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

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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 determine the technology sharing incentives. In equilibrium at most one firm shares some of its 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. No other equilibria can exist.

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1 Introduction

The paper studies the incentives of profit-maximizing firms to freely reveal their process 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 are weak or missing. For example, China is notorious for its weak intellectual property right enforcement, e.g. a recent newspaper article states: "Until recently, China's laws have generally been anything but clear on intellectual property, and have made it difficult to win a suit over an alleged infringement."[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 would be to adopt secrecy. "In other industries, secrecy remains the mainstay. (...) Lian, the consultant [at AT Kearny in Hong Kong], said he urges companies to keep some of their production processes outside China. 'The most effective methods are focused on keeping part of the production process secret,' Lian said."[2] By adopting secrecy, a firm avoids imitation by its competitors, and maintains its potential technological lead.

Alternatively, a firm may choose to share its technology with competitors. By sharing its technology, the firm persuades its competitors of the technology's efficiency, at the cost of losing any potential technological lead. 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. There exists a growing literature on open source technology (see e.g. Lerner and Tirole, 2001, 2002, Maurer and Scotchmer, 2006, Von Hippel, 2005), where a number of important motives for the adoption of open source technologies by profit-maximizing firms is analyzed. 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.

[1] "China Media Battle Hints at Shift on Intellectual Property," Howard W. French, *NYT*, 6 January 2007.

[2] "Companies Fight Back Against China Piracy," Elaine Kurtenbach, *AP*, 2 July 2006.

I analyze a model where firms strategically manage their competitor's expectations by freely revealing their technology or keeping it secret.

The paper gives a new explanation for the (endogenous) emergence of market structures where profit-maximizing firms adopt different technology sharing strategies. That is, firms with proprietary and open source technologies coexist in equilibrium. In practice there are several examples of high-technology markets where freely revealing firms compete with concealing firms. For example, IBM unilaterally switched to open source technology while its competitors remained producers of proprietary technology (see e.g. Moody, 2001).

Signaling and expropriation are motives that appear to play some role in the decision to freely reveal embedded Linux code by profit-maximizing firms. First, by sharing an efficient technology, a firm signals to its competitor that it will be an "aggressive" supplier in the product market. This signaling effect discourages the competitor to supply in the product market. For example, Henkel and Tins (2004) find that 45.4% of the embedded Linux hardware companies, participating in the survey, agreed that their company reveals code because "revealing good code improves [the] company's technical reputation," while 19.2% disagreed. For embedded Linux software companies 60.3% agrees, while only 8.6% disagrees.

Second, the disclosure of an efficient technology may make a firm's competitor more efficient, through imitation, which may encourage the competitor to expand his product market production. For example, Henkel and Tins (2004) report that 80% of the embedded Linux hardware 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. For the participating software companies the number is 75%. The trade-off between the signaling effect and the expropriation effect determines the incentive to share efficient technologies.

The incentive to share a technology is strongest for intermediate cost values, i.e., the profit difference between disclosure and secrecy 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 extremely high costs), while sharing "anticipated" news. Further, the technology sharing strategies are strategic substitutes. At most one firm shares some of its technology range. These observations yield four kinds of technology-sharing equilibria. First, if the cost distributions are identical or similar, both firms do not share their technologies. Second, if the cost distribution of a firm's competitor is skewed towards efficient technologies, then the firm has an incentive to unilaterally share any technology. Skewness limits the expected loss of expropriation, while the signaling gain remains. Third, if the competitor's technology distribution is skewed towards efficient technologies, there may 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.

The paper contributes to the literature on strategic disclosure of verifiable information. Grossman (1981), Milgrom (1981), Milgrom and Roberts (1986), and Okuno-Fujiwara *et al.* (1990) obtain an important "unraveling" result. When 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. 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.

The paper is closely related to Anton and Yao (2003, 2004), Encaoua and Lefouili (2006), and Jansen (2006, 2009a). Also these papers study the strategic disclosure incentives of competing, innovative firms in the presence of knowledge spillovers. Unlike the present paper, these papers study problems of one-sided asymmetric information. By contrast, I analyze a problem of two-sided asymmetric information here. This introduces a greater scope for profitable disclosure in equilibrium. 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.[3] For example, with one-sided asymmetric information there does not exist an equilibrium in which only technologies of intermediate productivity are shared (Jansen, 2009a), whereas such an equilibrium may exist with two-sided asymmetric information.

Gill (2008) studies a related model with two-sided asymmetric information. However, the present paper differs in some important ways from Gill. The analyses are complementary since Gill studies disclosure incentives in a model with discrete actions, while I study a model with a continuum of actions. Whereas Gill identifies conditions under which entry may be deterred by strategic disclosure, I characterize

[3] The present analysis differs in a second respect from Anton and Yao (2003-4). 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. In contrast to Anton and Yao's important results, I obtain equilibria that need not be fully revealing to firms.

conditions under which accommodating firms disclose. There are some other notable differences between the two papers. First, in Gill 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. 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.

Recently, a few other papers analyzed different economic problems with non-monotonic disclosure incentives (e.g., Sun, 2008, Board, 2009, and Jansen, 2009b). Sun (2008) and Board (2009) study the incentives of firms to disclose information about their location to consumers. By contrast, I analyze a model of global competition in which firms disclose to each other, not to a third party. Moreover, Sun and Board study symmetric distributions, whereas I also have results for skewed distributions. In fact, the skewness of technologies distributions plays a big role in my analysis. Jansen (2009b) 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.[4]

The paper is organized as follows. The next section describes the model. The third section discusses the equilibrium output levels of firms for different technology-sharing choices. Section 4 derives the equilibrium technology sharing strategies of firms. Section 5 discusses some extensions of the analysis. Finally, section 6 concludes the paper. All proofs of the paper's propositions are relegated to the Appendix.

2 The Model

Two firms produce differentiated goods. The firms have private information about their costs of production, θ_i for firm i, with $i = 1, 2$. Firm i obtains a process innovation and has production cost $\theta_i \in \Theta$, with technology space $\Theta \equiv [\underline{\theta}, \overline{\theta}]$ and 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

[4] Clinch and Verrecchia (1997) obtain non-monotonic disclosure strategies in a model of duopolistic Cournot competition where firms strategically disclose a common demand intercept. In contrast to this paper, my analysis does not rely on negative prices and quantities

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, firms make technology sharing choices. Firm i with cost θ_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 Θ (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, $\mathcal{O}_i$ is the set with technologies that firm i shares (i.e., technologies with an "open standard"), and $\mathcal{S}_i$ contains those technologies that firm i keeps secret. Firms make their technology sharing decisions simultaneously.

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.[5] Therefore, firm i has the following cost of production after technology sharing and adoption ($i, j \in \{1, 2\}$ 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. $P_i(\mathbf{x}) = \alpha - x_i - \beta x_j$, where $\mathbf{x} \equiv (x_i, x_j)$ 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 α is sufficiently high to obtain interior solutions in the product market. Parameter β represents the degree of product differentiation, with $0 < \beta \leq 1$. After technologies are adopted, firms simultaneously choose their output levels, $x_i \geq 0$ for firm i with $i = 1, 2$ (Cournot competition). Firms are risk-neutral, and the profit of firm i with cost c_i is ($i, j \in \{1, 2\}$ with $i \neq j$):[6]

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

[5] Whereas this paper studies a model where intellectual property rights are absent, papers such as Fried (1984), Gal-Or (1986), and Shapiro (1986) can be interpreted as analyses of models with perfect intellectual property right protection (i.e., no imitation upon disclosure).

[6] An alternative interpretation of this model is the following static model of winner-take-all R&D competition. 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: $\pi_i(\mathbf{x}; \theta_i) = [W - k\theta_i - kx_i - (W - T)x_j]\, x_i$. After normalization, i.e. $k = 1$, and defining $W = \alpha$ and $W - T = \beta$ we obtain the same profit function as in the Cournot competition model.

I solve the game backwards, and restrict the analysis to pure-strategy equilibria.

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 (θ_i, θ_j), imitation gives each firm the efficient technology $\min\{\theta_i, \theta_j\}$. Consequently, firm i supplies the following output in equilibrium (for $i, j \in \{1, 2\}$ and $i \neq j$):[7]

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

Second, if firm i shares θ_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 $i \neq j$):

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

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 $i \neq j$):

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

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

where

$$E_j(\min\{\theta_i, \theta_j\}|\theta_j \in \mathcal{S}_j) = F_j(\theta_i|\theta_j \in \mathcal{S}_j)E\{\theta_j|\theta_j \leq \theta_i, \theta_j \in \mathcal{S}_j\} + [1 - F_j(\theta_i|\theta_j \in \mathcal{S}_j)]\theta_i$$

[7] In x_i^{kl} 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 ($l = s$).

and

$$E\{\theta_j|\theta_j \leq \theta_i, \theta_j \in \mathcal{S}_j\} = \int_{\underline{\theta}}^{\theta_i} \frac{f_j(\theta|\theta_j \in \mathcal{S}_j)}{F_j(\theta_i|\theta_j \in \mathcal{S}_j)} \theta d\theta.$$

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:

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

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 firms' *interim* incentives to share technologies.

4.1 Basic Property of Equilibrium Strategies

Firms have a disincentive to share an inefficient technology for two reasons. First, any shared technology that gives a lower cost than $\overline{\theta}$ may be imitated by the competitor. If the competitor imitates the technology, he becomes a more "aggressive" competitor in the product market, which reduces the profits of the firm that shares the technology. Second, a firm that shares an inefficient technology signals to its competitor that it will be a "soft" competitor in the product market. Also this gives the competitor an incentive to be 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's incentive to share an efficient technology is determined by the trade-off between two effects. On the one hand, a 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. On the other hand, the firm's competitor may imitate the disclosed technology and thereby become a more "aggressive" competitor in the product market himself. This expropriation effect gives the firm a disincentive to share an efficient 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 *There exists no equilibrium in which both firms share some technologies, i.e., if firm i chooses strategy s_i with $\mathcal{O}_i \neq \emptyset$ in equilibrium, then firm j chooses strategy s_j with $\mathcal{O}_j = \emptyset$ in equilibrium for $i, j \in \{1, 2\}$ and $i \neq j$.*

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, θ_i, then firm i knows that its competitor has a technology which is at least as good as θ_i. As a consequence, the competitor (firm j) has no incentive to share a technology which is less efficient than θ_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 θ_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 to be more efficient than expected. This observation is consistent with previous results in models with one-sided asymmetric information (e.g., Anton and Yao, 2003-4, and Jansen, 2006, 2009a), 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 technology 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 always outweighs the signaling effect in this situation.

4.2 Equilibrium Strategies

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 does not exclude any equilibrium.

Firm i receives the profit of $x_i^{os}(\theta_i; \Theta)^2$ from sharing its technology θ_i when its competitor conceals all technologies.[8] The firm earns the profit $x_i^{ss}(\theta_i; \mathcal{S}_i, \Theta)^2$ if the firm conceals its cost and its competitor conceals all costs.[9] Firm i has an incentive to share its technology θ_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:

$$\psi_i(\theta_i; \mathcal{S}_i) \equiv -[1 - F_j(\theta_i)](E\{\theta_j | \theta_j \geq \theta_i\} - \theta_i) + \frac{\beta}{2}\left[E\{\theta_i | \theta_i \in \mathcal{S}_i\} - \theta_i\right]. \qquad (4.1)$$

The two terms in function ψ_i reflect the trade-off between the expropriation effect and the signaling effect.

The first term of ψ_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 θ_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 expression (4.1) is the difference between the expected cost of a competitor after technology sharing with subsequent imitation, and concealment. It thereby captures the expected loss from expropriation.

The second term of ψ_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 θ_i, the competitor knows that he competes with a firm with cost level θ_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 ($\beta/2$).

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

[9] 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 overall effect of a marginal increase of θ_i is as follows:

$$\psi_i'(\theta_i; \cdot) = [1 - F_j(\theta_i)] - \frac{\beta}{2}. \tag{4.2}$$

That is, an increase of θ_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 (4.1) is negative and increasing in θ_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 (4.1) is positive and decreasing in firm i's marginal cost).

The function ψ_i is strictly concave in cost θ_i, i.e. $\psi_i''(\theta_i; \cdot) = -f_j(\theta_i) < 0$ for all θ_i. An increase of θ_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 θ_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 θ_i. Eventually, the signaling effect becomes aligned with the expropriation effect and grows in θ_i at a constant rate. The expropriation effect weakens at a diminishing rate. This gives a growing disincentive to share technologies for high θ_i.

Hence, in equilibrium shared technologies have to form a single interval (i.e., $\mathcal{O}_i = [l, h]$ for $l, h \in \Theta$ and $l \leq h$).[10] The sign of $\psi_i'(\theta_i; \cdot)$ depends on the size of the cost θ_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 ψ_i reaches a maximum for the marginal cost:

$$\widehat{\theta}_i \equiv F_j^{-1}(1 - \beta/2). \tag{4.3}$$

For example, if goods are homogeneous (i.e. $\beta = 1$), then ψ_i reaches a maximum when θ_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. $\theta_i = \widehat{\theta}_i$.

These observations have immediate consequences for the equilibrium technology sharing strategies. In combination with Propositions 1-2, they imply that there can be at most four kinds of technology strategies in equilibrium: both firms share nothing, one firm shares all technologies, one firm shares only the best technologies, or one firm

[10] Lemma 1 in the proof of Proposition 2 shows that this property does not rely on the assumption that the competitor conceals all technologies, since it holds for any strategy of the competitor.

shares only intermediate technologies. The analysis below characterizes under what conditions these equilibria emerge.

4.2.1 Share Nothing

First, I characterize the conditions under which firms conceal all technologies in equilibrium. Suppose both firms conceal all their technologies (i.e., $\mathcal{S}_i = \Theta$ in (2.1) for all $i = 1, 2$), and the firms have beliefs consistent with full concealment. Consequently, firm i's competitor does not update its beliefs after concealment, and expects cost $E(\theta_i)$ of firm i. Hence, firm i has no incentive to deviate unilaterally from full concealment by sharing of technology θ_i, if $\psi_i(\theta_i; \Theta) \leq 0$ for all $\theta_i \in \Theta$, with ψ_i as in (4.1). A necessary and sufficient condition for the emergence of full concealment in equilibrium is therefore: $\psi_i(\widehat{\theta}_i; \Theta) \leq 0$ for $i = 1, 2$. This condition reduces to the following (for $i, j \in \{1, 2\}$ and $i \neq j$):

$$E\{\theta_j | \theta_j \geq \widehat{\theta}_i\} \geq E(\theta_i). \tag{4.4}$$

I summarize the analysis in the following proposition.

Proposition 3 *There exists an equilibrium where both firms conceal all technologies, i.e.* $s_i(\theta_i) = \varnothing$ *for all* $\theta_i \in \Theta$ *and* $i = 1, 2$, *if and only if condition (4.4) holds for* $i, j \in \{1, 2\}$ *and* $i \neq j$, *with* $\widehat{\theta}_i$ *as defined in (4.3).*

It is immediate that the condition is satisfied if the firms' cost distributions have equal means, i.e. $E(\theta_i) = E(\theta_j)$.[11] Moreover, the condition cannot be violated for more than one of the firms.

Condition (4.4) is violated 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.

[11] In that case, the condition holds, since $E\{\theta_j | \theta_j \geq \widehat{\theta}_i\} \geq E(\theta_j) = E(\theta_i)$.

4.2.2 Share All Technologies

Now I study the firms' incentives to share all their cost information, i.e. $s_i(\theta_i) = \theta_i$ for all θ_i, given that firm j conceals all. Again, I can use function ψ_i in (4.1) 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., $E(\theta_i|\varnothing) = \overline{\theta}$ or $\mathcal{S}_i = \{\overline{\theta}\}$. Firm i has no incentive to conceal information, given skeptical beliefs, if $\psi_i(\theta_i; \{\overline{\theta}\}) \geq 0$ for all θ_i. Concavity of ψ_i in θ_i reduces the equilibrium condition to $\psi_i(\underline{\theta}; \{\overline{\theta}\}) \geq 0$, which is satisfied if and only if:

$$E(\theta_j) \leq \left(1 - \frac{\beta}{2}\right)\underline{\theta} + \frac{\beta}{2}\overline{\theta}. \tag{4.5}$$

The following proposition states this result formally.

Proposition 4 *There exists an equilibrium where firm i shares all technologies while firm j conceals all technologies, i.e. $(s_i(\theta_i), s_j(\theta_j)) = (\theta_i, \varnothing)$ for all $\theta_i, \theta_j \in \Theta$, if and only if condition (4.5) 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 (4.5) the signaling effect dominates.

Notice that condition (4.5) does not require asymmetry between firms, since it can hold in a symmetric model (i.e., $E(\theta_1) = E(\theta_2) \leq (1 - \frac{\beta}{2})\underline{\theta} + \frac{\beta}{2}\overline{\theta}$). The condition only requires that a competitor's technology distribution should not be skewed towards inefficient technologies.

4.2.3 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 only its best technologies. It is necessary and sufficient that there exist some h, with $\widehat{\theta}_i < h < \overline{\theta}$, such that:

$$\psi_i(h; [h, \overline{\theta}]) = 0 \text{ and } \psi_i(\underline{\theta}; [h, \overline{\theta}]) \geq 0. \tag{4.6}$$

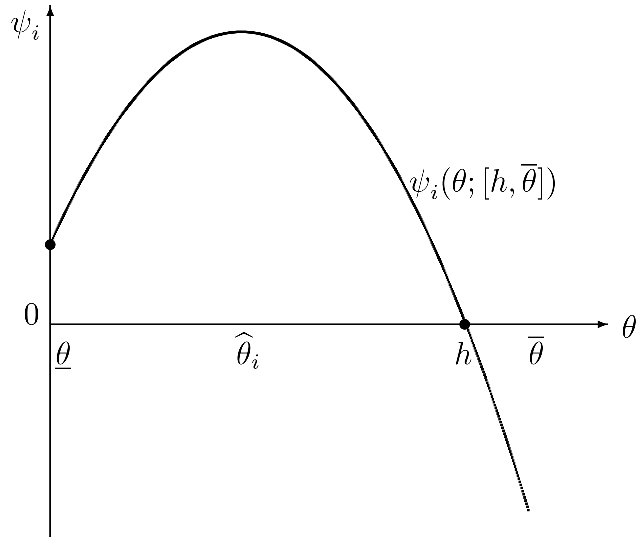

Figure 1: Sharing efficient technologies in equilibrium

Figure 1 illustrates these equilibrium conditions. The following proposition gives necessary conditions for the existence of such an equilibrium.

Proposition 5 ***(a)*** *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 (4.5) holds.* ***(b)*** *If firms have identical technology distributions, then there does not exist an equilibrium in which firm i chooses sharing strategy (2.1) with $\mathcal{S}_i = (h^*, \overline{\theta}]$ for any $\widehat{\theta}_i < h^* < \overline{\theta}$.*

Part (a) states that condition (4.5) is a necessary condition for the existence of such an equilibrium. Under this condition the expropriation effect is weak enough, and it makes 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. Part (b) 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 technology sharing can emerge in equilibrium under symmetry.

Finally, Proposition 6 gives specific, sufficient conditions for the existence of an equilibrium with sharing of only the best technologies by firm i.

Proposition 6 *Suppose that condition (4.5) 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 in which firm i shares technologies $\theta_i \in [\underline{\theta}, h^*]$, while all other technologies are kept secret.*

As before, condition (4.5) ensures that the expropriation effect is sufficiently weak. The restriction on the technology distribution G_i (...). For example, if firms draw their technologies from truncated exponential distributions, then the condition $E_{G_i}\{\theta_i|\theta_i > h\} \leq E_{\widetilde{F}_i}\{\theta_i|\theta_i > h\}$ can be satisfied for all h.

4.2.4 Share Only Intermediate Technologies

The previous analysis shows that firms have the greatest incentive to share technologies for intermediate cost values. 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 (2.1) 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.

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:

$$\psi_i(y; \Theta \backslash [l, h]\}) = 0, \text{ for } y \in \{l, h\}, \tag{4.7}$$

where 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 yields equilibrium values for l and h. The equilibrium conditions are illustrated in Figure 2. Below I characterize the conditions for the existence of a selective sharing equilibrium in two special cases.

To keep the analysis tractable, I first consider a symmetric model. For firms with identical technology distributions, the following proposition holds.

Proposition 7 *Suppose that firms have identical technology distributions, and condition (4.5) holds with strict inequality. Then there are critical values l^* and h^*, with $\underline{\theta} < l^* < \widehat{\theta}_i < h^* < \overline{\theta}$, such that for some $i \in \{1, 2\}$ there exists an equilibrium in which firm i shares any technology in $[l^*, h^*]$, while all other technologies are kept secret.*

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.

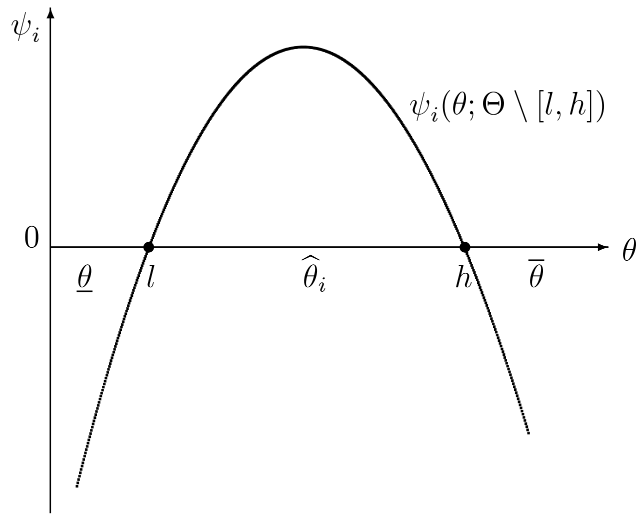

Figure 2: Sharing intermediate technologies in equilibrium

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 3), and full sharing by one of the firms (Proposition 4). However, Proposition 5(b) shows that in a symmetric model there exists no equilibrium in which one of the firms shares only its best technologies.

Second, I consider the situation where firms supply homogeneous goods ($\beta = 1$), and θ_j has a symmetric distribution on the interval Θ, 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 ψ_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. $l = \widehat{\theta}_i - \varepsilon$ and $h = \widehat{\theta}_i + \varepsilon$ for some $\varepsilon \in [0, \frac{1}{2}(\overline{\theta} - \underline{\theta})]$. This observation simplifies the analysis of the technology-sharing incentives considerably.

Proposition 8 *Suppose goods are homogeneous ($\beta = 1$), the distribution of θ_j is symmetric on Θ, and condition (4.4) is violated. Then there is an ε^*, with $0 < \varepsilon^* < \frac{1}{2}(\overline{\theta} - \underline{\theta})$, such that an equilibrium exists where firm i shares only technologies in the interval $[\widehat{\theta}_i - \varepsilon^*, \widehat{\theta}_i + \varepsilon^*]$ while firm j conceals all information, i.e., s_i^* and s_j^* as in (2.1) with $\mathcal{S}_i = \Theta \backslash [\widehat{\theta}_i - \varepsilon^*, h = \widehat{\theta}_i + \varepsilon^*]$ while $\mathcal{S}_j = \Theta$ 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 the firm 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 4.2.1). 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. As shown in Proposition 4, 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 type space Θ, 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 8 there does not exist an equilibrium with full concealment, since the condition (4.4) is violated (see Proposition 3). On the other hand, for a symmetric distribution of θ_j and homogeneous goods ($\beta = 1$) the condition (4.5) is satisfied and binding. Therefore, there also exists an equilibrium with full sharing by firm i (see Proposition 4).

Finally, the results in this subsection are notably different from the results in a model with one-sided asymmetric information. Jansen (2009a) shows that in a model with one-sided asymmetric there does not exist an 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.

4.3 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 λ_i is a measure of the skewness of the distribution. For $\lambda_i \to 0$ this distribution converges to the uniform distribution, while an increase of λ_i skews the distribution towards efficient technologies.

Figure 3 illustrates the equilibrium conditions of Propositions 3-6 for truncated exponential distributions. For the entire parameter space $(0, \infty)^2$ there always exists

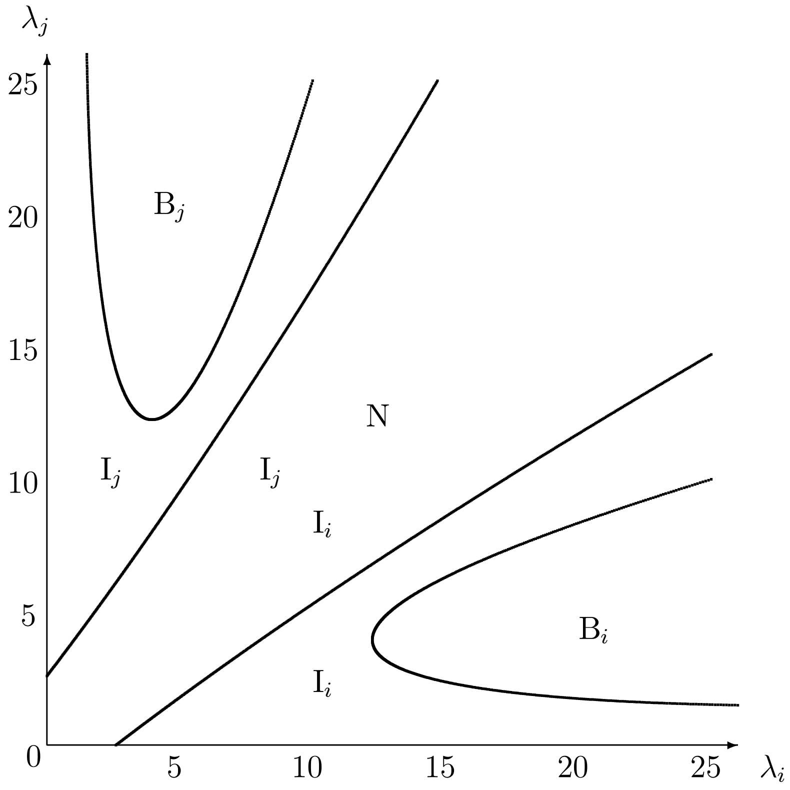

Figure 3: Technology sharing with truncated exponential distributions

an equilibrium in which one of the firms shares all technologies. The strength of the expropriation effect is moderate, since 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 λ_i and λ_j are of similar size. In area 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 5 (b) shows. Finally, numerical examples suggest that for parameter values in the areas I_i there exist equilibria in which firm i shares only intermediate technologies. Proposition 8 shows that such an equilibrium exists along the 45° line (i.e., for $\lambda_i = \lambda_j$). The example illustrates that there are many other situations where the strategy may emerge in equilibrium.

5 Extensions

In this section I discuss some extensions of the basic model.

5.1 Partial Sharing of Technology

The model above assumes that a firm's technology is indivisible in the sense that it needs to be shared completely or not at all. Moreover, imitation is costless and complete. Here I analyze the effect of introducing limited imitation of the innovation. Suppose that a rival can imitate only up to a bound $\theta_i + \widehat{\Delta}$ of shared technology θ_i, where $0 \leq \widehat{\Delta} < \overline{\theta} - \underline{\theta}$ (see also Gill, 2008, and Jansen, 2006). My contribution is to consider a setting in which both firms can choose to share. Of course, the smaller $\widehat{\Delta}$, the stronger the expropriation effect. The signaling effect remains the same. Therefore, technology sharing incentives grow if $\widehat{\Delta}$ increases.

5.2 Precommitment to Share Technology

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 license). However, there are cases in which long-term technology sharing decision are more realistic (e.g. in case of adopting a GPL open source license). There are greater incentives to precommit to technology concealment. A precommitting firm should be on average better off under technology concealment, whereas a strategic firm should prefer concealment for every possible technology. Clearly, the former requirement is weaker than the latter. Furthermore, a precommitting firm does not share its technology in all the cases where a strategic firm would share, since unraveling does not occur with non-strategic technology sharing.

5.3 Incentives to Invest in R&D

The technology distribution has been assumed to be exogenous. In practice, however, a firm affects the technology distribution by investing in research and development (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.

6 Conclusion

In this paper I characterized the conditions under which firms share their technologies in the absence of intellectual property rights. In particular, the relative skewness of the firms' technology distributions determine the firms' disclosure incentives.

This analysis may have implications for the incentives of firms to invest in R&D. The R&D investment of a firm skews the firm's technology distribution towards efficient technologies. In this case, a unilateral increase of the firm's investment has the direct effect of increasing the firm's expected efficiency, and the indirect effect of changing the technology sharing incentives of the firm's rival in the product market. This indirect effect may interact in an interesting way with the direct effect of R&D investments.

A Appendix

This Appendix provides proofs to the propositions.

Proof of Proposition 1

Suppose the opposite, i.e. suppose there exists an equilibrium where firm i hides $\theta_i \in [\underline{\theta}, l]$ and shares $\theta_i \in [l, \overline{\theta}]$, with $\underline{\theta} < l < \overline{\theta}$. Then firm j's belief must be $E\{\theta_i | \theta_i \leq l\} < \overline{\theta}$. Given such a belief, firm i has an incentive to hide technology $\overline{\theta}$. This follows from evaluating Ψ in (A.1) at $\theta_i = \overline{\theta}$:

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

since:

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

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 three steps. First, I show that the technology sharing incentives are particularly strong for intermediate values of the cost parameters. Consequently, in equilibrium the shared technologies of a firm have to form a single interval.

Lemma 1 *In any equilibrium there are some bounds $l_i, h_i \in \Theta$, with $l_i \leq h_i$, such that firm i chooses technology-sharing strategy (2.1) with $\mathcal{O}_i = [l_i, h_i]$, for $i = 1, 2$.*

Proof. Take any partition $\{\mathcal{O}_i, \mathcal{S}_i\}$ of the technology set Θ, and assume that firm j has beliefs consistent with the generic technology-sharing strategy s_i in (2.1) by firm i (for $i, j \in \{1, 2\}$ and $i \neq j$). That is, the expected cost of firm i after adoption of trade secrecy is: $E\{\theta_i | \theta_i \in \mathcal{S}_i\}$. Suppose that firm j chooses the technology sharing rule s_j^*

in (2.1) for some partition $\{\mathcal{O}_j, \mathcal{S}_j\}$ of the technology set Θ. Given these assumptions, firm i's expected profit from technology-sharing and secrecy are, respectively:

$$\begin{aligned}
\Pi_i^o(\theta_i, s_j^*) &\equiv \int_{\theta_j \in \mathcal{O}_j} \pi_i^{oo}(\theta_i, \theta_j) f_j(\theta_j) d\theta_j + \int_{\theta_j \in \mathcal{S}_j} \pi_i^{os}(\theta_i; \mathcal{S}_j) f_j(\theta_j) d\theta_j \\
\Pi_i^s(\theta_i, s_j^*) &\equiv \int_{\theta_j \in \mathcal{O}_j} \pi_i^{so}(\theta_i, \theta_j; \mathcal{S}_i) f_j(\theta_j) d\theta_j + \int_{\theta_j \in \mathcal{S}_j} \pi_i^{ss}(\theta_i; \mathcal{S}_i, \mathcal{S}_j) f_j(\theta_j) d\theta_j
\end{aligned}$$

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

$$\begin{aligned}
\Psi(\theta_i; \mathcal{S}_i, \mathcal{S}_j) &\equiv \Pi_i^o(\theta_i, s_j^*) - \Pi_i^s(\theta_i, s_j^*) \\
&= \int_{\theta_j \in \mathcal{O}_j} \left[x_i^{oo}(\theta_i, \theta_j)^2 - x_i^{so}(\theta_i, \theta_j; \mathcal{S}_i)^2 \right] dF_j(\theta_j) \\
&\quad + \Pr[\theta_j \in \mathcal{S}_j] \left[x_i^{os}(\theta_i; \mathcal{S}_j)^2 - x_i^{ss}(\theta_i; \mathcal{S}_i, \mathcal{S}_j)^2 \right] \qquad \text{(A.1)}
\end{aligned}$$

The first derivative of Ψ with respect to θ_i equals:

$$\begin{aligned}
\frac{\partial \Psi(\theta_i; \mathcal{S}_i, \mathcal{S}_j)}{\partial \theta_i} &= -\int_{\theta_j \in \mathcal{O}_j \cap [\theta_i, \overline{\theta}]} \left(\frac{2}{2+\beta} x_i^{oo}(\theta_i, \theta_j) - x_i^{so}(\theta_i, \theta_j; \mathcal{S}_i) \right) dF_j(\theta_j) \\
-\Pr[\theta_j \in \mathcal{S}_j] &\left(\frac{2\,(2 - \beta[1 - F_j(\theta_i | \theta_j \in \mathcal{S}_j)])}{4 - \beta^2} x_i^{os}(\theta_i; \mathcal{S}_j) - x_i^{ss}(\theta_i; \mathcal{S}_i, \mathcal{S}_j) \right)
\end{aligned}$$

since

$$\begin{aligned}
\frac{\partial}{\partial \theta_i} \left(\int_{\theta_j \in \mathcal{O}_j} x_i^{oo}(\theta_i, \theta_j)^2 dF_j(\theta_j) \right) &= \frac{\partial}{\partial \theta_i} \int_{\theta_j \in \mathcal{O}_j \cap [\underline{\theta}, \theta_i]} x_i^{oo}(\theta_i, \theta_j)^2 dF_j(\theta_j) \\
&\quad + \frac{\partial}{\partial \theta_i} \int_{\theta_j \in \mathcal{O}_j \cap [\theta_i, \overline{\theta}]} x_i^{oo}(\theta_i, \theta_j)^2 dF_j(\theta_j) \\
&= \frac{-2}{2+\beta} \int_{\theta_j \in \mathcal{O}_j \cap [\theta_i, \overline{\theta}]} x_i^{oo}(\theta_i, \theta_j) dF_j(\theta_j)
\end{aligned}$$

$$\begin{aligned}
\frac{\partial}{\partial \theta_i} \left(\int_{\theta_j \in \mathcal{O}_j} x_i^{so}(\theta_i, \theta_j; \mathcal{S}_i)^2 dF_j(\theta_j) \right) &= \frac{\partial}{\partial \theta_i} \int_{\theta_j \in \mathcal{O}_j \cap [\underline{\theta}, \theta_i]} x_i^{so}(\theta_i, \theta_j; \mathcal{S}_i)^2 dF_j(\theta_j) \\
&\quad + \frac{\partial}{\partial \theta_i} \int_{\theta_j \in \mathcal{O}_j \cap [\theta_i, \overline{\theta}]} x_i^{so}(\theta_i, \theta_j; \mathcal{S}_i)^2 dF_j(\theta_j) \\
&= -\int_{\theta_j \in \mathcal{O}_j \cap [\theta_i, \overline{\theta}]} x_i^{so}(\theta_i, \theta_j; \mathcal{S}_i) dF_j(\theta_j)
\end{aligned}$$

$$\begin{aligned}
\frac{\partial}{\partial \theta_i} x_i^{os}(\theta_i; \mathcal{S}_j)^2 &= \frac{-2}{4-\beta^2} \Big(2 - \beta[1 - F_j(\theta_i | \theta_j \in \mathcal{S}_j)] \Big) x_i^{os}(\theta_i; \mathcal{S}_j) \\
\frac{\partial}{\partial \theta_i} x_i^{ss}(\theta_i; \mathcal{S}_i, \mathcal{S}_j)^2 &= -x_i^{ss}(\theta_i; \mathcal{S}_i, \mathcal{S}_j)
\end{aligned}$$

The second derivative of Ψ equals:

$$\begin{aligned}\frac{\partial^2\Psi(\theta_i;\mathcal{S}_i,\mathcal{S}_j)}{\partial\theta_i^2} &= \Pr[\theta_j\in\mathcal{S}_j]\left(\frac{2}{(2+\beta)^2}-\frac{1}{2}\right)[1-F_j(\theta_i|\theta_j\in\mathcal{S}_j)] \\ &+I^o(\theta_i)\left(\frac{2}{2+\beta}x_i^{oo}(\theta_i,\theta_i)-x_i^{so}(\theta_i,\theta_i;\mathcal{S}_i)\right)f_j(\theta_i) \\ &+\Pr[\theta_j\in\mathcal{S}_j]\left[\tfrac{1}{(4-\beta^2)^2}\left(2-\beta[1-F_j(\theta_i|\theta_j\in\mathcal{S}_j)]\right)^2-\tfrac{1}{2}\right] \\ &-[1-I^o(\theta_i)]2x_i^{os}(\theta_i;\mathcal{S}_j)\tfrac{\beta}{4-\beta^2}f_j(\theta_i)\end{aligned}$$

where I^o is the indicator function

$$I^o(\theta_i)=\begin{cases}1, & \text{if } \theta_i\in\mathcal{O}_j\\ 0, & \text{if } \theta_i\notin\mathcal{O}_j\end{cases}$$

Clearly, the function Ψ is concave in θ_i since $\partial^2\Psi(\theta_i;\mathcal{S}_i,\mathcal{S}_j)/\partial\theta_i^2\leq 0$ for any $\theta_i,\mathcal{S}_i,\mathcal{S}_j$. This implies that in equilibrium the technology sharing strategy is as in (2.1) where $\mathcal{O}_j=[l_i,h_i]$ for some l_i and h_i with $\underline{\theta}\leq l\leq h\leq\overline{\theta}$. ■

Second, I find a necessary condition under which firm i shares only the technologies $\theta_i\in[l,h]$ in equilibrium, with $\underline{\theta}\leq l<h\leq\overline{\theta}$. Proposition 1 shows that firm i chooses no other strategy in equilibrium, if it shares some technologies.

Lemma 2 *If firm i has beliefs consistent with s_j in (2.1) for some $\mathcal{S}_j\subseteq\Theta$, and it chooses s_i in (2.1) for $\mathcal{O}_i=[l,h]$ in equilibrium, with $\underline{\theta}\leq l<h\leq\overline{\theta}$, then for all $\theta_i'\in[l,h]$:*

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

Proof. The expected profit gain for firm i of sharing technology θ_i, $\Psi(\theta_i;\mathcal{S}_i,\mathcal{S}_j)$ for any sets $\mathcal{S}_i,\mathcal{S}_j\subseteq\Theta$, is defined in (A.1). The first term of (A.1) is non-positive, since for any θ_i and θ_j:

$$\begin{aligned}x_i^{oo}(\theta_i,\theta_j)-x_i^{so}(\theta_i,\theta_j;\mathcal{S}_i) &= \frac{-\beta}{4-\beta^2}\Bigg(\theta_j-\min\{\theta_i,\theta_j\} \\ &\quad -\frac{\beta}{2}\left[E_i\left(\min\{\theta_i,\theta_j\}|\theta_i\in\mathcal{S}_i\right)-\min\{\theta_i,\theta_j\}\right]\Bigg) \\ &\leq \frac{-\beta(1-\frac{1}{2}\beta)}{4-\beta^2}\left(\theta_j-\min\{\theta_i,\theta_j\}\right)\leq 0 \qquad \text{(A.3)}\end{aligned}$$

Therefore, any expected gain from sharing a technology is created by the second term of (A.1). 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 $\Psi(\theta_i; \Theta \backslash [l,h], \mathcal{S}_j)$ in (A.1) 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 (A.2). ■

Notice that (A.2) reduces to $\Upsilon_i(\theta_i') > 0$ for $\theta_i' \in [l,h]$ with:

$$\Upsilon_i(\theta_i') \equiv -[1 - F_j(\theta_i'|\theta_j \in \mathcal{S}_j)] \left(E\{\theta_j|\theta_j > \theta_i', \theta_j \in \mathcal{S}_j\} - \theta_i'\right) + \frac{\beta}{2} \left[E\{\theta_i|\theta_i \notin [l,h]\} - \theta_i'\right] \tag{A.4}$$

Finally, I show that condition (A.2) implies that firm j has no incentive to share any technology.

Lemma 3 *If condition (A.2) holds for $\theta_i' \in [l,h]$, and firm j has beliefs consistent with s_i in (2.1) 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 θ_j is $\Psi(\theta_j; \mathcal{S}_j, \Theta \backslash [l,h])$ as defined in (A.1). The firm can only have an incentive to share a technology θ_j if the second term of $\Psi(\theta_j; \mathcal{S}_j, \Theta \backslash [l,h])$ is positive. (The first term is negative due to (A.3) 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:

$$\Upsilon_j(\theta_j) \equiv \frac{\beta}{2} \left[E\{\theta_j|\theta_j \in \mathcal{S}_j\} - \theta_j\right] - E_i\left(\theta_i - \min\{\theta_i, \theta_j\} \middle| \theta_i \notin [l,h]\right) \tag{A.5}$$

with

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

The function $\Upsilon_j(\theta_j)$ is continuous in θ_j. Moreover, it is concave in θ_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 θ_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 $\frac{1-F_i(\widetilde{\theta})}{F_i(l)+1-F_i(h)} = \frac{\beta}{2}$ and $\widetilde{\theta} \geq h$. 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.2). 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 $\frac{F_i(\widetilde{\theta})}{F_i(l)+1-F_i(h)} = 1-\frac{\beta}{2}$ and $\widetilde{\theta} < l$. Then for any $\theta_i' \in [l,h]$ the following holds:

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

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

The first inequality follows from the necessary condition (A.2). The last inequality follows from the facts that $E\{\theta_j|\theta_j \leq \theta_i', \theta_j \in \mathcal{S}_j\} \leq \theta_i'$, from $E\{\theta_i|\theta_i \leq \widetilde{\theta}\} < \widetilde{\theta} < l \leq \theta_i'$, and from the observation that $\Upsilon_i(\theta_i') > 0$ in (A.4) implies $E\{\theta_i|\theta_i \notin [l,h]\} \geq \theta_i'$, since $E\{\theta_j|\theta_j > \theta_i', \theta_j \in \mathcal{S}_j\} \geq \theta_i'$ and $F_j(\theta_i'|\theta_j \in \mathcal{S}_j) \leq 1$.

Cases (a) and (b) imply that there exists no technology that firm j wants to share, since $\Upsilon_j(\theta_j) \leq \Upsilon_j(\widetilde{\theta}) < 0$ for all θ_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

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

Proof of Proposition 4

The beliefs of firm j, which are consistent with full sharing by firm i, are skeptical beliefs, i.e., $E(\theta_i|\varnothing) = \overline{\theta}$ or $\mathcal{S}_i = \{\overline{\theta}\}$. Firm i has no incentive to conceal information, given skeptical beliefs, if $\psi_i(\theta_i; \{\overline{\theta}\}) \geq 0$ for all θ_i, where the function ψ_i is defined in (4.1). Concavity of ψ_i in θ_i reduces the equilibrium condition to $\min\{\psi_i(\underline{\theta}; \{\overline{\theta}\}), \psi_i(\overline{\theta}; \{\overline{\theta}\})\} \geq 0$. Evaluation of $\psi_i(.; \{\overline{\theta}\})$ for extreme costs gives: $\psi_i(\underline{\theta}; \{\overline{\theta}\}) = -(E\{\theta_j\} - \underline{\theta}) + \frac{\beta}{2}\left[\overline{\theta} - \underline{\theta}\right]$ and $\psi_i(\overline{\theta}; \{\overline{\theta}\}) = 0$. Consequently, the condition $\psi_i(\theta_i; \{\overline{\theta}\}) \geq 0$ is satisfied if and only if (4.5) holds. Finally, given full technology-sharing by firm i, Proposition 2 (in particular, inequality (A.3) for firm j in Lemma 2) shows that firm j has no incentive to share. □

Proof of Proposition 5

(a) For any h^*, with $\widehat{\theta}_i < h^* < \overline{\theta}$, a necessary condition for the existence of an equilibrium with $\mathcal{S}_i = [h^*, \overline{\theta}]$ is that $\psi_i(\underline{\theta}; [h^*, \overline{\theta}]) \geq 0 > \psi_i(\overline{\theta}; [h^*, \overline{\theta}])$, where ψ_i is defined in (4.1). If (4.5) 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.

(b) Take any h^* in the interior of Θ, 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 (i) $\psi_i(h^*; [h^*, \overline{\theta}]) = 0$, and (ii) $\psi_i(\underline{\theta}; [h^*, \overline{\theta}]) \geq 0$. Using symmetry, condition (i) gives:

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

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 6

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 (4.6) holds for $h = h^*$. The conditions in (4.6) can be written as $\widetilde{\psi}(h^*; F_i) = 0$ and $\underline{\psi}(h^*; F_i) \geq 0$ for the following continuous functions:

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

Notice that if (4.5) 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 $\psi_i(\widetilde{\theta}; [\widetilde{\theta}, \overline{\theta}]) = 0$.[12] 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 (4.5). Hence, there exists some θ_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,

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

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

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

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:

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

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

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

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 θ_i close to $\overline{\theta}$.

In summary, $\widetilde{\psi}(\theta_o;G_i) \leq 0 < \widetilde{\psi}(\overline{\theta} - \varepsilon;G_i)$ for small $\varepsilon > 0$ and $\underline{\psi}(\theta;G_i) \geq 0$ for all $\theta \geq \theta_o$. The intermediate value theorem implies that there exists an h^*, with $\theta_o \leq h^* < \overline{\theta}$, such that $\widetilde{\psi}(h^*;G_i) = 0$. Hence, h^* satisfies the equilibrium conditions. Finally, Proposition 2 shows that firm j has no incentive to share its technology θ_j in equilibrium. □

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 (4.5) 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 ψ_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 $\widetilde{l}:[\widehat{\theta}_i,\widetilde{\theta}]\to[\underline{\theta},\widehat{\theta}_i]$ with $\widetilde{l}(\widehat{\theta}_i)=\widehat{\theta}_i$ and $\widetilde{l}(\widetilde{\theta})=\underline{\theta}$.

Second, condition (ii) implicitly defines the continuous function $\widehat{l}:[\widehat{\theta}_i,\widetilde{\theta}]\to[\underline{\theta},\widehat{\theta}_i]$. 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:

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

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 $\widetilde{l},\widehat{l}:[\widehat{\theta}_i,\widetilde{\theta}]\to[\underline{\theta},\widehat{\theta}_i]$, 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 has no incentive to share its technology θ_j in equilibrium. $\square$

Proof of Proposition 8

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 ψ_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 $\widehat{\psi} : [0, \frac{1}{2}(\overline{\theta} - \underline{\theta})] \rightarrow \mathbb{R}$ 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 (4.4) 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 ε^*, with $0 < \varepsilon^* < \frac{1}{2}(\overline{\theta} - \underline{\theta})$, such that $\widehat{\psi}(\varepsilon^*) = 0$.

Finally, Proposition 2 shows that firm j has no incentive to share its technology θ_j in equilibrium. □

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