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Knowledge Disclosure and Transmission in Buyer–Supplier Relationships

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Abstract A buyer's technical knowledge may increase the efficiency of its supplier. Suppliers, however, frequently maintain relationships with additional buyers. Knowledge disclosure then bears the risk of benefiting one's own rival due to opportunistic knowledge transmission through the common supplier. We show that in one-shot relationships no knowledge disclosure takes place because the supplier has an incentive to transmit and, anticipating that, buyers refuse to disclose any of their knowledge. In repeated relationships knowledge disclosure is stabilized by larger technological proximity between buyers and suppliers and destabilized by the absolute value of the knowledge.

Keywords Knowledge disclosure · Spillovers · Innovation · Repeated games

JEL Classification O31 · O32 · L13 · L20

1 Introduction

Knowledge sharing among vertically related firms is commonly regarded as a key ingredient to efficient buyer-supplier relationships. The disclosure of technical

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knowledge[1] by a customer may increase the supplier's production efficiency.[2] In turn, increased supplier performance translates into lower input prices or enhanced input quality.[3] One would expect that buyers would have an incentive to disclose technical knowledge to their suppliers and, indeed, this presumption prevails in theoretical studies by Hughes and Kao (2001) and Ishii (2004).

One complication arises when competing firms purchase from the *same* supplier. If the common supplier is either not able or not willing to treat obtained knowledge confidentially, leakage of knowledge to rivals may outweigh the gains from increased supplier performance. Empirical studies by Grindley et al. (1994), Cassiman and Veugelers (2002), and Bönte and Keilbach (2005) confirm that such concerns are ubiquitous.

The present paper analyzes the circumstances under which knowledge disclosed leaks out to competitors through a common supplier. We employ a four-stage model. In the first stage two downstream firms (buyers) determine the amount of knowledge that they disclose to an upstream monopolist (common supplier). Disclosed knowledge increases the supplier's production efficiency. In the second stage the supplier decides how much of one buyer's knowledge it transmits to the other buyer. In the third stage the supplier sets the wholesale price. In the fourth stage the downstream firms compete in output quantities. This scenario is analyzed both for a one-shot buyer-supplier relationship and for repeated relationships.

For the one-shot setting we find that each buyer discloses its technical knowledge completely as long as the common supplier does not transfer 'too much' of that knowledge to its counterpart. The supplier, however, has an incentive to give away all of its knowledge to each buyer. The announcement to treat obtained knowledge confidentially (e.g., to install 'firewalls') is not credible (not a subgame perfect equilibrium), and, anticipating that, a downstream firm will not disclose any of its knowledge in the first place.

These predictions change if the buyer can threaten not to disclose its knowledge in the future. We discuss two types of knowledge-sharing equilibria in the repeated game. In the first one each buyer discloses its knowledge completely whereby the supplier does not transmit 'too much' of it. In the second, more subtle one, each buyer, again, discloses its knowledge completely, but the supplier transmits all of it. This equilibrium occurs because revealing *and* receiving knowledge implies a net benefit for the downstream firms. Both types of equilibria are stabilized by a larger technological proximity between the buyers and the supplier and destabilized by the absolute value of knowledge.

The paper is arranged as follows: In Sect. 2 we discuss related literature. Section 3 sets up the model. In particular we derive the downstream firms' optimal output quantities in the fourth stage and the supplier's input price in the third stage of the model. In Sect. 4 we analyze the downstream firms' incentives for knowledge disclosure in

[1] Alternative types of valuable knowledge in vertical relationships are demand and cost information; see Lee and Whang (2000) for a survey of supply chain information sharing.

[2] Kotabe et al. (2003) document this positive effect empirically for suppliers in the U.S. and Japanese automotive industries.

[3] For instance, Dyer and Hatch (2004) relate Toyota's superior quality and profit performance to its more intense knowledge sharing with suppliers as compared to General Motors, Ford, and Daimler-Chrysler.

a one-shot relationship. In Sect. 5 we investigate the case in which firms interact repeatedly. Section 6 concludes.

2 Related Literature

The combination of potential supplier opportunism and downstream competition is the key ingredient to our knowledge sharing model. Only a few previous studies consider these issues. Baiman and Rajan (2002) address the role of opportunism in buyer-supplier relationships. In contrast to our work they focus on a bilateral buyer-supplier relationship in which the supplier misappropriates the information by using it for himself; for instance, the supplier may emerge as a competitor to the knowledge-sharing buyer.

Li (2002) and Zhang (2002) consider information sharing of competing downstream firms to a common supplier. In their model, however, information is about demand or cost. The supplier takes advantage of this information to seek more rents from its buyers. In addition information transmission has a negative (positive) effect on downstream firms' profits if demand information (cost information) is at stake. In contrast, the disclosure of technical knowledge in our model benefits buyers within the bilateral buyer-supplier relationship. Information transmission always decreases (increases) the revealing (receiving) buyer's profit.

Harhoff et al. (2003) propose that two downstream firms may reveal their innovations because their common supplier may refine them. Refinements are only profitable if both downstream firms adopt the improved innovation. This causes a downstream firm to reveal its innovation if and only if it expects the other downstream firm to adopt it too. Our study, in contrast, is motivated by the above-mentioned empirical studies that suggest that firms disclose their innovation specifically if the innovation cannot be adopted too easily by their competitor.

Baccara (2007) analyzes a setting in which outsourcing leads to involuntary information leakage to contractors. Contractors can sell information to the outsourcing firm's competitors. As such buyers do not have an incentive to disclose any information to contractors and the contractors will only transmit information if they are financially compensated. Our paper, in contrast, focuses on voluntary disclosure of knowledge whereby buyers and suppliers have incentives to transmit knowledge without financial compensation.

Because in our paper knowledge disclosure is a continuous and endogenous choice variable, our work is related to studies that have implicitly assumed knowledge disclosure within vertical relationships. At least three presumptions prevalent in the literature are affected by our results. First, Hughes and Kao (2001) presume that a supplier does not transmit (demand) information, except to an owned downstream division. Second, Milliou (2004) investigates the welfare effects of firewalls in a setting with exogenous knowledge flows from a buyer to a vertically integrated supplier but leaves open the question of whether such a firewall would be installed in the first place. Third, the case of complete vertical knowledge disclosure analyzed by Ishii (2004) might, in fact, not be an equilibrium.

Finally our repeated game setting is related to work by Veugelers and Kesteloot (1994) and Kesteloot and Veugelers (1995), who study the stability of cooperative R&D. Unlike our model their focus is on bilateral horizontal knowledge disclosure rather than on knowledge disclosure in buyer-supplier relationships.

3 The Basic Model

We consider two downstream firms, $i = 1, 2$, who transform the intermediate input produced by a common monopolistic supplier, u, into a final output. Our model consists of four stages: In the first stage each downstream firm (buyer) determines the amount of knowledge it discloses to the upstream supplier. This lowers the supplier's production costs. Once the supplier possesses the knowledge of i it decides, in the second stage, whether it transmits this knowledge to j. In the third stage the upstream firm sets the intermediate input price, and in the fourth stage downstream firms compete in the final output market a la Cournot.

The upstream firm produces with marginal costs of production, $c - Y$, where c is an exogenous parameter, $c > Y$, and

$$Y = t(\alpha_1 x_1 + \alpha_2 x_2) \tag{1}$$

represents the amount of cost-reduction that the upstream firm realizes due to the knowledge transfer of the downstream firms. In particular x_1 (x_2) measures the size of Firm 1's (Firm 2's) proprietary knowledge. The endogenous variables $\alpha_i \in (0, 1)$, $i = 1, 2$, represent the fraction of x that the downstream firms actually disclose to u. The parameter $t \in (0, 1)$ captures the degree of technological proximity between the upstream firm and the downstream firms.[4]

The downstream firms' marginal costs of production are $A + w - X_i$, where A is an exogenous parameter, $A > X_i$ w is the intermediate input price and

$$X_i = x_i + \alpha_j \beta_i x_j, \quad i = 1, 2, \quad i \neq j \tag{2}$$

is the amount of cost-reduction that each downstream firm realizes due to the sum of its own proprietary knowledge, x_i, and the fraction of its rival's knowledge, x_j, that gets into its domain.[5] The ith firm receives its rival's knowledge according to the fraction α_j, that the rival has previously revealed to the upstream monopolist and the

[4] Empirical studies typically make use of patent data in order to measure technological proximity between firms and industries. Jaffe (1986), for example, has proposed a measure of technological proximity that is based on the idea that the distributions of the firms' patents across technology-based patent classes characterize the technological positions of the firms. The measures of technological proximity are the uncentered correlations between firms' patent portfolios, which are close to zero if firms' portfolios are very different and are close to one if they are very similar.

[5] The amount of proprietary knowledge is a function of a firm's R&D efforts. In the literature on research joint ventures X is called a firm's effective R&D activity, being "the sum of a firm's own R&D spending plus a fraction of the rival's R&D spending" (Kamien and Zang 2000, p. 997). This assumes a multidimensional R&D process in which firms, for example, go through different trial and error processes. A 'dead end' found by one firm saves the other from going through the same process. See Kamien et al. (1992).

fraction $\beta_i \in (0, 1)$, $i = 1, 2$, that is transferred from firm j's knowledge to firm i via the common supplier. According to equation (2) the ith downstream firm will utilize all of its rival's knowledge if $\alpha_j = \beta_i = 1$. This specification makes sense if firms have chosen to follow the same technological trajectories. This is in line with findings of Molto et al. (2005) and Wiethaus (2005), who show that competing firms indeed tend to adopt identical R&D approaches. Since we are interested in firms' incentives to disclose their proprietary knowledge but not in their incentives to create that knowledge we assume throughout that both firms possess an innovation of given and identical size: $x = x_i = x_j$.[6]

We summarize these considerations in the firms' profit functions: The ith downstream firm's profit-function can be written as

$$\pi_i = (P(Q) - (A + w - X_i))q_i, \quad i = 1, 2, \tag{3}$$

where $P(Q) = a - Q$, determines the price of the final product as a function of the firms' joint output quantity, $Q = q_i + q_j$ and $a > A + w$. We assume that both downstream firms pay the same input price w: i.e., the monopolist supplier does not differentiate the input price.[7] On the assumption that the final product is produced with a 1:1 technology (one unit of final product requiring exactly one unit of input) the upstream firm's profit-function is

$$\pi_u = (w - (c - Y))Q, \tag{4}$$

where we assume $w > c$.

Using the standard backwards induction procedure we first derive the firms' decisions starting in the fourth stage. Differentiation of (3) with respect to q_i and q_j respectively and then solving both first-order-conditions simultaneously for q_i and q_j yield the firms' equilibrium output quantities,

$$q_i^* = \frac{a - A - w + 2X_i - X_j}{3} \quad i = 1, 2 \;\; i \neq j \tag{5}$$

where X_i and X_j, are given by (2). We assume that the downstream firms take w as given.

In the third stage the upstream firm sets the intermediate input price. Anticipating the downstream firms' behavior in the final product market the upstream firm maximizes its profits upon substitution of

$$Q^* = q_1^* + q_2^* = \frac{2(a - A - w) + X_1 + X_2}{3} \tag{6}$$

[6] Firms' R&D investments have been analyzed extensively by, among others, D'Aspremont and Jacquemin (1988) and Kamien et al. (1992) for the case of horizontally related firms and by Ishii (2004) for the case of vertically related firms.

[7] While this assumption is technically motivated to keep the analysis tractable it might be justified by the fact that antitrust authorities are concerned about price discrimination by dominant firms.

for Q in (4). Solving the first-order-condition, $\partial \pi_u / \partial w|_{Q=Q^*} = 0$, for w yields the intermediate input price

$$w^* = \frac{2(a - A + c - Y) + X_1 + X_2}{4}. \tag{7}$$

By (6) and (7) it is apparent that a decrease of marginal costs in the downstream industry due to an increase in knowledge (X_1, X_2) creates an *additional demand effect* for the intermediate input, that, in turn, increases the monopolist's profit-maximizing price, $\partial w^* / \partial X_i > 0$, and its profits, respectively. If the downstream firms, however, disclose their knowledge to the upstream firm, this also lowers upstream production costs by $Y = t(\alpha_i x + \alpha_j x)$ and, as a consequence, w^*. We will refer to this latter mechanism as the *cost efficiency effect*.

4 Knowledge Disclosure in a One-Shot Relationship

We investigate two scenarios. First the parameter β is assumed to be exogenous because the upstream firm does not deliberately transmit knowledge obtained. Therefore, in this scenario the game reduces to a three-stage game. Second we consider an upstream monopolist who decides opportunistically whether or not to transmit knowledge in the second stage.

Absence of Supplier Opportunism In this section we analyze a downstream firm's incentive to disclose its knowledge to the upstream monopolist assuming that the latter does not behave opportunistically. In other words the supplier treats disclosed knowledge confidentially and does not therefore take any action to pass on the disclosed knowledge to the other downstream firm.

In order to obtain the ith firm's output quantity we substitute w^* for w in (5), which yields

$$q_i^{**} = \frac{2(a - A - c + Y) + x(2 + 7\alpha_j \beta_i - 5\alpha_i \beta_j)}{12} \quad i = 1, 2 \;\; i \neq j, \tag{8}$$

given the monopolist's optimal price w^* and prior to i's knowledge disclosure to its supplier. The parameters β_i and β_j take the value zero if the upstream firm is able to keep the shared knowledge fully secret, whereas positive values reflect the leakage of knowledge to downstream firms that is (here) not intended by the upstream firm. Making use of (8) and (7) we can write (3) as

$$\pi_i^* = (a - (q_i^{**} + q_j^{**}) - (A + w^* - X_i))q_i^{**} \quad i = 1, 2 \;\; i \neq j. \tag{9}$$

Differentiating (9) with respect to α_i yields

$$\frac{\partial \pi_i}{\partial \alpha_i} = x(2t - 5\beta_j)\frac{2(a - A - c + Y) + x(2 + 7\alpha_j \beta_i - 5\alpha_i \beta_j)}{72}. \tag{10}$$

Note that the fraction in (10) is strictly positive, which means that the sign of $(2t - 5\beta_j)$ alone determines whether knowledge transfer to the upstream monopolist is profitable from a downstream firm's point of view. We state this more precisely in:

Lemma 1 *There exists a critical level of knowledge leakage from the upstream firm, u, to the ith firm's rival j, which determines whether the ith firm discloses all or nothing of its knowledge to the upstream firm. Denoting this critical level β_j^c, we have*[8]

$$\alpha_i^* = 1 \Longleftrightarrow \beta_j \leq \beta_j^c = \frac{2}{5}t,$$

and

$$\alpha_i^* = 0 \textit{ otherwise}, \quad i = 1, 2 \;\; i \neq j.$$

Proof. By (10), $\partial\pi/\partial\alpha_i > 0 \Longleftrightarrow 2t - 5\beta_j > 0$, for all $\alpha_i \in (0, 1)$.

Disclosing knowledge to a common supplier has a threefold impact on a buyer's profit function. First, there is a positive cost efficiency effect because the buyer's knowledge decreases the supplier's costs and wholesale price, respectively. This positive effect is stronger the closer is the technological proximity between buyer and supplier. Second, there is a negative additional demand effect to the extent that the common supplier passes on knowledge to the other buyer which increases the latter's productivity and the wholesale price respectively. Third there is a negative strategic effect arising from increased competitiveness of the downstream rival. This effect is stronger i) the closer is the technological proximity between buyers and suppliers (albeit weaker as compared to the efficiency effect); and ii) the greater is the knowledge pass-on through the common supplier. Lemma 1 specifies the exact parameter ranges up to which the positive efficiency effect dominates the negative demand and strategic effects.[9]

Presence of Supplier Opportunism So far, we have assumed that the upstream firm tries to treat shared knowledge confidentially. We will now endogenize β and allow for opportunistic behavior of the supplier. To derive the upstream firm's second stage-profit function we first substitute w^* for w in (6) to get

$$Q^{**} = \frac{2(a - A - c + Y) + X_1 + X_2}{6}, \tag{11}$$

the final product production quantity, given w^*. Then, keeping in mind that w^* and Q^{**} are functions of X_1 and X_2 the upstream firm maximizes

[8] If buyers are indifferent about disclosing their knowledge to the supplier (i.e. $\beta_i = \frac{2}{5}t$), we assume that they will disclose.

[9] A critical leakage level does also exist for knowledge disclosure in *horizontal* research joint ventures (RJVs) between competitors. Atallah (2003) shows that firms will not disclose their knowledge to their RJV partners (insiders) if leakage of knowledge to rivals that are not RJV partners (outsiders) exceeds a critical level. The latter is increasing (decreasing) in the number of insiders (outsiders).

$$\pi_u^* = (w^* - (c - Y))Q^{**} \tag{12}$$

with respect to β_i. The first-order-condition,

$$\frac{\partial \pi_u}{\partial \beta_i} = \frac{1}{12}\alpha_j x(2(a - A - c + Y) + X_i + X_j) \geqslant 0 \tag{13}$$

is non-negative, as we have assumed that $a > A + w$ and $w > c$, which brings us to:

Proposition 1 *The upstream firm will always transfer all of the knowledge that it obtains from a downstream firm, i, to i's rival, j, i.e.* $\beta_i^* = 1, \quad i = 1, 2.$

Proof. Straightforward by (13).

The reason for this result is the additional demand effect. From a comparison of (11) and (13) it is obvious that for any unit of knowledge that the upstream firm transfers from one downstream firm to another, the upstream firm increases the demand for its own intermediate input proportionally. However, if the ith firm expects that the upstream firm has an incentive to transfer all of the knowledge it receives from i to firm j – i.e., $\beta_j^* = 1$ – we can conclude the following:

Proposition 2 *In the non-cooperative case the downstream firms will not disclose any of their knowledge to their (common) upstream supplier, i.e.,* $\alpha_i^* = 0, \quad i = 1, 2, \quad i \neq j.$

Proof. Straightforward by Proposition 1 and Lemma 1.

5 Knowledge Disclosure in Repeated Relationships

The result stated in Proposition 2 is not fully satisfying because in reality we do observe knowledge sharing in buyer-supplier relationships.[10] Therefore, in this section, we seek an alternative explanation of knowledge disclosure based on firms' repeated interaction. In particular we assume that the following (previously defined) stage game is repeated infinitely: (1) downstream firms choose α_i, (2) the upstream firm chooses β_i, (3) the upstream sets w, and (4) the downstream firms determine their output quantities, q_i.

Of course infinitely repeated interactions support an unlimited number of potential equilibria (folk theorem). However, we consider two equilibria more likely to emerge. These equilibria occur under the following assumptions: First, firms employ trigger strategies. Being rather straightforward may justify their application in reality.[11] Second, buyers act symmetrically. Under symmetric exogenous parameters, asymmetric strategies are hard to justify. Third, firms focus on cooperative equilibria that are Pareto optimal. Given a setting under certainty, cooperative actions will never

[10] See Lhuillery (2006) for a recent empirical study.

[11] We employ trigger strategies to derive some basic comparative static results regarding whether certain variables stabilize or destabilize cooperative solutions. Abreu's (1986, 1988) optimal punishment strategies would decrease the critical discount factor (i.e., increase the stability of the cooperative outcome) relative to trigger strategies but would not qualitatively change the comparative statics of that discount factor.

be answered by uncooperative ones. This means risk is no issue, and firms choose, if any, the most profitable cooperative outcome. Fourth, cooperation is restricted to stages one and two; the stage game's third and fourth subgame perfect equilibria as given by (7) and (8) remain unchanged. This is because firms wish to avoid antitrust scrutiny regarding price and quantity setting in the input market and product market, respectively. Even a completely implicitly attained cooperation that hurts consumers is generally subject to antitrust scrutiny. As firms are likely to communicate in stages one and two, antitrust concerns become yet more severe.

Cooperation may be attained on a vertical basis, between buyer and supplier, and on a horizontal basis, between buyers. Vertically, the upstream firm u can promise not to behave opportunistically by disclosing not too much of i's knowledge to j: that is, the common supplier installs a *weak firewall*. Horizontally, even if u behaves opportunistically, downstream firms may bilaterally disclose knowledge to the upstream firm, as the *full transmission* outcome, $\alpha_i = \alpha_j = \beta_i = \beta_j = 1$, is Pareto superior to the no-disclosure subgame perfect equilibrium of the one-shot game. We will investigate these settings in more detail below.

Weak Firewall Setting Suppose cooperation on a vertical basis and the following trigger strategy by the ith downstream firm: In the first period it fully discloses its knowledge to the upstream firm, $\alpha_i = 1$. In the t^{th} stage, if firm u has maintained a weak firewall of $\beta_j \leq \frac{2}{5}t$ in all $t-1$ periods, then the ith firm plays $\alpha_i = 1$; otherwise it plays the subgame-perfect outcome of the stage game, $\alpha_i = 0$. Notice that there is no alternative trigger strategy in support of a (weakly) more efficient outcome. In particular, if $\beta_j \leq \frac{2}{5}t$, then $\alpha_i = 1$ maximizes the i'th buyer's profit by Lemma 1, while it obviously maximizes the supplier's profit. That is for Pareto efficient cooperation, we can't have $\beta_j \leq \frac{2}{5}t$ and $\alpha_i < 1$. Further, by Lemma 1, if $\beta_j > \frac{2}{5}t$, the i'th buyer is better off playing the stage game's subgame perfect Nash equilibrium $\alpha_i = 0$. This means not to share any knowledge is a credible threat, and i 's trigger strategy prevents $\beta_j > \frac{2}{5}t$. Finally, the i'th buyer cannot enforce a stronger firewall, $\beta_j < \beta_j^c = \frac{2}{5}t$, because for any $\beta_j < \beta_j^c$, sharing all of its knowledge, $\alpha_i = 1$, makes the buyer (weakly) better off than playing its stage game's equilibrium $\alpha_i = 0$. That is, the i'th buyer's trigger strategy can't enforce $\beta_j < \beta_j^c = \frac{2}{5}t$.

Let $\pi_u^{2/5}$ denote u's weak firewall profit: i.e., both downstream firms (symmetrically) disclose their knowledge, and $\beta_j = \beta_i = \frac{2}{5}t$; let π_u^1 denote u's cheat profit: i.e., both downstream firms disclose their knowledge, and the upstream firm behaves opportunistically ($\beta_j = \beta_i = 1$); and let π_u^{00} denote u's profit if neither downstream firm discloses its knowledge to u. Note, again, that by Lemma 1 the ith downstream firm has no incentive to cheat as long as the upstream firm maintains its weak firewall. Computing the respective profits by (12), (11) and (7) yields

$$\pi_u^{2/5} = \frac{1}{6}(a - A - c + \left[1 + \frac{12}{5}t\right] x)^2, \tag{14}$$

$$\pi_u^1 = \frac{1}{6}(a - A - c + [2 + 2t]\, x)^2. \tag{15}$$

The squared bracketed terms in (14) and (15) reveal that the upstream firm has indeed a short-term incentive to behave opportunistically and to transfer the received knowledge completely; but, as indicated by

$$\pi_u^{00} = \frac{1}{6}(a - A - c + x)^2, \tag{16}$$

the upstream firm will suffer from this opportunistic behavior in subsequent periods when the downstream firms withhold their knowledge. The supplier will maintain its weak firewall (i.e., $\beta_j = \beta_i = \frac{2}{5}t$) if

$$\frac{1}{1-\delta}\pi_u^{2/5} \geqslant \pi_u^1 + \frac{\delta}{1-\delta}\pi_u^{00}, \tag{17}$$

where $\delta = (1-p)/(1+r)$ is the common discount rate, p is the probability that the game ends immediately, and r is an interest rate. Solving (17) for δ yields the critical discount factor to sustain the weak firewall equilibrium, δ_w:

$$\delta_w = \frac{(5-2t)(10(a-A-c)+(15+22t)x)}{25(1+2t)(2(a-A-c)+(3+2t)x)}. \tag{18}$$

Proposition 3 *Maintenance of a weak firewall, $\beta_i = \beta_j = \frac{2}{5}t$ and repeated downstream knowledge disclosure, $\alpha_i = \alpha_j = 1$, is stabilized by an increase in the technological proximity between the downstream and the upstream firm, $\partial\delta_w/\partial t < 0$, and destabilized by an increase in the value/amount of knowledge, $\partial\delta_w/\partial x > 0$.*

Proof. The derivatives are contained in the appendix.

The more knowledge that the supplier can utilize (via t), the more that it will miss that knowledge once buyers withhold it. Therefore closer technological proximity stabilizes maintenance of a (weak) firewall. On the other hand the upstream firm's incentive to transmit received knowledge is driven by the additional demand effect, which is stronger the larger is the amount/value of knowledge.

Full Transmission Setting Suppose now that there is cooperation on a horizontal basis. The supplier behaves opportunistically, $\beta_i = \beta_j = 1$. The ith firm may employ the following trigger strategy: In the first period it fully discloses its knowledge to the upstream firm, $\alpha_i = 1$. In the t^{th} stage, if both firms, $i = 1, 2$, have fully disclosed their respective knowledge in all $t-1$ periods, then the ith firm plays $\alpha_i = 1$; otherwise it plays the subgame-perfect outcome of the stage game, $\alpha_i = 0$. Notice that there is no other trigger strategy in support of a (weakly) more efficient outcome. This is because the i'th firm's profit is strictly increasing in symmetric knowledge exchange, $\alpha_i = \alpha_j = \alpha$.[12]

Let π_i^{11} denote the ith firm's profit if both firms disclose their knowledge, π_i^{01} if only $j \neq i$ and π_i^{00} if neither firm discloses its knowledge. Then by (9), (8) and (7) we have

[12] By (9), $\partial\pi_i^*|_{i=j,\beta=1}/\partial\alpha = 1/18(1+2t)x(a-A-c+x(1+\alpha(1+2t))) > 0$.

$$\pi_i^{11} = \left(\frac{1}{6}(a - A - c) + \left[\frac{1}{3} + \frac{1}{3}t\right]x\right)^2, \tag{19}$$

$$\pi_i^{01} = \left(\frac{1}{6}(a - A - c) + \left[\frac{3}{4} + \frac{1}{6}t\right]x\right)^2. \tag{20}$$

By the squared bracketed terms in (19) and (20) it is apparent that for any $x > 0$, π_i^{01} strictly exceeds π_i^{11}. This is due to the competitive advantage that the ith firm can achieve relative to its counterpart in the product market if j discloses but i withholds its knowledge. The squared bracketed term also reveals that the incentive to deviate from the knowledge-sharing strategy decreases the more that the upstream firm can utilize the downstream firms' knowledge, as captured by a larger t. Finally note that the downstream firms' profits of the one-shot non-disclosure equilibrium,

$$\pi_i^{00} = \left(\frac{1}{6}(a - A + x)\right)^2 \tag{21}$$

are clearly smaller than those given by (19) and (20). The i th firm continues to disclose its knowledge as long as

$$\frac{1}{1-\delta}\pi_i^{11} \geqslant \pi_i^{01} + \frac{\delta}{1-\delta}\pi_i^{00} \tag{22}$$

where the discount rate δ is defined as above. Solving (22) for δ yields the critical discount factor to sustain the knowledge sharing equilibrium, δ_f:

$$\delta_f = \frac{(5 - 2t)(4(a - A - c) + (13 + 6t)x)}{(7 + 2t)(4(a - A - c) + (11 + 2t)x).} \tag{23}$$

Proposition 4 *Full knowledge transmission, $\beta_i = \beta_j = 1$, and repeated downstream knowledge disclosure, $\alpha_i = \alpha_j = 1$, is stabilized by an increase in the technological proximity between the downstream and the upstream firm, $\partial\delta_f/\partial t < 0$, and destabilized by an increase in the value/amount of knowledge, $\partial\delta_f/\partial x > 0$.*

Proof. The derivatives are contained in the appendix.

The intuition behind this result is that downstream firms not only benefit directly from each other's knowledge but also benefit from the reduction of the intermediate input price. The latter benefit occurs only to the extent that the downstream firms' knowledge lowers the supplier's production costs, as captured by t. Hence technological proximity between vertically related firms stabilizes knowledge disclosure via the cost efficiency effect (see (7)). In contrast a larger value of information, x, increases the downstream firms' incentives to achieve a short-term competitive advantage more than it increases the benefit of the cost-efficiency effect. Thus more valuable information destabilizes knowledge disclosure.

The equilibrium described above may provide an explanation for intraindustry knowledge spillovers. These are usually regarded as an involuntary leakage of knowledge. According to our results intraindustry spillovers may well be the result of voluntary knowledge disclosure to suppliers and further knowledge transmission respectively.[13] A higher degree of technological proximity between customers and suppliers facilitates voluntary *inter*industry knowledge spillovers as well as intraindustry spillovers.

6 Summary and Conclusion

We have analyzed the conditions for knowledge disclosure and transmission in buyer-supplier relationships. The key feature of our model is the notion of a common supplier through which knowledge disclosed by one buyer may leak out to another. Downstream knowledge disclosure thus bears the risk of benefitting one's rival.

As regards one-shot relationships, our analysis provides the following results: Downstream competitors are willing to share knowledge to their mutual supplier so long as the latter does not pass on too much of that knowledge. However, the common supplier has an incentive to pass on all of the knowledge transmitted by one buyer to the other one. Anticipating this, downstream competitors do not disclose any knowledge in the first place.

In the case of repeated relationships we discuss two particularly likely equilibria. In the first one, buyers proceed with complete knowledge disclosure so long as the supplier maintains a weak firewall. In the second, more subtle one, knowledge disclosure occurs even under full knowledge transmission through the supplier. Here the supplier acts as an intermediary for implicit downstream knowledge sharing. Both the weak firewall and the full transmission setting are stabilized by an increase in the degree of technological proximity between downstream and upstream firms, whereas they are destabilized by an increase in the value/amount of knowledge. The latter suggests that a firm's disclosure of incremental innovations is more likely than the disclosure of major innovations.

Our model has several possible extensions. Formal cooperation between downstream firms and the upstream firm or formal cooperation between downstream firms is likely to increase the incentives for knowledge disclosure.[14] Further interesting questions arise in the case of multiple suppliers. In the repeated game setting, for instance, a supplier could increase its knowledge stock by building a reputation for discretion.[15]

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[13] As Sain-Paul (2003) shows, voluntary knowledge sharing occurs in the absence of punishment mechanisms but contingent on cumulative innovations.

[14] It can be shown that in the one-shot game and under joint buyer-supplier profit-maximization, buyers reveal their entire knowledge to a common supplier. This extension is available from the authors upon request.

[15] We wish to thank an anonymous referee for this idea.

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Appendix

Proposition 4 By (18) we calculate

$$\frac{\partial \delta_w}{\partial t} = -\frac{24(10((a-A)^2+c^2)+F_1+F_2+F_3)}{25(1+2t)^2(2(a-A-c)+(3+2t)x))^2} < 0,$$

where

$$\begin{aligned} F_1 &= (a-A)(25+24t+4t^2)x \geqslant 0, \\ F_2 &= (15+36t+28t^2)x^2 \geqslant 0, \\ F_3 &= (20(a-A)+(25+24t+4t^2)x)c > 0, \end{aligned}$$

and

$$\frac{\partial \delta_w}{\partial x} = \frac{24t(5-2t)(a-A-c)}{25(1+2t)(2(a-A-c)+(3+2t)x))^2} > 0.$$

Proposition 5 By (23) we have

$$\frac{\partial \delta_f}{\partial t} = -\frac{16(24((a-A)^2+c^2)+G_1+G_2+G_3)}{(7+2t)(4(a-A-c)+(11+2t)x)^2} < 0,$$

with

$$\begin{aligned} G_1 &= (a-A)(109+52t+4t^2)x \geqslant 0, \\ G_2 &= (127+148t+28t^2)x^2 \geqslant 0, \\ G_3 &= (48(a-A)+(109+52t+4t^2)x)c > 0. \end{aligned}$$

Finally note that

$$\frac{\partial \delta_f}{\partial x} = \frac{8(5+8t-4t^2)(a-A-c)}{(7+2t)(4(a-A-c)+(11+2t)x)^2} > 0.$$

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