2} + p_i^3$, which is illustrated as area (f) in Figure 5(b), firm $j$ has an incentive to deviate unilaterally. In other words, in the areas (b)-(e) of Figure 5(b) both firms conceal all technologies in equilibrium, when firm $j$ has a uniform technology distribution.

**Share all technologies:** For $\mathcal{S}_i = \{\theta^3\}$, firm $i$ has an incentive to share all its technologies, iff $\psi_i^d(\theta^m; \{\theta^3\}) \geq 0$ for $m = 1, 2$, which reduces to:

$$\begin{aligned} \frac{\beta}{2}(3-m)\Delta &\geq \sum_{k=m}^{3} p_j^k \, (k-m) \, \Delta \text{ for } m = 1, 2 \\ &\Leftrightarrow \; p_j^1 \geq 1 - \beta + p_j^3 \end{aligned} \tag{C.3}$$

This is the discrete version of condition ($\mathrm{C}_O$). As before, firm $i$ shares all technologies in equilibrium only if the technology distribution of firm $j$ is skewed towards efficient technologies. The expropriation effect is sufficiently weak if the average technology of your competitor is efficient.

First, if firms are identical and goods are homogenous, then Figure 5(a) illustrates the parameter values of condition (C.3) by area A (i.e., $p^1 \geq p^3$). In area A there exist two equilibria with full technology sharing: one in which firm 1 shares all while firm 2 conceals all, and another in which the reverse holds. Second, if firm $j$'s technology distribution is uniform and goods are homogeneous, then condition (C.3) is binding. Hence, for all parameter values in Figure 5(b) there exists an equilibrium in which firm $i$ shares all technologies. Furthermore, for $p_i^1 \geq p_i^3$, i.e., in the areas (d)-(f) of Figure 5(b), there exists an equilibrium in which firm $j$ shares all technologies, while firm $i$ keeps all technologies secret.

**Share only the best technology:** For $\mathcal{S}_i = \{\theta^2, \theta^3\}$, firm $i$'s expected cost is $E\{\theta_i|\theta_i \neq \theta^1\} = \frac{1-p_i^1-p_i^3}{1-p_i^1}\theta^2 + \frac{p_i^3}{1-p_i^1}\theta^3 = \theta^2 + \frac{p_i^3}{1-p_i^1}\Delta$. Firm $i$ has an incentive to share technology $\theta_i = \theta^1$ and conceal technology $\theta_i = \theta^2$, iff $\psi_i^d(\theta^1; \{\theta^2, \theta^3\}) \geq 0$ and $\psi_i^d(\theta^2; \{\theta^2, \theta^3\}) \leq 0$, which can written as:

$$\begin{aligned} \frac{\beta}{2}\left(1 + \frac{p_i^3}{1-p_i^1}\right)\Delta \quad &\geq \quad \sum_{k=1}^{3} p_j^k\,(k-1)\,\Delta \text{ and } \frac{\beta}{2}\cdot\frac{p_i^3}{1-p_i^1}\Delta \leq p_j^3\Delta \\ &\Leftrightarrow \quad \left(1 - \frac{\beta}{2} - p_j^1\right) + p_j^3 \leq \frac{\beta}{2}\cdot\frac{p_i^3}{1-p_i^1} \leq p_j^3 \qquad \text{(C.4)} \end{aligned}$$

The inequalities imply that $p_j^1 \geq 1 - \frac{\beta}{2}$ must hold, i.e., the distribution of firm $j$ should be skewed towards efficient technologies. The necessary condition $p_j^1 \geq 1 - \frac{\beta}{2}$ in combination with feasibility condition $p_j^3 < 1 - p_j^1$ gives (C.3) as Proposition 1 (a) shows for a continuous type space.

First, in the symmetric model the condition (C.4) is binding. That is, $p^1 = 1 - \frac{\beta}{2}$, which is illustrated in area B of Figure 5(a) for homogeneous goods. If $p^1$ would be greater than $1 - \frac{\beta}{2}$, then a firm would have an incentive to deviate by sharing the intermediate technology, since the expropriation effect would become weaker. For $p^1$ smaller than $1 - \frac{\beta}{2}$, there would be no incentive to share the best technology, since expropriation becomes more likely. This knife-edge case only emerges in the discrete model, as Proposition 1 (b) shows.

Second, if firm $j$ has a uniform technology distribution, then there is no equilibrium in which firm $i$ shares only the best technology, since (C.4) cannot hold for $p_j^1 = p_j^3 = \frac{1}{3}$. However, there may exist an equilibrium in which firm $j$ shares only the best technology. In particular, for $p_i^1 \geq 1 - \frac{3}{4}\beta + p_i^3 \geq 1 - \frac{\beta}{2}$, such an equilibrium exists. For $\beta = 1$, this inequality corresponds to area (e) in Figure 5(b). For the best technology of firm $j$, the signaling effect is substantial, while expropriation is limited, since it is likely that firm $i$ has the best technology already. A change from the best technology to the intermediate technology, weakens the signaling effect at a faster rate than the expropriation effect, since $p_i^2$ is low.

**Share only intermediate technology:** For $\mathcal{S}_i = \{\theta^1, \theta^3\}$, firm $i$'s expected cost is $E\{\theta_i|\theta_i \neq \theta^2\} = \frac{p_i^1}{p_i^1+p_i^3}\theta^1 + \frac{p_i^3}{p_i^1+p_i^3}\theta^3 = \theta^2 + \frac{p_i^3-p_i^1}{p_i^1+p_i^3}\Delta$. Firm $i$ has an incentive to share only technology $\theta_i = \theta^2$, iff $\psi_i^d(\theta^1; \{\theta^1, \theta^3\}) \leq 0$ and $\psi_i^d(\theta^2; \{\theta^1, \theta^3\}) \geq 0$, which gives:

$$\begin{aligned} \frac{\beta}{2}\left(1 + \frac{p_i^3 - p_i^1}{p_i^1 + p_i^3}\right)\Delta &\leq \left(1 - p_j^1 + p_j^3\right)\Delta \text{ and } \frac{\beta}{2}\cdot\frac{p_i^3 - p_i^1}{p_i^1 + p_i^3}\Delta \geq p_j^3\Delta \\ \Leftrightarrow\ p_j^3 &\leq \frac{\beta}{2}\cdot\frac{p_i^3 - p_i^1}{p_i^1 + p_i^3} \leq \left(1 - \frac{\beta}{2} - p_j^1\right) + p_j^3 \qquad \text{(C.5)} \end{aligned}$$

Notice that this inequality can only hold if $p_j^1 \leq 1 - \frac{\beta}{2}$. Hence, if firms are not in the knife-edge case $p_j^1 = 1 - \frac{\beta}{2}$, the comparison of (C.5) and (C.4) gives the following. Whenever there exists an equilibrium in which firm $i$ shares only the intermediate technology, there cannot exist equilibria in which firm $i$ shares only the best technology.

First, if the firms are identical and they produce a homogeneous good, then the following situation emerges. A firm has no incentive to share the best technology, $\theta^1$. An individual firm has an incentive to share only the intermediate technology, $\theta^2$, for parameters in area I of Figure 5(a), i.e., $p^1 < p^3 < \frac{1}{2} < p^2$. For these parameter values, the signaling effect from sharing technology $\theta_i = \theta^2$ is strong (since $E\{\theta_i|\theta_i \neq \theta^2\} \approx \theta^3$), while the expropriation effect is weak, since it is very likely that the competitor already has the intermediate technology ($p^2 > \frac{1}{2}$).

Second, if firm $j$'s technology is uniformly distributed and goods are homogeneous, then firm $i$ has an incentive to only share the intermediate technology in equilibrium for technology distributions that are skewed towards the worst technology (i.e., $p_i^1 \leq 5p_i^3$). In Figure 5(b) these parameter values correspond to areas (a)-(b). As before, there is no incentive to share the best technology. For the intermediate technology, the skewness of firm $i$'s distribution gives a strong signaling effect and the symmetry of firm $j$'s distribution gives a relatively weak expropriation effect.

The analysis above characterizes the necessary and sufficient conditions for the existence of equilibria in pure-strategies in the model with a simple, discrete technology space. In this example, there may also exist equilibria in mixed strategies. However, it goes beyond the scope of the paper to characterize the conditions under which they could exist.

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