The Interaction between Knowledge Codification and Knowledge Sharing Networks

De Liu
University of Kentucky
de.liu@uky.edu

Gautam Ray
University of Minnesota
rayxx153@umn.edu

Andrew B. Whinston
University of Texas at Austin
abw@uts.cc.utexas.edu

Abstract

Current knowledge management (KM) technologies and strategies advocate two different approaches: knowledge codification and knowledge sharing networks. However, the extant literature has paid limited attention to the interaction between them. This research draws upon the literature on formal modeling of networks to examine the interaction between knowledge codification and knowledge sharing networks. The analysis suggests that an increase in codification may damage existing network-sharing ties. Anticipating that, individuals may hoard their knowledge to protect their network ties, even when there are nontrivial rewards for codification. We find that despite the aforementioned tension between the codification and the network approach, a firm may still benefit from combining the two approaches. Specifically, when the future sharing potential between knowledge workers is high, a combination of the two approaches may outperform a codification-only or a network-only approach as the codification reward causes fewer network ties to break down and the benefit from increased codification can offset the loss of some network ties. However, when the future sharing potential is low an increase in codification reward can quickly break down the whole network, thus firms may be better off by pursuing a codification-only or a network-only strategy.

Keywords: Knowledge Management, Codification, Knowledge Sharing Network, Sharing Potential.

1. Introduction

One of the main challenges in managing a firm's knowledge is transferring knowledge from its source to where it is needed (Alavi and Leidner 1999; Fahey and Prusak 1998; Ruggles 1998). However, unlike tangible assets, firms often do not know where the knowledge is located or how much is it worth to them. Firms have coped with such challenges by mainly using two knowledge management (KM) approaches (Zack 1999b; Hansen et al. 1999). One approach, often referred to as the *codification* approach, involves codifying knowledge into electronic repositories, which are made accessible to all the knowledge workers (KWs) in the firm. The other approach, often referred to as the *network* approach, centers on facilitating interpersonal knowledge sharing through networks of people (Liebeskind et al., 1996; Hansen et al 1999; Borgatti and Cross 2003; Singh 2005; Wasko and Faraj 2005).

Prior studies have compared the two approaches to help firms choose the right KM approach for their specific situation. Zack (1999a) concludes that firms should use codification for sharing explicit knowledge and the network approach for sharing tacit knowledge. Hansen et al. (1999) argue that codification enjoys "scale economies" in knowledge reuse, while the network approach enjoys "expert economies" in providing value-added customized solutions. Hansen et al. (1999) conclude that firms that focus on providing standard solutions should follow the codification approach, and firms that focus on providing highly-customized services should follow the network approach. Besides the above mentioned differences, the two approaches provide different incentives for KWs to codify and/or to share their knowledge. In codification, the knowledge is transferred from KWs to the firm, and KWs are rewarded by the firm in the form of prizes, bonuses, salary increases, or promotions. In network sharing, KWs often remain owners of their knowledge and are rewarded by their peers through reciprocity. Thus, the two approaches can also be viewed as two distinctive incentive systems for knowledge transfer.

By studying the codification and the network approach separately, prior studies have made an implicit assumption that the two approaches work independent of each other. However, evidence suggests that the two incentive systems for knowledge transfer may interact. For example, Garud and Kuraraswamy (2005) studied KM in Infosys Technologies and found that when the firm introduced explicit rewards for codifying knowledge, network sharing was affected. Similarly, studies in consulting firms show that they have run into serious trouble when they failed to stick with one approach to KM (Hansen et al. 1999). These studies suggest that codification may interact with network sharing just as "some drugs interfere with the potentially positive effects of other drugs" (Huber 2001). Thus, one may no longer view codification and network sharing as independent, parallel solutions for managing knowledge. The goal of this paper is to model the interaction between codification and network sharing and to derive firms' best course of action while taking into account such interactions.

To study the interaction between codification and network sharing we treat the level of codification and network sharing as interrelated decisions of KWs. In particular, we formalize a network tie as a self-enforcing sharing agreement between two KWs. Knowledge sharing within a network tie is enforced through the benefits of future reciprocity from one's sharing partner, if one shares according to the sharing agreement; and the withdrawal of such benefits if one defaults.[1] Network sharing interacts with codification because codification provides KWs "outside options," i.e., benefits that they could get were they to lose their network ties. Using this framework, we examine how KWs choose their codification level and network ties to maximize their total benefits from codification and network sharing, and how the firm chooses the codification reward to optimally balance between codification and network sharing. In this way our analysis differs from studies that treat codification or the knowledge network as given and studies that consider codification and network sharing separately.

The analysis makes the following two contributions. First, we gain a better understanding of KWs' sharing behavior by considering the interaction between codification and network sharing. From KWs' perspective, as the benefit from codification increases, so does the value of the "outside option" to network-sharing, making it harder to sustain network ties. Anticipating the negative impact of codification on their network ties, KWs may keep their codification level down to protect their network ties, even when the firm gives nontrivial rewards for codification. We call this phenomena "knowledge hoarding." We also find that how many ties a KW will lose because of a marginal increase in her codification level depends

[1] Similar formalization has been used in studying inter-firm cooperation (Parkhe 1993) and in studying buyer-seller cooperation (Heide and Miner 1992).

mainly on a construct we call *sharing potential*. *Sharing potential* is determined by how often KWs demand each other's knowledge and by how much they value future sharing benefits. When the *sharing potential* is low, a small increase in the codification level causes a large number of network ties to terminate; so KWs either pursue a network-sharing-only strategy (when the codification reward is low) or a codification-only strategy (when the codification reward is high). However, when the *sharing potential* is high, an increase in the codification level causes fewer network ties to terminate, so KWs may benefit from combining codification and network sharing, and get higher payoffs.

Second, we outline firms' optimal strategies. When the *sharing potential* is low, the tension between codification and network sharing is high - a slight increase in the codification reward causes many network ties to break down. Thus, the firm has to choose between a network-only strategy (by not rewarding codification) and a codification-only strategy (by providing a high reward for codification). However, when the *sharing potential* is high, the tension between codification and network sharing is low, and the firm may benefit from combining the two approaches (i.e., a hybrid strategy) by giving a moderate reward for codification. Such a hybrid strategy induces a codification level that benefits KWs who are not covered by network ties, without causing too many network ties to terminate. A hybrid strategy is also more beneficial when KWs *social embeddedness* - the percentage of KWs who have social contact with each other and thus may form network ties - is low, as in such a case the firm can gain from the scale economy and reach of codification, without causing too many network ties to terminate. The rest of the paper is organized as follows. Section 2 presents the model, section 3 presents the analysis, and section 4 discusses the results.

2. The Model

We consider knowledge - know-how or know-what - as exogenous endowments to KWs and focus on the knowledge transfer problem among them. A firm employs a continuum of KWs. Time proceeds infinitely in descrete periods. All KWs discount next period payoffs by a factor δ ($0 < \delta < 1$). We may interpret δ as the probability that a KW will remain with the firm at the end of each period. A high discount factor δ would imply a low turn-over rate and/or more knowledge transfer opportunities (i.e., shorter periods).

In every period, with probability p each KW is endowed with one unit of distinctive knowledge from her knowledge domain, and this KW becomes a *supplier*.[2] To model that KWs have different demands for each others' knowledge, we assume that KWs are uniformly located on a knowledge circle of circumference 2 with density D. A KW's location on the knowledge circle is interpreted as the KW's knowledge domain. We assume that the probability for KW j to demand KW i's knowledge (q_{ij}) is inversely related to the *knowledge distance* (x_{ij}) between them. Specifically, we assume $q_{ij} = 1 - x_{ij}$. Thus, the farther away two KWs are from each other on the knowledge circle, the less likely they are to demand each other's knowledge (please see Figure 1 for an illustration). Given this model of demand and supply, the total expected demand for a supplier's knowledge is $2D \int_0^1 (1-x)\, dx = D$. Thus, D is also the expected number of demanders for a supplier's knowledge.

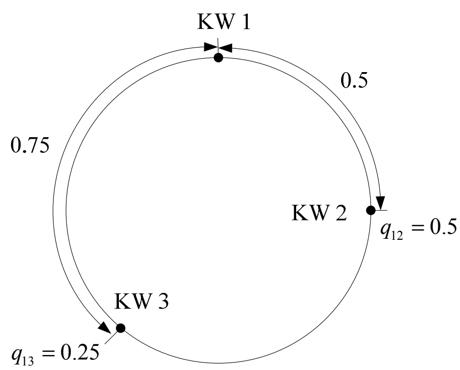

Figure 1: The Knowledge Circle

Knowledge can be transferred from suppliers to demanders through codification or through network sharing. In codification, a supplier codifies her knowledge and the codified knowledge is stored in a knowledge repository that is accessible to all the KWs for free. In network sharing, a supplier shares her knowledge with another KW, if they are connected by a knowledge sharing tie (which we will define shortly).

For each unit of knowledge obtained from network ties, a KW gets a benefit of 1.[3] For each unit of knowledge obtained from the knowledge repository, a KW gets a benefit of α ($\alpha \leq 1$). α captures the explicitness of the knowledge. The more explicit the knowledge, the

[2] For simplicity, we assume KWs are identical *ex ante*. This allows us to study a representative KW.
[3] As the focus of this paper is on knowledge transfer, this may be considered as a normalization.

greater the α.[4] As network ties provide higher value, we assume that KWs prefer network-shared knowledge to codified knowledge when the same knowledge is available from the repository as well as from network ties.[5]

As our focus is on knowledge transfer, we assume that KWs can *search* for knowledge in the knowledge repository or among their network-sharing partners at no cost. Knowledge *transfer*, however, is costly. At the minimum knowledge transfer requires KWs' time. We focus on suppliers' costs, which have been identified as the main impediment to organizational knowledge transfer.[6] We assume that the cost of network-sharing a unit of knowledge with each additional KW is e, and the one-time cost of codifying the same knowledge for access to all KWs is βe, where e is an exogenous random cost factor. We use e to capture KWs' opportunity cost of time (Reagans and McEvily 2003) and/or the complexity of the knowledge. β captures how high the codification cost is relative to the network-sharing cost. We assume that in each period all suppliers' cost factors are drawn independently from a uniform distribution $F(e)$ on [0, 1]. We allow KWs to codify and network-share at the same time, and assume that costs are additive if they choose to do both.

Codification. The incentive for codification comes from rewards for codification. Firms often encourage codification by rewarding contributors (Kankanhalli et al., 2005). These rewards may include prizes, bonuses, salary increases, or promotions. For example, Siemens provides points (like frequent flier miles) and shares for codification (Maccormack 2002). In this model, we assume that the firm gives a reward r to the supplier each time her codified knowledge is used by a KW.[7] We assume that KWs use a threshold codification strategy, i.e., a KW will codify her knowledge only if her cost factor is less than or equal to a threshold level e_c. We call e_c the KW's *codification level*.

[4] Several scholars (e.g., Inkpen and Dinur 1998) have suggested that "the distinction between explicit and tacit knowledge should not be viewed as a dichotomy but rather as a continuum with the two knowledge types at either end."

[5] To simplify the exposition, we also assume that KWs obtain network-shared knowledge from its original owner and that there is no market for second-hand knowledge.

[6] KWs may receive intrinsic joy from sharing (Constant et al., 1996). While such intrinsic joy has been found in contexts such as open source developments, we believe that they are less likely to be a dominating factor in organizational settings where individuals are expected to produce individual performances. Demanders may also incur costs from obtaining knowledge, such as the cost of absorbing the knowledge. We assume that these costs are outweighed by the benefits of receiving the knowledge.

[7] Assuming that the firm rewards contributors on a per-codification basis does not change the results.

Knowledge Sharing Network. We view a knowledge sharing network as a collection of dyadic ties. We say that two KWs have a knowledge sharing tie if they both honor an implicit knowledge sharing agreement. We assume that the agreement takes the following form: (i) i is obligated to share with j whenever i's cost of doing so does not exceed a threshold level e_s, and vice versa, and (ii) i will honor the agreement as long as j does the same. If j defaults, i will stop sharing with j in all future periods, and as a result the knowledge sharing tie between i and j will cease to exist.[8] We call e_s the *sharing level* between i and j. We assume that, because of peer monitoring, KWs know whether their sharing partners have defaulted on a sharing obligation.

We assume that two KWs will form a tie whenever: (i) they have social contact with each other, and (ii) both are better off from forming such a tie. The criterion (i) captures the fact that some KWs, despite being close knowledge-distance wise, may lack the opportunity to know each other, and therefore are not able to form a tie. We assume that a θ percentage of KW pairs have social contact with each other, where θ is exogenously given. We interpret θ as KWs' *social embeddedness*. The higher the *social embeddedness* θ, the more KWs may be covered by network sharing. θ may be affected by the size of the firm, the geographic distribution of the KWs, and by the firm's efforts in bringing KWs in touch with each other. The criterion (ii) captures the self-enforcing nature of knowledge sharing ties.

We assume that KWs choose the sharing level, e_s, for each of their network ties at the beginning of the game; and once chosen, these sharing levels remain constant throughout the existence of the network ties. We further assume that KWs choose sharing levels to maximize the sustainability of their network ties. Note that if two KWs maintain their tie even when their payoff from the tie is the lowest, then the tie always sustains. Thus, KWs choose their sharing levels to maximize the *lowest* payoff from their network ties. This criterion reflects the long-term nature of network-sharing ties. By choosing sharing levels this way, KWs ensure that their ties have the maximal chance of survival.

We assume that the firm's profits from knowledge transfer is μ times KWs' private benefit. So, each time a unit of codified knowledge is used by a KW, the firm gets $\alpha\mu$, and each time

[8] Similar framework has been used in modeling cooperation in Green and Porter (1984) and Kranton (1996).

a unit of knowledge is shared through a network tie, the firm gets μ. The firm chooses the codification reward r to maximize its profits,[9] which are the total profits from knowledge codification and network sharing, less the cost of codification rewards. Table 1 summarizes all the variables in the model.

Table 1. Definition of Variables

Variables		**Interpretation**
General Knowledge Sharing Environment	x	Distance between two KWs on the knowledge circle.
	p	Probability for a KW to be endowed with one unit of knowledge.
	δ	Discount factor
	β	Ratio between codification cost and network-sharing cost.
	μ	Firm's profit from per unit of knowledge transferred.
	D	Density of knowledge workers on the knowledge circle.
Network Sharing	e	Cost of network sharing.
	θ	Social embededness: The percentage of KWs who have social contact with each other and thus can form a network tie.
	e_s	Sharing level: The maximal cost factor below which a KW will choose to share with a sharing partner.
Codification	α	Value of codified knowledge
	r	Reward for knowledge codification based on usage.
	e_c	Codification level: The maximal cost factor below which a KW will choose to codify.

The game proceeds as follows (Figure 2). At the beginning of the game, the firm announces the codification reward r, and each pair of KWs who have social contact choose the sharing levels e_s for their network ties. Next, KWs enter a stage game that is repeated indefinitely. At the beginning of each period, each KW independently and simultaneously chooses her codification level e_c, taking into account the effect of her codification level on the sustainability of her network ties. Next, the supply and the demand of knowledge are endowed and suppliers' cost factors are realized. Then each supplier decides whether to codify and whether to network-share on each of her network ties, depending on her realized cost factor and her codification and sharing levels. Demanders attempt to obtain knowledge in network-shared form or in codified form (if the former is not available). The firm rewards codifiers based on the usage of their codified knowledge. KWs observe whether their sharing partners have honored their sharing agreement and if not, punish them by terminating their ties forever. In the next section we analyze KWs' decisions and the firm's optimal strategy.

[9] The firm may engineer the knowledge sharing network in the long run, e.g., by nurturing a culture of mutual sharing. Nevertheless, the knowledge sharing network may not be fully engineered (Ingram and Roberts 2000). For this reason, we use r as the decision variable to study the interaction between codification and network sharing.

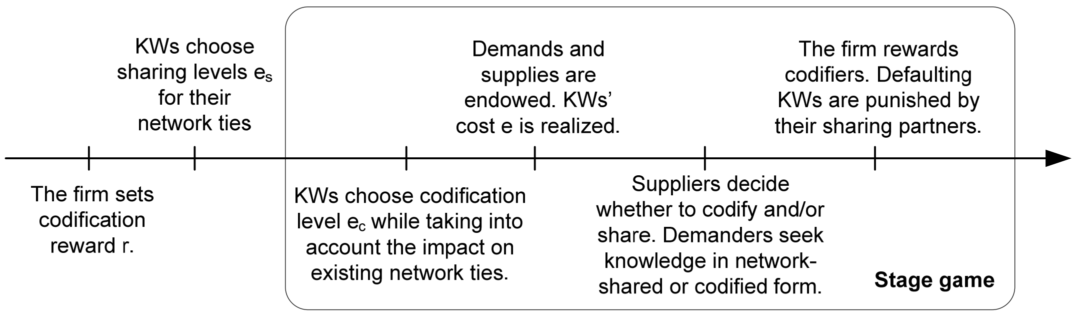

Figure 2: The Game Timeline

3. Analysis

In this section we first examine KWs' choice of sharing levels (i.e., e_s) for their network ties. We then study KWs' choice of codification level (i.e., e_c) while taking into account the impact of the codification on KWs' existing network ties. Next, we examine the firm's optimal choice of the codification reward that maximizes the total profits from codification and network sharing. Finally, we conduct comparative statics analysis on two key parameters.

3.1 The Choice of Sharing Levels

In our model, two KWs choose their sharing level at the beginning of the game to maximize the lowest payoff from their network tie. A KW's total payoff from a tie consists of her current-period payoff and her discounted future payoffs. Consider the tie ij (assuming i and j have social contact with each other and thus can form a tie). KW i's expected payoff from tie ij in any one future period is $p(1-x)F(e_s) - p(1-x)\int_0^{e_s} e de$, where the first term is i's expected benefit as a demander, and the second term is i's expected cost as a supplier. i's current-period payoff depends on the realization of demand and supply, and is the lowest when i is a pure supplier, i.e., j is not obligated to share with i, i is obligated to share with j, and i's cost of sharing with j is exactly e_s. So i's lowest total discounted payoff from the tie is

$$\begin{aligned} u_i(e_s) &= \frac{\delta}{1-\delta}\left[p(1-x)F(e_s) - p(1-x)\int_0^{e_s} e de\right] - e_s \\ &= \underbrace{\frac{\delta p}{1-\delta}(1-x)\int_0^{e_s}(1-e)\,de}_{\text{discounted future payoff}} - \underbrace{e_s}_{\text{current-period cost}} \end{aligned} \quad (1)$$

where the first term in (1) is the discounted future payoff and the second term is the current-period cost. We term

$$A \equiv \frac{\delta}{1-\delta} p \tag{2}$$

as the *sharing potential*. Its meaning is derived from the fact that the higher the discount factor δ, and the higher the probability p for a KW to be endowed with one unit of knowledge, the higher the future payoffs from the network tie (the first term in (1)). The sharing potential is intimately related to how sustainable a tie is. As the sharing potential becomes higher, the discounted future payoff from the tie increases, and the KWs are willing to incur a higher opportunity cost to maintain the tie. The role of sharing potential in sustaining a network tie is sometimes referred to as the "shadow of the future" (Heide and Miner 1992; Parkhe 1993). The sharing potential captures how long a shadow the future casts on a network tie.[10]

By our assumption, KWs will choose their sharing level to maximize (1), from which we can derive the KWs' sharing level as:

$$e_s(x) = 1 - \frac{1}{A(1-x)}. \tag{3}$$

We know immediately from (3) that the sharing level decreases in the knowledge distance x and increases in the sharing potential A. This is consistent with the observation that KWs tend to build stronger ties with KWs whose knowledge domains are more closely related and with whom they expect to interact more frequently and for a longer period of time (Brass et al. 2004).

3.2 The Condition for a Tie to be Sustainable

For a knowledge sharing tie to be sustainable, each party must get at least as much benefit from keeping the tie as from not keeping it. Therefore, the sustainability of a tie is determined not only by the payoff derived from the tie but also the payoff from *outside options*, in our case, the payoff from codification.

[10] The sharing potential may have both an individual-level component (e.g., the probability that a particular individual will leave the firm) and a firm-level component (e.g., the firm's overall hiring and retention practice). We focus on the firm-level component as we are more interested in the firm-level implications (note that we assume symmetry among KWs).

Let y_{ij} denote the difference in KW i's total discounted payoff between maintaining the tie with j and not maintaining the tie with j, assuming that i and j's codification levels are both e_c. When the tie ij exists, i and j will get each others' knowledge through network sharing. We already know that i's (lowest) total discounted payoff from network tie ij is $u_i(e_s)$. When the tie ij does not exist, i will forgo the entire $u_i(e_s)$, but i can get codified knowledge of value α from j with probability $p(1-x)F(e_c)$. Also, i can get an additional codification reward r with probability $p(1-x)F(e_c)$ because j will start using codified knowledge from i, as their tie does not exist any more. Thus, the condition for i to maintain the tie ij is

$$y_{ij} = u_i\left(e_s\right) - \frac{\delta}{1-\delta} p\left(1-x\right)\left[\alpha F(e_c) + rF(e_c)\right] \geq 0 \tag{4}$$

Proposition 1. *Denote* $e_c^0 \equiv \frac{1}{2(\alpha+r)}(1-\frac{1}{A})^2$*. When* $e_c < e_c^0$*, a pair of KWs can sustain their tie if and only if* $x \leq 1 - \frac{1}{A\left(1-\sqrt{2(\alpha+r)e_c}\right)}$*. When* $e_c \geq e_c^0$*, no network tie can exist.*

We define $\bar{x} \equiv 1 - \frac{1}{A\left(1-\sqrt{2(\alpha+r)e_c}\right)}$ for $e_c < e_c^0$ and $\bar{x} \equiv 0$ for $e_c \geq e_c^0$. Proposition 1 shows that (all proofs are in the appendix) the maximal knowledge distance below which KWs can sustain a tie is $\bar{x}$. We interpret $\bar{x}$ as the *scope of a KW's network*. For example, $\bar{x} = 0.6$ means that a KW can sustain network ties with KWs who are within 0.6 knowledge distance. The network scope $\bar{x}$ decreases in the codification level e_c. Intuitively, as the codification level increases, the benefit from codification increases, and so does the value of the "outside option" to network-sharing, making it harder for two KWs to sustain a network tie. The ties between distant KWs will be terminated first because when KWs are farther apart on the knowledge circle, not only do they have fewer knowledge sharing opportunities, but they also have lower sharing levels (as in (3)).

Proposition 1 suggests that the network scope $\bar{x}$ and the maximal codification level e_c^0 increase with the sharing potential A. When the sharing potential is high, KWs have larger sharing networks and it will take a higher level of codification to break down the entire network. Proposition 1 also suggests that the sharing potential affects the negative impact of codification on network ties. When the sharing potential is higher, an increase in codification threatens fewer existing ties, implying that a higher sharing potential mitigates the negative impact of codification on the knowledge sharing network.

Proposition 1 also suggests that network scope $\bar{x}$ and the maximal codification level e_c^0

decrease with knowledge explicitness α and the codification reward r. This is because as α increases, the value of codified knowledge increases for the demander; and as r increases, the value of codification increases for the supplier, thus making the codification approach stronger vis a vis network sharing.

3.3 The Equilibrium Codification Level

We are interested in a symmetric Nash equilibrium codification level e_c^* such that a KW finds it optimal to adopt a codification level e_c^*, given that all other KWs adopt the codification level e_c^*. As codification impacts network ties, a KW chooses her codification level to maximize her aggregate payoff from codification and network sharing. We first consider a KW i's per-period payoff from codification. The demand for i's codified knowledge comes from (a) KWs who do not have social contact with i and thus don't have a tie with i, and (b) KWs who have social contact with i but are not able to maintain a tie with i. Thus, the total expected demand for i's codified knowledge is: $(1-\theta)\int_0^1 (1-x)\,2Ddx+\theta\int_{\bar{x}}^1 (1-x)\,2Ddx = D\left[(1-\theta)+\theta\,(1-\bar{x})^2\right]$. By symmetry, the expected number of KWs who will share with i through codification is: $D\left[(1-\theta)+\theta\,(1-\bar{x})^2\right]$. Assuming i codifies at level e_c, and every other KW codifies at level e_c', i's per-period payoff from codification is:

$$\underbrace{pF(e_c)rD[(1-\theta)+\theta(1-\bar{x})^2] - p\int_0^{e_c} \beta e de}_{\text{as a supplier}} + \underbrace{\alpha F(e_c')pD[(1-\theta)+\theta(1-\bar{x})^2]}_{\text{as a demander}}. \tag{5}$$

KW i's expected per-period payoff from the knowledge sharing network is i's expected benefit from the network as a demander less i's expected cost from the network as a supplier,

$$\underbrace{\int_0^{\bar{x}} p\theta\,(1-x)\,e_s\,(x)2Ddx}_{\text{as a demander}} - \underbrace{\int_0^{\bar{x}} p\theta\,(1-x)\int_0^{e_s(x)} ede2Ddx}_{\text{as a supplier}}. \tag{6}$$

i's total expected per-period payoff is the sum of (5) and (6), which can be rewritten as

$$w(e_c, e_c') = pD(e_c r+e_c'\alpha)[(1-\theta)+\theta(1-\bar{x})^2]-\frac{1}{2}p\beta e_c^2+2pD\theta\int_0^{\bar{x}}(1-x)[e_s(x)-\frac{1}{2}e_s(x)^2]dx. \tag{7}$$

A symmetric equilibrium codification level, e_c^*, satisfies $w(e_c^*, e_c^*) \geq w(e_c, e_c^*)$ for any e_c.

Please note that in (7) the network scope ($\bar{x}$) is a function of the KW's codification level (see Proposition 1), reflecting the impact of codification on KWs' network ties. If KWs ignore this impact, they would choose a *naïve codification level*, i.e., one that maximizes the total payoff (7) pretending that $\bar{x}$ is not affected by codification. When KWs choose a codification level that is lower than the naïve codification level, we say that they "hoard."

Proposition 2. *(a) For any A, there always exists a codification reward $r^0 (> 0)$ below which KWs only network-share. (b) For any A, there always exists a codification reward $r^1 (\geq r^0)$ above which KWs only codify, and the equilibrium codification level is given by $e_c^* = Dr/\beta$. (c) A KW does not codify and network-share at the same time if $A < \sqrt{\frac{\theta}{1-\theta}\left(\frac{2\alpha}{r}+1\right)}$. (d) A KW codifies and network-shares at the same time if $A > \frac{1}{1-\sqrt{2(\alpha+r)Dr/\beta}}$ and $A > \sqrt{\frac{\theta}{1-\theta}\left(\frac{2\alpha}{r}+1\right)}$, and the equilibrium codification level e_c^* is the solution to*

$$rD - \beta e_c - \theta D\left[r + \frac{2\alpha + r}{A^2\left(1-\sqrt{2\left(\alpha+r\right)e_c}\right)^2}\right] = 0. \tag{8}$$

Proposition 2(a) implies that KWs pursue a *network-only* strategy (i.e., no codification) for a sufficiently low codification reward. Intuitively, when the codification reward is very low, the gain from codification is trivial compared with the loss of benefits from the network ties that would be eliminated because of the codification. So KWs are better off not codifying. In this case KWs hoard completely, i.e., their equilibrium codification level is zero whereas the naïve codification level is positive. Here KWs hoard not because they have no time for both codification and network sharing; rather, it is because KWs anticipate the negative consequence of codification on their network ties and choose to not codify.

Proposition 2(b) suggests that KWs pursue a *codification-only* strategy (i.e., no network sharing) when the codification reward is sufficiently high. It is intuitive that when the reward for codification is very high, the outside options are very valuable, and KWs will give up all their existing network ties and only codify. In the case of a codification-only strategy, the equilibrium codification level increases with the codification reward r and the number of demanders (D), and decreases with the cost of codification (β).

Proposition 2(c) and 2(d) shed light on when it is optimal for KWs to adopt a *hybrid* strategy, i.e., to simultaneously network-share and codify. When the sharing potential is low, a KW may not use a hybrid strategy (Proposition 2(c)). This is because when the sharing potential is low, an increase in the codification level causes many ties to terminate, thus, KWs have to choose between codification and network sharing. In such a case, KWs network-share when the codification reward is low and codify when the codification reward is high. However, Proposition 2(d) shows that KWs may pursue a hybrid approach when the sharing potential is sufficiently high. When the sharing potential is high, an increase in the codification level causes fewer network sharing ties to terminate, thus KWs can increase their total benefits by combining codification and network sharing.[11]

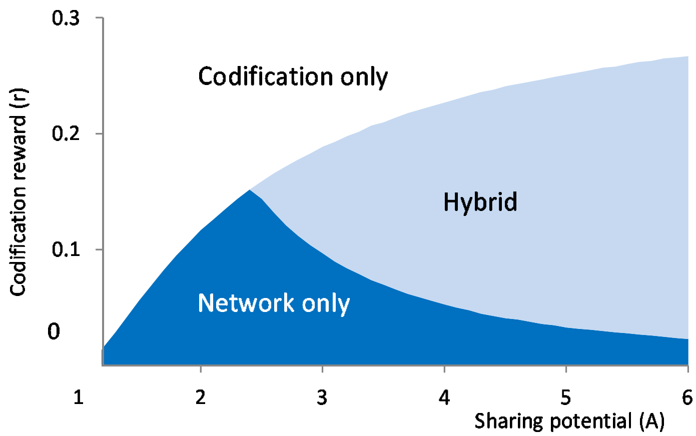

Figure 3: A KW's Equilibrium Strategy

According to (8), in the case of a hybrid strategy, the equilibrium codification level increases with the sharing potential (A); and decreases with the codification cost (β), the value of the codified knowledge (α), and the social embeddness (θ). The intuition is as follows. As A increases, an increase in the codification level causes fewer network sharing ties to terminate (see Proposition 1). As a result, KWs are more willing to increase their codification level. However, when α increases, codification poses a larger threat to existing ties, as codified knowledge is closer in value to network-shared knowledge. Thus, KWs adjust their codification level downward to protect their existing network ties. Similarly, when θ increases, there are more ties within a unit distance, so an increase in codification also causes more ties to terminate. Thus, by the same token, KWs decrease their codification level to protect their network ties.

[11] Other parameter may also influence the number of ties that are affected by an increase in the codification level. For example, when the social embeddedness (θ) is high, there are more sharing partners within a unit distance on the knowledge circle. So an increase in codification causes more ties to be eliminated. In such a case, a higher sharing potential may be required for a hybrid strategy to be optimal for KWs (this can be seen from the second condition of Proposition 2(d)). We discuss the effect of θ in section 3.5.

Figure 3 shows how KWs change their strategies with the codification reward and the sharing potential.[12] Unless specified we set p=0.5, β=2, D=3, θ=0.4, α=0.6, and μ=0.7 for all the figures in the paper. Figure 3 illustrates that at any A, KWs adopt a network-only strategy for a low enough (but positive) codification reward, and a codification-only strategy for a high enough codification reward. When A is relatively low (below 2.4), KWs never adopt a hybrid strategy. Whereas when A is high (2.4 and above), KWs adopt a hybrid strategy for a moderate codification reward.

To gain further understanding about KWs' equilibrium strategy, in Figure 4 we plot KWs' equilibrium codification level (e_c) and network scope ($\bar{x}$) when the sharing potential is low (A=1.5 by letting δ=0.75) and when the sharing potential is high (A=4.5 by letting δ=0.9). We also plot KWs' naïve codification-level, i.e., their codification level if they ignore the interaction between codification and network-sharing. When the sharing potential is low (Figure 4, left panel), KWs only network-share (i.e., the equilibrium codification level is zero) for r between 0 to 0.06. In this parameter range KWs hoard completely and the network scope remains unchanged. However, as soon as r goes beyond 0.06, the network scope drops to zero (i.e., there are no network ties left for network sharing), and KWs turn to a codification-only strategy. In this parameter range, KWs do not hoard at all (note that the equilibrium codification level coincides with the naïve codification level), and the equilibrium codification level increases steadily with r. This illustrates that when A is low KWs hoard completely for r up to a threshold level (r=0.06, in this case), and as soon as r exceeds that threshold level, KWs stop hoarding and switch to a codification-only strategy.

When the sharing potential is high (Figure 4, right panel), we observe similar behaviors in the case of low r (between 0 and 0.04) and in the case of high r (above 0.24). What's different is that for r between 0.04 and 0.24, KWs codify and network share at the same time. In this parameter range, the network scope decreases and the codification level increases with r, but KWs still hoard to some degree as the equilibrium codification level is lower than the naïve codification level. As r goes beyond 0.24, KWs turn to a codification-only strategy, and their network scope drops suddenly from a significant level to zero. In this way this

[12] We thank an anonymous reviewer for suggesting this figure.

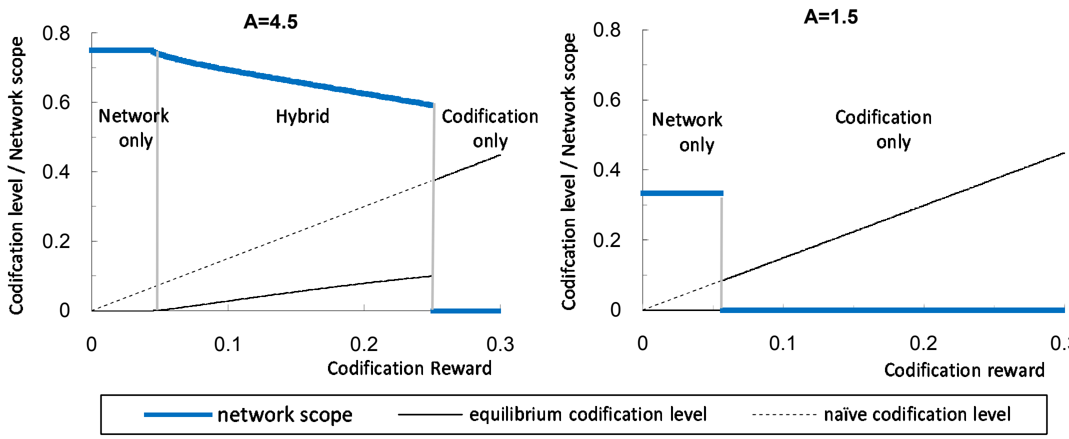

Figure 4: KWs' Equilibrium Codification Level and Network Scope

figure illustrates that when A is high KWs hoard completely for r up to a threshold level (r=0.04, in this case), and then adopt a hybrid strategy but still hoard to some degree for a moderate r, and finally stop hoarding and switch to a codification-only strategy for a high r (above 0.24, in this case).

In summary when A is high, an increase in the codification level causes a relatively small decrease in the scope of network ties, so KWs can benefit from codification without losing too many of their network ties. In contrast, when A is low, the benefits from a marginal increase in codification are unable to offset the loss of network ties. Thus, KWs optimally choose between a network-only and a codification-only strategy. Proposition 2 implies that if the firm raises the codification reward from zero to some significant level, KWs will move away from a network-sharing-only state towards an equilibrium where they codify more.

3.4 The Firm's Profits

The firm profits from knowledge transfer (through codification and/or through network sharing) and pays the codification reward. We first consider the firm's profits from codification. Each KW codifies her knowledge with probability $F(e_c^*)$, which has an expected demand of $D\left[(1-\theta)+\theta\left(1-\bar{x}\right)^2\right]$. For each unit of knowledge transferred through codification, the firm gets $\alpha\mu$ and pays r. So the expected profit from codification by one KW is

$$pF(e_c^*)D\left[(1-\theta)+\theta(1-\bar{x})^2\right](\alpha\mu-r), \tag{9}$$

where e_c^* is the equilibrium codification level chosen by KWs given codification reward r, and $\bar{x}$ is the network scope given r and e_c^*.

Now we consider the firm's profits from network sharing. A KW network-shares with KWs she has social contact with and who are within the maximal knowledge distance $\bar{x}$. A KW will share her knowledge with a sharing partner as long as her cost factor is less than her sharing level with this network partner. For each unit of knowledge shared, the firm derives a profit μ. Therefore, the expected profit from network sharing by one KW is

$$p \int_0^{\bar{x}} (1-x) F(e_s(x)) 2D\theta dx \cdot \mu \tag{10}$$

The firm's total profits are the sum of profits from codification (9) and network sharing (10), which reads:

$$\pi(r) = DpF(e_c^*) \left[(1-\theta) + \theta (1-\bar{x})^2\right] (\alpha\mu - r) + 2Dp\theta\mu \left(\bar{x} - \frac{\bar{x}^2}{2} - \frac{1}{A}\bar{x}\right) \tag{11}$$

We first consider the firm's problem when the sharing potential is low such that KWs either pursue a network-only strategy or a codification-only strategy. When KWs pursue a network-only strategy, ${e_c}^*$=0 and $\bar{x} = 1 - 1/A$, and the firm's total profit is

$$Dp\theta\mu(1-1/A)^2. \tag{12}$$

When KWs pursue a codification-only strategy, $\bar{x}$=0, ${e_c}^*$=Dr/β, and the firm's total profit is

$$DpDr(\alpha\mu - r)/\beta. \tag{13}$$

Proposition 3: *When the sharing potential is low, the firm may pursue either a codification-only strategy or a network-only strategy. The firm should pursue a network-only strategy when* $D\alpha^2\mu/\beta \leq 4\theta (1-1/A)^2$, *and a codification-only strategy otherwise. In the network only case, the optimal codification reward* r^* *is zero; and in the codification only case the optimal codification reward is* $\alpha\mu/2$.

Proposition 3 suggests that codification becomes more advantageous from the firm's point of view when D (the expected number of demanders for a unit of knowledge), α (the value of codified knowledge) and μ (the firm's appropriation ratio) are higher;[13] and when β (relative

[13] In codification, the firm gives rewards in exchange for codified knowledge. The firm can appropriate the value of this codified knowledge when other KWs use it. Thus, the higher the firm's appropriation ratio, the higher revenue these codification rewards can bring to the firm, so the more advantageous the codification strategy becomes.

cost of codification), A (the sharing potential) and θ (the social embeddedness of KWs) are lower.

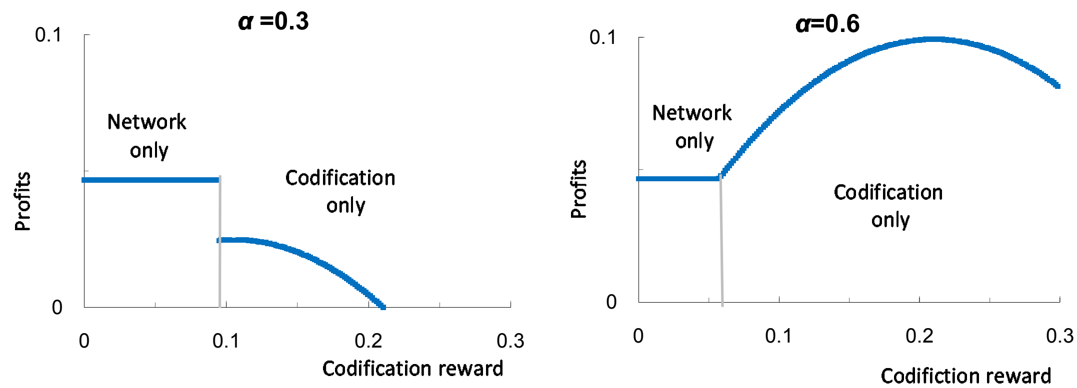

Figure 5: Choice between a codification-only strategy and a network-only strategy when A is low

To illustrate Proposition 3, we use the value of codified knowledge α to adjust the relative advantage of codification. Figure 5 illustrates the firm's profits as a function of the codification reward at two different levels of α, when the sharing potential is low (A=1.5). In the first case (α=0.3), network-sharing has relative advantage, thus the firm's optimal strategy is to induce a network-only strategy among KWs by choosing a zero reward for codifcation. In the second case (α=0.6), codification has relative advantage, thus the firm's optimal strategy is to induce a codification-only strategy by choosing a codification reward of 0.21. In this example (i.e, at $A = 1.5$) there is no value of α where it is optimal for the firm to induce a hybrid strategy.

We now turn to the case of high sharing potential (A=4.5). We know from Proposition 2 that when the reward for codification is moderate, KWs may codify and network-share at the same time. Figure 6 shows that the firm's total profits in such a case may be higher than that in the network-only case or in the codification-only case, and as a result, inducing a combination of codification and network sharing may be the best strategy for the firm.

In Figure 6, the firm's total profits peak at r=0.17. Under this codification reward, KWs both codify and network-share. The explanation is as follows. When the sharing potential is high, an increase in the codification reward causes fewer ties to terminate. Therefore, the firm can gain codification profits without losing too much of the network-sharing profits,

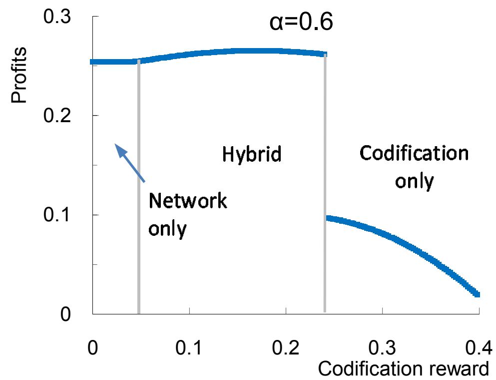

Figure 6: The firm may optimally induce a hybrid strategy when A is high

implying an increase in total profits compared with the network-only case. Of course, when the relative advantage of codification is too high, the firm may prefer a codification-only strategy to a hybrid strategy. Similarly, the firm may pursue a network-only strategy when codification is extremely disadvantaged compared to network-sharing (such as when α=0.01 in the above case).

Corollary 1: *When the sharing potential is high, the firm may be better off by inducing a combination of codification and network sharing among KWs.*

3.5 Comparative Statics Analysis

This section explores the implications of one key codification side parameter (α), and one key network side parameter (θ).

Impact of Knowledge Explicitness α. We first evaluate the impact of α on KWs' behavior and then on the firm's optimal codification reward. We consider two cases, A=1.5 and A=4.5. To best illustrate our findings, we use default values p=0.5, β=2, D=3, θ=0.6, α=0.6, and μ=0.7. For each case, we record the lowest codification reward beyond which KWs start to codify (r^0), and the lowest codification reward beyond which no network ties exist (r^1). So KWs pursue a network-only strategy when the codification reward is lower than r^0, and pursue a codification-only strategy when the codification reward is higher than r^1. When $r^0 < r^1$ KWs adopt a hybrid strategy for codification reward between r^0 and r^1. Otherwise (i.e., when $r^0 = r^1$) no hybrid strategy is possible, and KWs will switch from network-only strategy to codification-only strategy when r increases above r^0. We also record the firm's optimal codification reward (r^*) and the corresponding codification level

(e_c^{**}). Note that $r^* = 0$ indicates that pursuing a network-only strategy (N) is optimal for the firm, $r^0 < r^* \leq r^1$ indicates that pursuing a hybrid strategy (H) is optimal, and $r^* > r^1$ indicates that pursuing a codification-only strategy (C) is optimal.

When the sharing potential is low (A=1.5), KWs choose either a network-only strategy or a codification-only strategy (seen from $r^0 = r^1$), depending on the codification reward chosen by the firm (see Table 2). The firm chooses a reward to pursue a network-only strategy when α is low ($\alpha < 0.6$) and chooses a reward to pursue a codification-only strategy when α is higher ($\alpha \geq 0.6$). When the sharing potential is high (A=4.5), KWs are more likely to adopt a hybrid strategy (seen from $r^0 < r^1$). It is also optimal for the firm to induce a hybrid strategy. Quite interestingly, when the sharing potential is high (A=4.5), codification may not dominate the hybrid strategy even when α is 1 (i.e., the firm may still find a hybrid strategy optimal). This is because the relative advantage of codification depends on multiple parameters (see Proposition 3), and a high α alone does not guarantee that the codification-only strategy will dominate the hybrid-strategy.

Table 2. The Effect of Knowledge Explicitness (α)

	***A*=1.5**				***A*=4.5**			
α	r^0	r^1	r^*	e_c^{**}	r^0	r^1	r^*	e_c^{**}
0.1	0.197	0.197	0→ N	0	0.017	0.505	0.035→ H	0.009
0.2	0.144	0.144	0→ N	0	0.033	0.427	0.068→ H	0.016
0.3	0.110	0.110	0→ N	0	0.049	0.363	0.100→ H	0.019
0.4	0.088	0.088	0→ N	0	0.065	0.310	0.131→ H	0.021
0.5	0.073	0.073	0→ N	0	0.081	0.267	0.161→ H	0.022
0.6	0.062	0.062	0.21→ C	0.32	0.097	0.241	0.191→ H	0.022
0.7	0.054	0.054	0.25→ C	0.37	0.113	0.220	0.219→ H	0.021
0.8	0.048	0.048	0.28→ C	0.42	0.129	0.202	0.201→ H	0.011
0.9	0.043	0.043	0.32→ C	0.47	0.145	0.186	0.185→ H	0.004
1	0.039	0.039	0.35→ C	0.53	0.161	0.173	0.172→ H	0.001

Impact of Social Embeddedness θ. The higher the parameter θ, the more the number of KWs who can be connected through network ties, and the denser the knowledge network. As a result, the higher the θ, the higher the number of network ties that are threatened by an increase in codification, and the greater the tension between codification and network-sharing. Though we do not formally model "network search" in this paper, θ may also be interpreted as the number of knowledge sharing partners a KW can search to meet a knowledge need.[14] In other words, if the search cost within the knowledge network is very low, θ is high; and if the search cost within the knowledge network is high, θ is low.

Table 3. Comparative Statics on θ

	A=1.5				**A=4.5**			
θ	r^0	r^1	r^*	e_c^{**}	r^0	r^1	r^*	e_c^{**}
0.1	0.057	0.057	0.21→ C	0.315	0.007	0.241	0.171→ H	0.183
0.2	0.057	0.057	0.21→ C	0.315	0.016	0.241	0.165→ H	0.132
0.3	0.057	0.057	0.21→ C	0.315	0.027	0.241	0.165→ H	0.095
0.4	0.057	0.057	0→ N	0	0.041	0.241	0.171→ H	0.066
0.5	0.057	0.057	0→ N	0	0.063	0.241	0.177→ H	0.042
0.6	0.063	0.063	0→ N	0	0.097	0.241	0.191→ H	0.022
0.7	0.072	0.072	0→ N	0	0.157	0.260	0.215→ H	0.006
0.8	0.081	0.081	0→ N	0	0.288	0.288	0→ N	0
0.9	0.092	0.092	0→ N	0	0.317	0.317	0→ N	0
1	0.101	0.101	0→ N	0	0.347	0.347	0→ N	0

When the sharing potential is low (A=1.5), the knowledge network is weak, and the KWs tend to pursue either a codification-only or a network-only strategy (see Table 3). When θ is low ($\theta < 0.4$), the number of network ties are few and the total profits from network sharing is low, so it is optimal for the firm to induce a codification-only strategy. However, when θ is high ($\theta \geq 0.4$), the firm induces a network-only strategy. When the sharing potential is high (A=4.5), the knowledge network is strong. When θ is relatively low ($\theta \leq 0.7$), a relatively smaller proportion of KWs are connected through network ties; thus more KWs can benefit from an increase in codification and fewer network ties are threatened by such an increase. Thus, the KWs and the firm have relatively more to gain from combining codification and network sharing. However, when θ is high ($\theta > 0.7$), a large proportion of KWs are connected through network ties. This implies that few KWs can benefit from an increase in codification while more network ties will be threatened by such an increase. Therefore, when θ is high, it may not be a good strategy for KWs and the firm to adopt a hybrid strategy, even though the sharing potential may be as high as 4.5.[15] Intuitively, if θ is very high, KWs can meet their knowledge needs through their many network ties and codification can hardly achieve

[14] We thank an anonymous reviewer for this insight.

[15] It may be noted that as long as θ is less than 1, there exists a high value of A for KWs to adopt a hybrid strategy. But in the extreme case of θ=1, KWs will never combine codification and network-sharing. Please note from Proposition 2(c) and 2(d) that when θ=1, the sharing potential for KWs to choose a hybrid strategy is undefined.

its scale economy. However, when A is high and θ is low, KWs have fewer opportunities to meet their knowledge needs through network sharing, but codification can achieve scale economy without causing too many ties to terminate, thus, the firm has relatively more to gain from combining codification and network sharing.

4. Discussion and Conclusion

This paper uses a formal game-theoretic framework to provide an initial account of how knowledge codification and knowledge sharing network interact with each other. We find that codification threatens the sustainability of knowledge sharing ties by increasing KWs "outside options." Anticipating such consequences, KWs may hoard their knowledge, even when the firm provides nontrivial rewards for codification. These findings lend support to the evidence that rewarding knowledge codification may affect network sharing (e.g., Garud and Kuraraswamy 2005) and overly aggressive IT-enabled codification strategy may disturb the balance between individual's private knowledge and the public codified knowledge (Griffith et al. 2005). We also provide an alternative explanation for hoarding: KWs may refuse to codify their knowledge for the purpose of preserving their network ties (rather than because of codification cost).

At the firm level, our analysis suggests that Hansen et al (1999)'s assertion that firms should not pursue the two KM approaches at the same time may only be true when the network's sharing potential is low. When the sharing potential is low, an increase in codification is accompanied by a rapid decrease in network sharing. Thus, trying to encourage codification while the network still exists can cause the firm's overall profits to decline. However, when the sharing potential is high, the benefits from an increase in codification induced by a moderate reward for codification can more than compensate for the mild loss in network sharing, and thus, the firm may be better off by combining the two approaches. A combination strategy is also more likely to be optimal when KWs are not highly socially embedded (i.e., θ is not very high).

This paper suggests that ignoring the interaction between codification and network sharing may mislead the firm into adopting an approach to KM that could be detrimental. For example, when A=1.5 and α=0.3 (Figure 5 left panel), the optimal codification reward of 0 generates a total profit of 0.047; whereas a naïve codification reward of 0.105, though leads to a higher level of codification, generates a profit of 0.025.[16] This suggests that a codification reward that ignores the interaction between codification and network sharing may lead to a decrease in total profits.

The sharing potential of the knowledge network emerges as the key theoretical construct that governs the interaction between codification and network sharing. Sharing potential reflects how the future benefits derived from a network tie are valued in the present by KWs. The higher the present value of future benefits, the higher the sharing potential, and the higher the opportunity cost that KWs would be willing to incur to share with their network partners. In our problem setting, higher sharing potential also implies that KWs can codify at a relatively higher level without threatening their network ties. In other words, a high sharing potential mitigates the tension between network sharing and codification.

Prior literature on social networks has largely focused on *sharing levels* – how much cost is a KW willing to incur to share her knowledge with a network partner (Coleman 1990; Burt 1992; Krackhardt 1992; Hansen 1999; Wasko and Faraj 2005). However, the literature has not distinguished between the *sharing level* between two parties and their abilities to sustain such sharing level. While the sharing level is useful in capturing the flow of benefits derived from network ties, it does not capture the dynamics that describe how ties are sustained over time. The concept of *sharing potential* is an attempt to distinguish between these two different facets of ties.

The analysis in this paper generates several predictions that can be examined empirically. The analysis suggests that the determinants of sharing potential – turnover rate, expected tenure, and knowledge sharing opportunities – are positively related to the sharing levels and the number of network ties. Similarly, KWs who are likely to remain with firm for longer periods of time and have abundant knowledge sharing opportunities are more likely to codify and network-share at the same time. Conversely, KWs with lower expected tenure and fewer sharing opportunities are likely to pursue either a codification-only or a network-sharing only strategy. It will also be interesting to empirically examine the finding that firms with high

[16] The naïve codification reward is chosen to maximize total codification profits, pretending that the knowledge network is not affected by codification.

sharing potential are more successful when they pursue a combination of codification and network sharing, whereas firms with low sharing potential are more successful when they pursue a pure KM approach.

This study has certain limitations which suggest directions for further research. The current notion of sharing potential is very rudimentary. Given the importance of sharing potential, more field work is required to enrich the understanding of mechanisms through which network sharing is enforced. For example, the notion of sharing potential may be extended to the case where individuals commit to sharing with a network of people and sharing is enforced within a network closure (Coleman 1990), rather than just as dyadic relationships. This paper, for simplicity, assumes global search and symmetric relationships. Studying a knowledge sharing network with localized search in the spirit of Sundararajan (2005) and with asymmetric network ties, will add richness and realism to the current analysis. Finally, codification and network sharing may interact and complement each other in other ways, if we look beyond the domain of knowledge transfer. For example, in some contexts network sharing may lead to more knowledge being created (Kogut and Zander 1992; Okhuyzen and Eisenhardt 2002), and as a result, lead to more knowledge codification. In this paper we have abstracted away from these issues as our emphasis has been on knowledge transfer. Modeling and examining these other interactions between codification and network sharing is an important direction for future research.

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Appendix

Proof of Proposition 1.

Substituting (1) and (3) into (4), we have $y_{ij} = A(1-x)\{\frac{1}{2}[1-\frac{1}{A(1-x)}]^2 - (\alpha + r)e_c\}$. y_{ij} changes sign (from positive to negative) when the term in curly brackets changes sign, which happens when $x = 1 - \frac{1}{A\left(1-\sqrt{2(\alpha+r)e_c}\right)}$. The critical codification level e_c^0 is determined by solving $1 - \frac{1}{A\left(1-\sqrt{2(\alpha+r)e_c}\right)} = 0$, which yields $e_c^0 = \frac{1}{2(\alpha+r)}\left(1-\frac{1}{A}\right)^2$. It is straightforward that $\bar{x}$ and e_c^0 increase in A, and $\bar{x}$ decreases in e_c. To see that $\bar{x}$ decreases faster in e_c as A decreases, note that

$$\frac{\partial \bar{x}}{\partial e_c} = -\frac{\sqrt{2(\alpha+r)/e_c}}{2A\left(1-\sqrt{2(\alpha+r)e_c}\right)^2}, \tag{14}$$

implying $|\partial \bar{x}/\partial e_c|$ decreases in A.

Proof of Proposition 2.

The equilibrium codification level e_c^* is the solution to $e_c^* = \arg\max_{\{e_c\}} w(e_c, e_c^*)$. Denote $w_1(e_c, e_c') \equiv \partial w(e_c, e_c')/\partial e_c$. Note that when e_c is low so that $\bar{x} > 0$, $w(e_c, e_c')$ is given by (7). So $w_1(e_c, e_c') = pDr\left[(1-\theta) + \theta(1-\bar{x})^2\right] - pD(re_c + \alpha e_c')\theta(1-\bar{x})\frac{\partial \bar{x}}{\partial e_c} - p\beta e_c + 2pD\theta(1-\bar{x})\left[e_s(\bar{x}) - \frac{1}{2}e_s(\bar{x})^2\right]\frac{\partial \bar{x}}{\partial e_c}$. Substituting the formulas for e_s (see equation (3)), $\bar{x}$ (see Proposition 1), and $\partial \bar{x}/\partial e_c$ (14), we have

$$w_1(e_c, e_c') = rpD - p\beta e_c - \theta pD\left[r + \frac{2\alpha + r}{A^2\left[1-\sqrt{2(\alpha e_c + re_c')}\right]^2}\right], \text{ when } \bar{x} > 0. \tag{15}$$

When e_c is high so that $\bar{x} = 0$, the KW's total payoff (7) simplifies to

$$w(e_c, e_c') = pD(e_c r + e_c'\alpha) - p\beta e_c^2/2, \text{ when } \bar{x} = 0. \tag{16}$$

So,

$$w_1(e_c, e_c') = rpD - p\beta e_c, \text{ when } \bar{x} = 0. \tag{17}$$

According to (15) and (17), $w_1(e_c, e_c')$ decreases in e_c (i.e., $w(e_c, e_c')$ is concave in e_c) both when the KW has network ties (i.e., $\bar{x} > 0$) and when she does not (i.e., $\bar{x} = 0$). Based on this knowledge, we analyze the sufficient conditions for a network-only strategy ($e_c^* = 0$), a hybrid strategy ($e_c^* > 0$ and $\bar{x} > 0$), and a codification-only strategy ($e_c^* > 0$ but $\bar{x} = 0$) to be equilibrium.

(a) A network-only strategy ($e_c^* = 0$) is equilibrium if (i) $w_1(e_c, 0) \leq 0$ for e_c such that $\bar{x} > 0$ (so i does not deviate to a hybrid strategy) and (ii) $w(0,0) > w(e_c, 0)$ for e_c such that $\bar{x} = 0$ (so i does not deviate to a codification-only strategy). Because $w_1(e_c, 0)$ is a decreasing function of e_c, a sufficient condition for (i) is $w_1(0,0) \leq 0$. Note that as $r \to 0$, $w_1(0,0) \to -2\theta pD\alpha/A^2$, so $w_1(0,0) < 0$ must hold for a sufficiently low r, say r_i^0. We now turn to (ii). Note that when $\bar{x} = 0$, $w(e_c, 0) = pDe_c r - p\beta e_c^2/2 < \frac{1}{2}pr^2D^2/\beta$. Note also $\frac{1}{2}pr^2D^2/\beta \to 0$ as $r \to 0$ but $w(0,0) = 2pD\theta \int_0^{\bar{x}} (1-x)\left[e_s(x) - \frac{1}{2}e_s(x)^2\right] dx$ is strictly positive as $r \to 0$. So there must be a small enough r, say r_{ii}^0, such that for all $r < r_{ii}^0$, $w(0,0) > w(e_c, 0)$. Thus for $r < r^0 = min\{r_i^0, r_{ii}^0\}$, both (i) and (ii) hold and a network-only strategy is optimal.

(b) A codification-only strategy e_c^* is equilibrium if $w(e_c^*, e_c^*) > w(e_c, e_c^*)$ for any $e_c \neq e_c^*$. We first need that $w_1(e_c^*, e_c^*) = 0$ (so i does not deviate to any other codification-only strategy), which implies $e_c^* = rD/\beta$ (according to (17)). So $w(e_c^*, e_c^*) = pD^2(\frac{1}{2}r^2 + r\alpha)/\beta$. We also need $w(e_c^*, e_c^*) > w(e_c, e_c^*)$ for any e_c such that $\bar{x} > 0$ (so the KW does not deviate to a hybrid or a network-only strategy). Note that $w(e_c, e_c^*)$ is less than the sum of $w(0,0)$ (the network-only payoff) and $pDe_c^0(r+\alpha) - p\beta(e_c^0)^2/2$ (the maximal codification payoff under a hybrid strategy). The latter is less than $pDe_c^0(r+\alpha)$, which equals $pD(1-1/A)^2/2$ after we substitute the formula for e_c^0 (see Proposition 1). Note that $w(0,0) + pD(1-1/A)^2/2$ is not a function of r but $w(e_c^*, e_c^*) \to \infty$ as $r \to \infty$. So we know for high enough r, say $r > r^1$, $w(e_c^*, e_c^*) > w(e_c, e_c^*)$ holds for any e_c such that $\bar{x} > 0$. In sum, for any $r > r^1$, a codification-only strategy $e_c^* = rD/\beta$ is equilibrium.

(c) Given r, a hybrid strategy e_c is not equilibrium if $w_1(0, e_c) \leq 0$. Note that $w_1(0,0) > w_1(0, e_c)$. So $w_1(0,0) < 0$ is sufficient to rule out a hybrid-strategy equilibrium. The condition $A < \sqrt{\frac{\theta}{1-\theta}\left(\frac{2\alpha}{r} + 1\right)}$ follows from the fact that $w_1(0,0) = rpD - \theta pD\left(r + \frac{2\alpha + r}{A^2}\right)$ (by (15)). Restating this condition, we have that a hybrid strategy is not equilibrium when $r < \frac{2\alpha\theta}{(1-\theta)A^2 - \theta} \equiv r^c$. To see that a hybrid strategy is not equilibrium for *any* r under a low A, it is sufficient to ensure that $r^c > r^1$(r^1 is defined in (b)), so that if $r > r^c$, a KW will deviate to a codification-only strategy. Note that r^c decreases with A, whereas r^1 increases with A (because payoff from network sharing increases with A). So $r^c > r^1$ tends to hold for low A values. In other words, KWs tend to not codify and network-share at the same time when A is low.

(d) For a hybrid strategy equilibrium to exist, it is sufficient to have (i) $w_1(0,0) > 0$ (so a network-only strategy is dominated), and (ii) $w_1(e_c, \cdot) < 0$ for any $e_c > e_c^0$ (so a KW does not deviate to a codification-only strategy). The condition $A > \sqrt{\frac{\theta}{1-\theta}\left(\frac{2\alpha}{r} + 1\right)}$ comes from (i) (note that $w_1(0,0) = rpD - \theta pD\left(r + \frac{2\alpha + r}{A^2}\right)$). Because when $\bar{x} > 0$, $w_1(e_c, \cdot)$ is a decreasing function of e_c for $e_c > e_c^0$ (17), $w_1(e_c^0, \cdot) \leq 0$ is sufficient to ensure condition (ii). The condition $A > 1/[1 - \sqrt{(2(\alpha + r))Dr/\beta}]$ follows from that $w_1(e_c^0, \cdot) = rpD - p\beta e_c^0$ (by (17)) and Proposition 1.

Finally, there can be at most one hybrid-strategy equilibrium. Suppose e_c^* is a hybrid-strategy equilibrium. We have for any $e_c < e_c^*$, $w_1(e_c, e_c) > w_1(e_c^*, e_c^*) = 0$ (because $w_1(e_c, e_c)$ decreases in e_c) and for any $e_c^0 > e_c > e_c^*$, $w_1(e_c, e_c) < w_1(e_c^*, e_c^*) = 0$. This means that any other hybrid strategy or the network-only strategy cannot be equilibrium. Similarly we can show that there can be at most one codification-only equilibrium.

Proof for Proposition 3.

(a) When A is sufficiently low, KWs will not codify and network-share at the same time (see Proof of Proposition 2(c)), so the firm does not have a choice of a hybrid approach to begin with. The firm's codification profit reaches a maximum of $pD^2\alpha^2\mu^2/(4\beta)$ when adopting a codification reward $r^* = \alpha\mu/2$. Comparing this profit with the network-only profit (12) yields the condition in Proposition 3.

Corollary 1: We show by example (Figure 6) that the firm may optimally pursue a hybrid approach by choosing a moderate r when A is high. The comparative statics on α in section 3.5 also further confirms such a pattern. In general, if for a particular A a hybrid approach dominates a network-only approach and a codification-only approach in terms of total profits, then the hybrid approach also dominates when A is even higher. This is because, for the same r, KWs codify more as A becomes higher (which can be seen from Proposition 2(c)). Meanwhile, as A becomes higher, the negative impact of codification on network sharing is lesser (Proposition 1). Overall this means more knowledge is codified with smaller marginal impact on network sharing, which generally implies a higher gain from a hybrid approach.