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## Direct Communication, Costs of Networking and Localisation of Technical Knowledge

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**ERSA 39th European Congress**  
**23rd - 27th August 1999**

**Direct Communication, Costs of Networking and Localization of  
Technical Knowledge**

by

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## **Abstract**

We investigate the localization of technical knowledge in a setup where firms or researchers compete for the value of a preemptive innovation. All researchers could gain by sharing information due to the uncertainty of the arrival time of the discovery. As receiving information while withholding expertise improves the competitive position of the actor there is a short-run incentive not to cooperate. Informal trade of technical know-how in a matching market is brought about by pre-trade communication on the reputation of players and the refusal to disclose information to agents with a bad reputation. This community enforcement results without the players following contagious strategy profiles. If the communication on the reputation of players is associated with costs depending on geographic distances, researchers have a strong incentive to cluster in geographical space. The number and pattern of agglomerations depends on the initial distribution of firms over geographical space and relocation costs.

## Introduction

This paper gives an explanation for the geographic concentration of innovative activities which is based on the hypothesis that research firms or individual researchers seek locations close to each other because proximity facilitates the exchange of technical information. Empirical investigations (e. g. von Hippel 1987, Saxenian 1994) have confirmed this hypothesis.<sup>1</sup> These empirical observations lead to two major questions:

- First, why should agents who dispose of proprietary knowledge of economic value reveal such knowledge to competitors? Why should researchers believe that informally traded information is reliable? The theoretical model on innovation races (1972, Loury 1979, Lee and Wilde 1980, Reinganum 1989) predict, in complete contrast to the above mentioned empirical studies that researchers will not cooperate, neither by sharing information. The general non-cooperative behavior is seen as the reason for an inefficient R&D sector at large, calling for corrective government action (cf. Mortensen 1982 and Stewart 1983).
- A second major question is, why, given that researchers cooperate in research activities, they benefit from locating close to each other. In view of the dramatic increase of technical communication possibilities, it appears to be striking that communication is facilitated to a significant degree by geographical proximity. Why has the decrease of communication costs not led to a dissolution of geographic clusters of innovative activities? The assertion that to convey technical information requires face-to-face communication (v. Hippel 1988, Audretsch 1998, Feldman/Audretsch 1999) entails the question why this sort of information cannot be transferred via e-mail, facsimile or phone.

The consequences of the localized exchange of information have been investigated at different levels of aggregation: at the industry level as localization effects (Marshall 1890, Arrow 1962), at the urban interindustry level as urbanization effects (Jacobs

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<sup>1</sup> A competing hypothesis of the localisation of technologies is based on labour market pooling arguments (David and Rosenbloom 1990, Antonelli 1995). In this literature there is, however, no explanation of why R&D staff should be particularly immobile.

1984), in the non-price interaction models of agglomeration (Papageorgiu/Thisse 1985, Fujita/Ogawa 1982 and Imai 1982) and in relation to national endogenous growth (Lucas 1988, 1993, Dudley 1999).

In the second subsection we present in detail the model of technological competition. Researchers compete for the value of an innovation that is completely protected against imitation and duplication. As the research process is stochastic all researchers could gain from coordination of strategies but are unable to ex ante commit to cooperation. In the third subsection we first review the evidence of the behavior of researchers which is in stark contrast to the results of the models of innovation races: Researchers do share proprietary know-how which is relevant for the ongoing research process, without having explicit contracts and without any accounting of the mutual support. Second we develop a model on how networking between researchers to communicate past experiences in bilateral information trades leads to a "community enforcement" of cooperative behavior in a matching market for know-how. That is, there is no local interaction which is established by the matching mechanism. The general cooperation is shown for exogenously given networks of overlapping neighborhoods. We then endogenize networks, assuming that bilateral network links are the more costly the larger the geographic distance between any two potential network members. these networking casts imply that networks locate at individual points in geographic space. Depending on whether relocation costs of firms are distance dependent one or several centers of specific research activities may form.

## **2 Competition and cooperation in R&D**

The environment that is considered here is one in which a particular invention is sought simultaneously by  $M$  identical potential inventors or firms (for other classes of models cf. Reinganum 1989). The firm which succeeds in producing the invention first is awarded a patent, which completely protects it from imitation or duplication. To take part in the research activities a firm  $i$  incurs a fixed cost  $F_i$  and chooses a research intensity measured by current expenditures  $x_i$  measured in monetary units. Given sufficient time, the research objectives will be realized but the expected time lag before discovery is a negative function of the variable research expenditures.

Let  $h = h(x_i)$  be the instantaneous probability that a firm  $i$  makes the invention at any point in time.  $h$  is assumed to be a positive function only of the research expenditures per period  $x$  and does not vary over time.  $h(x_i)$  is assumed to be strictly increasing and twice differentiable. This implies that the random variable  $\tau$  indicating the time at which a firm makes the discovery has an exponential distribution  $f(t) = he^{-ht}$ , so that the probability of making a discovery prior to period  $t$  is  $\Pr\{\tau \leq t\} = 1 - e^{-ht}$ , and the expected time of discovery is  $E\tau = 1/h$ .

Let  $\mathbb{X}$  denote the set of firms and  $h(x_j)$  be the instantaneous probability that some other firm  $j$  will be the winner of the innovation race, and assume that in the absence of communication firms' research activities are independent of one another. In that case the time at which any of the other firms makes the discovery also has an exponential distribution  $g(t) = ae^{-at}$ , where

$$a = \sum_{j \neq i} h(x_j), \quad i, j \in \mathbb{X}. \quad (1)$$

and the probability that one of the other firms will be successful prior to time  $t$  is  $\Pr\{\tau \leq t\} = 1 - e^{-at}$ . The discovery has an expected value of  $P$ , where  $P$  is the discounted worth of the profit stream generated by the use of the innovation over time.  $\iota$  denotes the common discount rate of all firms. Since the game is completely symmetric, the expected payoff of taking part in the innovation race  $V$  to any one firm  $i$  is a function of its own investment  $x_i$  and the aggregate rival hazard rate  $a$ :

$$\begin{aligned} V^i(x, a) &= \int_0^{\infty} [Pe^{-\iota t} h(x_i) e^{-(a+h(x_i))t} - x_i] dt - F_i \\ &= \frac{Ph(x_i) - x_i}{a + h(x_i) + \iota} - F_i, \quad \text{for all } i \in \mathbb{X} \end{aligned} \quad (2)$$

A best response function for firm  $i$  to the aggregate rival hazard rate  $a$  is a function  $\hat{x}(a)$  such that for all  $a$   $V^i(\hat{x}(a), a) \geq V^i(x, a)$  for all  $x$ . The symmetric Nash equilibrium for a given number of firms  $M$  will be denoted  $x^*(M)$  and satisfies the relation  $x^* = \hat{x}(a^*)$ , where  $a^* = (M-1)h(x^*)$ . Under "the stability condition"  $1 - (M-1)h'(x^*)\hat{x}'(a^*) > 0$ , which avoids an equilibrium where firms stop doing research altogether, Lee and Wilde (1980) have shown that a firm's equilibrium research

expenditures are an increasing function of the number of firms. An increase in the number of firms is associated with an earlier invention date on average as there are more firms and each firm invests at a higher rate. The value of taking part in the innovation race is a decreasing function of the number of competing firms. With free entry it decreases until equilibrium expected profits are zero. Even with a fixed number of firms each firm invests at a higher rate than is jointly optimal. Free entry results in too many firms each having too high a level of research expenditures compared to a cooperative solution.

If the social value of the invention is also  $P$ , then the comparison of the noncooperative equilibrium and joint optimality are also applicable to the comparison between noncooperative equilibrium and social optimality: The excessive investment in research is the result of two forces. First, each firm wants to win the race, while society typically has no preference as to the identity of the winner of the innovation race. Second, because there is unrestricted access to the common pool of undiscovered innovations, too many firms compete.

Mortensen (1982) and Stewart (1983) have discussed the normative question whether a mechanism could be implemented to correct for the externalities associated with the innovation race. A social optimum would be reached if the winning firm receives the value  $P$  less a compensation paid to each losing firm which is equal to the foregone value of continuing the research process. This institution induces noncooperative firms to select the socially optimal R&D expenditure provided entry is restricted to the number of firms in the unregulated noncooperative equilibrium.

The winning firm, receiving the capital value  $P$  must compensate the remaining  $M-1$  firms paying  $P(1-\sigma)/(M-1)$  each. Thus, the firm which wins the innovation race retains the amount of  $\sigma P$ . In this case, we can write the expected profit to firm  $i$  if it invests at rate  $x_i$  while the aggregate hazard rate is  $a$  as

$$V^i(x, a) = \frac{P[\sigma h(x_i) + a(1-\sigma)/(M-1)] - x}{a + h(x_i) + \iota} - F_i, \text{ for all } i \in \mathbb{N}. \quad (3)$$

At a symmetric Nash equilibrium for this game, which is denoted by  $x^*(M, \sigma)$ , the following necessary optimality condition must hold:

$$\frac{\partial V(x^*, a^*)}{\partial x} = \frac{(\text{Mh}(x^*) + r)(P\sigma h'(x^*) - 1) - (\text{Ph}(x^*) - x^*)h'(x^*)}{(\text{Mh}(x^*) + \iota)^2} = 0 \quad (4)$$

Joint profits MV are maximized for  $x^{**}(M)$  such that

$$\frac{(r + \text{Mh}(x^{**}))(\text{Ph}'(x^{**}) - 1) - (\text{Ph}(x^{**}) - x^{**})\text{Mh}'(x^{**})}{(\text{Mh}(x^{**}) + \iota)^2} = 0. \quad (5)$$

Thus,  $x^* = x^{**}$  if

$$\sigma = \sigma^*(M) \equiv \frac{\text{Ph}'(x^{**}(M)) + M - 1}{M\text{Ph}'(x^{**}(M))}. \quad (6)$$

$\sigma^*(M)$  is the winner's share which would induce noncooperative firms to invest at the socially optimal level. However, since the compensation of losers raises the expected profits of all firms relative to the noncooperative equilibrium it entails an incentive of additional entry to that industry. Thus, the cooperating firms must also be protected from further entry in order to fully internalize the externality associated with the innovation race. This problem has given rise to doubts that members of an industry can credibly set up such an institution for sharing the reward for innovation.

In what follows we interpret the winners share as an indicator of imperfect patent protection due to communication among competing researchers or firms. That competing firms network in their R&D activities is an often reported fact in the empirical literature. This leads to the question why firms should exchange know-how, given that providing information weakens the competitive position and receiving information strengthens it. Short-run incentives should make the firms refuse to communicate. We discuss these questions in the next subsection before asking how, given that direct communication is associated with distance-related costs, networking provides an explanation for the geographical clustering of innovating firms.

### 3 The informal trade of technical know how

Our concern here is to look for an explanation of the cooperation of firms in research and development even in those cases where inventions could be perfectly protected. Some of the empirical literature suggests that the cooperation is based on the informal



sharing of information during the research process in networks between research departments of firms (von Hippel 1987,1988; R. Allen 1983; T. Allen et al. 1983). As von Hippel (1987, p. 292) notes:

"A firm's staff of engineers is responsible for obtaining or developing the know-how its firm needs. When required know-how is not available in-house, an engineer typically cannot find what he needs in publications either. Much is very specialized and not published anywhere. He must either develop it himself or learn what he needs to know by talking to other specialists. Since in-house development can be time-consuming and expensive, there can be a high incentive to seek the needed information from professional colleagues. And often, logically enough, engineers in firms which make similar products or use similar processes are the people most likely to have that needed information. But are such colleagues willing to reveal their proprietary know-how to employees of rival firms? Interestingly, it appears that the answer is quite uniformly "yes" in at least one industry, and quite probably in many."

He reports in his study of US steel minimill firms that there was no explicit accounting of favors given and received but that the obligation to return a favor seemed to be strongly felt by the recipient. The supply of information is restricted to the network, according to the findings of von Hippel, in contrast to the interpretation of historical evidence by Robert Allen (1983, p.2) that all competitors were given free access to proprietary know-how.

In trying to explain the cooperation in R&D it was however only shown that there is a prisoners' dilemma situation with potential gains from cooperation when the competitive advantage of obtaining information and withholding the own know-how is small relative to the payoff using the non-cooperative strategy (v. Hippel 1987, pp. 297-300). It does not explain why the informal trade of know-how occurs. In fact, to withhold information is a dominant strategy independent of the value of the competitive advantage obtained by receiving information from a competitor and keeping the own knowledge secret. In our attempt to explain the informal exchange of proprietary technical knowledge we draw on the literature which gives reason to the cooperative behavior of sellers who have private information on the product quality and nevertheless refrain from providing low quality. "Community enforcement" provides a mechanism that induces sellers to behave cooperatively even when they meet particular buyers only

infrequently and have a short-term incentive to cheat (Klein and Leffler 1981, Okuno-Fujiwara and Postlewaite 1995, Kandori 1992 and Milgrom et al. 1990).

Of particular relevance is a class of models where players are unable to recognize their opponents in a large but finite population setting. In these models sequential equilibria have been shown to exist on the basis of contagious strategies: All players who have been disappointed once stop cooperating with any of the potential opponents, understanding that the whole society is in a process of switching to non-cooperative behavior. In the sequential equilibrium the players stick to the cooperative strategy to avoid the general switch to the socially negative behavior (Kandori 1992 and Ellison 1994). Community enforcement due to contagious strategies has the problematic consequence that cooperation is unstable in the sense that a single defection would render cooperation impossible for all other agents.

For the networking between the staff of the research and development departments we need to consider an informal information transmission mechanism which is imperfect in the sense that defection, withholding or giving incomplete or distorted information, cannot be always punished immediately and that knowledge of the defection may only spread to part of the population of players. To model this type of community enforcement we draw on the model on word-of-mouth communication of Ahn and Suominen (1996).

At discrete rounds  $r = 1, 2, \dots$  two of the finite population of  $M$  researchers are randomly matched to bilaterally exchange technical information which is of interest for the common research objectives. The quality of the information provided is not recognized immediately but becomes evident in the course of the ongoing research activities. Both have a short term incentive to cheat: To withhold useful information while the opponent reports truthfully leads to an increase of the individual's instantaneous probability of making the discovery and avoids an enhancement of the imitation possibilities of the competitors in case they loose the innovation race. As, however, the opponents are able to detect useless or misleading information, private reputations evolve. This follows from the fact that all participants send and receive signals on the opponent's behavior in previous bilateral meetings to firms in their neighborhood forming

a network. If these signals are correct, a sequential equilibrium exists where all members of the research network report truthfully in every round.

More formally, members of a finite set of players  $\mathbb{X} = \{1, 2, \dots, M\}$  trade know-how bilaterally and send and receive signals on the reputation of other researchers. The individuals are identified by their names.

An individual  $i \in \mathbb{X}$  is randomly matched in round  $r$  with a player  $\theta_r^{-1}(i) \in \mathbb{X}$  to play the following 2x2 information trade game on the position relative to taking part in the innovation race, with  $g > 0$  and  $1+g-k < 2$ :

**Table 1: Gains from the informal trade of know-how**

		Player i	
		disclose	withhold
Player j	disclose	1,1	-k,(1+g)
	withhold	(1+g),-k	0,0

If both players refuse to communicate there is no change compared to the situation of the isolated innovation race. The change of the round value of continuing the innovation race with mutual disclosure of information is equal to one.  $(1+g)$  is the value of continuing one more round receiving information but without revealing the own know how and  $k$  the loss resulting from revealing information while being cheated by the opponent. To receive information while refusing to offer a return increases the player's instantaneous probability of winning the innovation race and avoids increasing the re-engineering and imitation possibilities of the competitors in case of being the winner. A researcher who reports truthfully and is cheated weakens his position even relative to not communicating at all, as the share of the capital value of the innovation is reduced when that researcher wins the innovation race. Consequently, the strategy pair {withhold, withhold} is the only Nash equilibrium of the one-shot trade game. Without any further information, both parties would try to win the innovation race in isolation.

The overall payoffs are, however, the discounted sums of payoffs from the repetition of the trade game. We assume that the individuals have a common discount factor  $\delta \in$

(0,1). In each round  $r = 0,1,2,\dots$  there is preplay communication among the participants before the next round of know-how trade takes place. More precisely, this preplay communication proceeds as follows:

- a. Each firm is member of a network  $\mathcal{N}_r^i$  with  $A+1$  members in its neighborhood. After each round of matching  $\Theta$  each player  $i$  recognizes the identity of his own opponent  $\theta_r^{-1}(i)$  and the opponents  $\theta_r^{-1}(n)$  of all members  $n \in \mathcal{N}_r^i$  of the network. We assume that the quality of the information provided is not publicly observable but is discovered by the receiving party during the subsequent research process.
- b. After the next round of matching and before the informal trading of know-how takes place each player  $i$  sends a signal on the value of the report of  $\theta_r^{-1}(n)$  in past rounds to the  $A$  members of the network. Thus each player receives one or more messages on the reputation of his current opponent if the latter is not unknown to all members of the network.

Let  $C = \{\gamma, \beta\}$  be the set of possible signals,  $\gamma$  meaning "good" and  $\beta$  meaning "bad".  $m_r^i(n)$  is then the message of firm  $i$  to the other firms  $n$  of the network and  $m_r(i) \in \{\gamma, \beta\}^A$  is the tuple of messages player  $i$  receives.

- c. The researchers who meet bilaterally play the above 2x2 simultaneous move game.

The quality of the information is denoted as  $\alpha_r(i) \in \{\gamma, \beta\}$ . The total information player  $i$  receives in each round can be written as  $\{\theta_r, m_r(i), \alpha_r(i)\}$ .  $H^t(i)$  denotes the set of all possible histories for a player up to but not including round  $r$ . By convention  $H^0(i) = \emptyset$ . An element  $\eta_r(i) \in H^t(i)$  includes the identity of all past matches, all past messages sent by player  $i$ , all past messages received, and all observations of the quality of reports to that date:

$$\eta_r(i) = \left( \theta_\tau, m_\tau(i), m_\tau^i, \alpha_\tau(i) \right)_{\tau=0}^{r-1}$$

The pure strategies for player  $j$  are then

$$\hat{m}_r^i: \Theta \times H^r(i) \rightarrow \{\gamma, \beta\}^N, \text{ and } \hat{b}_r: \Theta \times H^r(i) \rightarrow \{\text{disclose, withhold}\}.$$

$\hat{m}_r^j(\theta_r, h^r(i))$  determines the A-tuple of signals that buyer  $i$  with history  $h^r(i)$  sends to the other network members in round  $r$ .  $\hat{b}_r^j(\theta_r, h^r(i), m_r(i))$  specifies the choice of action of player  $i$  in round  $r$ . The behavioral strategies of the agents are  $\{\sigma_r^i\}_{r=0}^\infty$  which are sequences of the map

$$\hat{\beta}_r^i: \Theta \times H^r(j) \times \{\gamma, \beta\}^N \rightarrow \Delta\{\text{disclose, withhold}\}.$$

The equilibrium concept we apply is the sequential equilibrium. A sequential equilibrium requires that after any history a player's equilibrium strategy maximizes the expected payoff, taken as given all other players' strategies and his beliefs about the signals and actions taken by other players in all previous rounds. The beliefs have to be consistent with the equilibrium strategy profile and the private history. One sequential equilibrium is the refusal to provide know-how after any history. In what follows we are interested in identifying a sequential equilibrium that supports a stable system of informal trades of technical know-how.

The analysis concentrates on a particular strategy profile which is called "unforgiving". With this strategy profile players meet and do trade information if they have never experienced or heard of a bad behavior of the opponent. It requires them to deliver truthful information in know-how trade in round zero and in every round thereafter if a) they have always done so, and b) they have never obtained a bad status.

The concentration on the unforgiving strategy profiles can be justified by its tractability and its being a non-contagious benchmark in that it provides the maximum punishment.

Information about an agent's behavior may spread through personal experience and the pretrade communication of the network members. The effectiveness of that spread depends on the size of the network communicating on the opponents' past behavior. The signals depend on the private histories of the agents who are members of the network. Under the unforgiving behavior of the players, player  $i$  pursues the following strategy profile in each round  $r = 0, 1, 2, \dots$  of bilateral encounters.

- a. In the first round disclose information truthfully. After that, if your opponent's past behavior was cooperative, continue to report truthfully.
- b. Withhold information otherwise.
- c. If a player  $i$  has ever been cheated by the opponent  $\theta_r^{-1}(n)$  of player  $n$ ,  $i, n \in \mathcal{N}_i$ , she or he will signal  $\beta$ . Otherwise the signal is  $\gamma$ . Upon receiving a bad signal player  $n$  withholds information.
- d. A researcher  $n$  cooperates otherwise.

In each round two types of incentive compatibility constraints have to be met: First each agent must find it optimal to cooperate when everyone else is cooperating. Second, each agent must find it optimal to play non-cooperatively, after having obtained a bad status.

To keep a player reporting honestly in the bilateral encounters the gain per round from cheating  $g$  must be outweighed by the long-term loss resulting from the spread of the bad reputation among the fellow players. The spread of the bad reputation reduces the probability of being matched with another player that does not know about the bad status himself and belongs to a network of which no other member can report on a bad experience. The second condition holds if a player who has once cheated cannot gain by switching to cooperation to slow down or turn around the process of the spread of the bad reputation.

### 3.1 Networks with exogenous connections

Contacts to other researchers or firms arrive according to a Poisson process with an arrival rate such that there is exactly one encounter per round. The conditions for the cooperative sequential equilibrium are then given in Proposition 1.

**Proposition 1:** *Given an exogenous collection of overlapping networks of size  $A+1$  whose members communicate on the reputation of opponents in a random matching game of information trades, the strategy profile defined above is a sequential equilibrium under the following conditions:*

$$g \leq -1 + \frac{1}{(1-\delta)_2 F_1(1, 2 + (-1+x)M, 1-M, \delta)} = g^* \quad (7)$$

$$b_0 < \frac{1}{1+\delta - (1-\delta)g} \quad (8)$$

$$g \geq \frac{1 - (1-\delta)S}{1 - b_0 + (1-\delta)S} \equiv g^{**}, \text{ with} \quad (9)$$

$$S = \frac{(M-A-2)!(M-K-1)!}{(M-1)!(M-K-A-2)!} {}_2F_1(1, 2 + \ddot{A} - M, 1+K-M, \delta) \quad (10)$$

$$g^{**} \leq g \leq g^* \quad (11)$$

**Proof:** As stated above the sequential equilibrium of reporting honestly in bilateral information trades depends on whether first, on the equilibrium path, it is profitable to cooperate in all rounds  $r = 0, 1, 2, 3, \dots$ . Second, once a player has obtained a bad reputation, it must be optimal to continue to behave non-cooperatively.

Cooperating when all other players follow the equilibrium strategy of cooperating results in the payoff of 1 in each round. All agents assume an infinite sequence of encounters and therefore have an infinite time horizon. All have a discount factor of  $\delta$ . The total expected payoff of cooperation is then

$$T_C = \sum_{r=0}^{\infty} \delta^r \quad (12)$$

$T_C$  is an increasing function of the discount factor.

If a player successfully cheats in all of the rounds  $r$  and the exogenous networks are all of size  $A+1$  the probability of realizing  $(1+g)$  is

$$b_r = \frac{\binom{M-1-r}{A+1}}{\binom{M-1}{A+1}}, \quad r = 0, 1, 2, \dots \quad (13)$$

The nominator of  $b_r$  indicates the number of networks of size  $A+1$  as subsets of the total of all agents excluding the agent  $i$  and those who have been cheated before. The

denominator indicates the number of networks which could be formed out of the set of all researchers excluding researcher  $i$ .

After  $M-A-2$  cases of receiving the payoff  $(1+g)$  any opponent will refuse to cooperate and the firm is isolated. The total expected payoff of defecting permanently is then

$$T_D = (1+g) \sum_{r=0}^{M-A-2} \delta^r \frac{\binom{M-1-r}{A+1}}{\binom{M-1}{A+1}} \quad (14)$$

$T_D$  is a decreasing function of the network size as the decrease of denominator is greater than the decrease of the nominator with an increasing  $A$  and the number of rounds in which  $(1+g)$  can be realized decreases. It is an increasing function of the discount factor.

Behaving cooperatively is a sequential equilibrium if

$$T_C \geq T_D, \text{ or}$$

$$\frac{1}{1-\delta} \geq (1+g) {}_2F_1(1, 2+A-M, 1-M, \delta) \quad (15)$$

with  ${}_2F_1$  denoting the hypergeometric function. The hypergeometric function is a degressively increasing function of the network size.

Taking  $A$  to be a percentage  $x$  of  $M$  with  $x = i/M$  and  $i$  being non-negative integers we obtain the expression  $S_C$  as the netgain of cooperating

$$S_C = \frac{1}{1-\delta} - (1+g) {}_2F_1(1, 2+M(-1+x), 1-M, \delta) \quad (16)$$

$S_C$  is an increasing function of the discount factor as

$$\frac{\partial S_C}{\partial \delta} = \frac{1}{(1-\delta)^2} + \frac{1}{M-1} (1+g)(2-M(1-x)) {}_2F_1(2, 3+M(-1+x), 2-M, \delta) > 0 \quad (17)$$

The condition for the net gain of cooperative behavior to be non-negative can be expressed as a maximal value of  $g$  as a function of  $x$  and  $\delta$ . Solving equation (15) for  $g$  we obtain



$$g \leq -1 + \frac{1}{(1-\delta)_2 F_1(1, 2 + (-1+x)M, 1-M, \delta)} \equiv g^* \quad (18)$$

for  $\delta \in (0,1)$ , and  $0 \leq x \leq (M-A-2)/M$ .

For cooperation to be the social optimum and  $k$  being positive,  $g$  has to be larger than one. From this follows the condition on the hypergeometric function

$${}_2F_1(1, 2 + (-1+x)M, 1-M, \delta) < \frac{1}{2(1-\delta)} \quad (19)$$

Next we identify the conditions under which an agent who has a bad reputation with some of the  $M$  researchers will continue to behave non-cooperatively. Assume that  $K$  players assign a bad status to researcher  $i$ . By the principle of dynamic programming it suffices to check that a one-time switch to cooperative behavior is not profitable after any history of having obtained a bad status.

Cooperating in round  $r$  with  $K$  players knowing about agent  $i$ 's bad status and returning to non-cooperation afterwards results in the total expected payoff.

$$T_{\text{DEV}} = \frac{\binom{M-K-1}{A+1}}{\binom{M-1}{A+1}} - k \left( 1 - \frac{\binom{M-K-1}{A+1}}{\binom{M-1}{A+1}} \right) + (1+g) \sum_{r=0}^{M-K-A-2} \delta^{r+1} \frac{\binom{M-K-1-r}{A+1}}{\binom{M-1}{A+1}} \quad (20)$$

If player  $i$  instead continues to behave non-cooperatively in every round his total expected payoff is

$$T_{\text{NC}} = (1+g) \sum_{r=0}^{M-K-A-2} \delta^r \frac{\binom{M-K-1-r}{A+1}}{\binom{M-1}{A+1}} \quad (21)$$

If player  $i$  is to continue to defect in every round  $T_{\text{NC}}$  must be greater than  $T_{\text{DEV}}$ . To save notation we define

$$b_0 = \frac{\binom{M-K-1}{A+1}}{\binom{M-1}{A+1}}, S_0 = \sum_{r=0}^{M-K-A-2} \delta^r \frac{\binom{M-K-1-r}{A+1}}{\binom{M-1}{A+1}} \text{ and}$$

$$S_1 = \sum_{r=1}^{M-K-A-2} \delta^r \frac{\binom{M-K-1-r}{A+1}}{\binom{M-1}{A+1}}.$$

We then have

$$\begin{aligned} T_{NC} - T_{DEV} &= (1+g)(1-\delta)S_0 - b_0 + k(1-b_B) \\ &= (1+g)(1-\delta)S_1 - b_0 + k(1-b_B) + (1+g)(1-\delta)b_0 \geq 0 \end{aligned} \quad (22)$$

If the sum of the latter three terms of the above right hand side are positive,  $T_{NC}$  is greater than  $T_{DEV}$  as the first term is necessarily positive. From this follows an upper bound for  $b_0$  and implicitly on the minimum network size:

$$b_0 \leq \frac{k}{1+\delta-(1-\delta)g} \quad (23)$$

Taking the smallest possible  $k$  we obtain an expression for the upper bound of  $b_0$  that holds for all admissible values of  $k$ :

$$b_0 \leq \frac{g-1}{(1+g)\delta-1}. \quad (24)$$

In general, the second incentive compatibility constraint for the cooperative sequential equilibrium is satisfied if

$$\begin{aligned} g &\geq \frac{1-(1-\delta)S}{1-b_0+(1-\delta)S} \equiv g^{**}, \text{ with} \\ S &= \frac{(M(1-x)-2)!(M-K-1)!}{(M-1)!(M(1-x)-K-2)!} {}_2F_1(1, 2+M(1-x), 1+K-M, \delta) \end{aligned} \quad (25)$$

$g^{**}$  is a decreasing function of  $S$ .  $S$ , in turn, is a decreasing function of  $K$ . To obtain a sufficient condition for the existence of the sequential equilibrium we have to determine the difference between  $g^*$  and  $g^{**}$  for the maximal  $K$ . The maximal possible  $K$  for which a player with a bad reputation might check the usefulness of switching to cooperative behavior is  $K = M - A - 2$ . In this case the expression for  $g^{**}$  reduces to

$$g^{**}|_{K=M-A-2} = 1 + \frac{1-2\delta}{\delta - \binom{M-1}{A+1}}. \quad (26)$$

As  $g^{**}$  has to be larger than one and the denominator of the second term of the right hand side is always negative  $\delta$  must be larger than one half. The smallest denominator, and therefore the largest value for  $g^{**}$  is obtained for the largest and the smallest network size.

Taking both incentive compatibility constraints together we have

$$g^{**} \leq g \leq g^* \quad (27)$$

If a member  $j$  of the network of the opponent  $\theta_r^{-1}(i)$  has been cheated by player  $i$  before he cannot gain by giving the wrong signal  $\gamma$  and should therefore signal the bad reputation of player  $i$ . If he has been matched with player  $i$  before and received useful information he should signal  $\gamma$ . Otherwise  $i$  or  $\theta_r^{-1}(i)$  would be perceived as having a bad reputation and switch to non-cooperative behavior in future encounters under the conditions given in proposition 1. If so, this would reduce the expected payoff of the player who has given the wrong signal.

### 3.2 Networks with endogenous connections

We now relax the assumption that network links are exogeneously given. The costs of maintaining a network link between researcher  $i$  and researcher  $j$  depend on its geographical distance  $d_{ij}$ . The costs per unit of distance  $c$  are assumed to be constant. The distance dependence of the costs of networking are considered to be due to the fact that the communication on the reputation of competitors in the informal trade of know-how requires confidential and personal contacts. The costs of such contacts decrease with the geographical proximity of the agents. With each firm ordering the potential network members according to the distances of the links the total costs of networking per round of matching is

$$C_i = \sum_{j=\bar{j}}^{\bar{j}} c d_{ij}, \quad (28)$$

where  $\bar{j}$  denotes the closest network member and  $\bar{j}$  the most distant one. With a non-uniform distribution of research firms over geographical space, the costs of networking are the lower the higher the density of researchers in the neighborhood of an individual firm.

Before examining the consequences of a non-uniform distribution of researchers over space we have to check whether there is an incentive to network at all. If the surplus of cooperative behavior is positive for a network size of zero firms would cooperate without an incentive to network regardless of the density of competitors. If the network size is zero the expression for the surplus of cooperating in all rounds reduces to

$$S_c = \frac{1}{1-\delta} - \frac{(1+g)(M(1-\delta)-1)}{(M-1)(1-\delta)^2}. \quad (29)$$

It is negative for

$$M > \frac{g+\delta}{g(1-\delta)} \equiv M^* \quad (30)$$

for  $\delta \in (0,1)$ .

If the population size is larger than  $M^*$  researchers have an incentive to network. For a smaller population they would cooperate with all  $M^*-1$  competitors even without a network.

To concentrate on the consequences of a non-uniform distribution of firms with fixed locations we assume for a moment a special geographic configuration in that firms locate around a circle and that all firms are double-indexed according to their location, the index  $i$  running from 1 to  $M$  and  $M+1$  to  $2M$ . The network which firm  $i$  maintains is denoted as  $\mathcal{N}_i$ . We then have as the general expression for the surplus of cooperation in the repeated game, averaging over all possible sequences of bilateral meetings

$$\begin{aligned}
S_{C_i} = & \frac{1-C_i}{1-\delta} - (1+g)\left\{1 + \delta \frac{1}{M-1} \sum_{j_1=i+1}^{i+M-1} \frac{|\mathcal{N}_{j_1}^i|}{M-1}\right. \\
& + \delta^2 2! \prod_{s=1}^r \frac{1}{M-s} \sum_{j_1=i+1}^{i+M-2} \sum_{j_2=j_1+1}^{i+M-1} \frac{|\left(\mathcal{N}_{j_1}^i \cup \mathcal{N}_{j_2}^i\right)'|}{M-1} \\
& + \dots + \\
& \left. + \delta^{M-1} (M-1)! \prod_{s=1}^r \frac{1}{M-s} \sum_{j_1=i+1}^{i+1} \sum_{j_2=j_1+1}^{i+2} \dots \sum_{j_{M-1}=j_{M-2}+1}^{i+M-1} \frac{\left|\left(\bigcup_{s=1}^r \mathcal{N}_{j_s}^i\right)'\right|}{M-1}\right\}
\end{aligned} \tag{31}$$

As the model is symmetric all network links will be reciprocal: If a firm  $i$  maintains a network link to firm  $j$ , firm  $j$  will bear the costs of having a link to firm  $i$ . It then follows directly from the above expression that a firm is the more prepared to cheat the larger its own network, due to a high density of researchers in the neighborhood, and the more dispersed the geographical distribution of the competitors. Firms will choose the minimal network size that will prevent members of the largest network to cheat, if the surplus of cooperative behavior in the repeated game is non-negative. Otherwise they will participate in the innovation race in isolation, as long as its value is non-negative.

Unless all of the potential network members of firm  $i$  are located at a single point,  $C_i$  is a progressively increasing function of the number of network members. The higher the density of firms the larger will be the network at a given average cost of networking. The larger the network the more the network members are protected against being cheated by others.

### 3.2.1

#### *Relocation of firms with fixed relocation costs*

We now allow firms or researchers to relocate. For convenience we assume that an arbitrary number of firms can locate at a single point in geographical space.

**Proposition 2:** *With a non-uniform initial distribution of innovators over geographical space and in the absence of relocation costs all firms will relocate to the point with the highest initial density of researchers under the following conditions:*

$$M^* < M, \tag{32}$$

with  $M^*$  following from (30), and

$$g < \frac{\delta}{1-\delta}. \tag{33}$$

**Proof:** To examine the relocation decisions of research firms we assume that the intensity of the informal trading of know-how is no longer completely determined by the exogenous matching mechanism but under the control of the researchers or firms. That is, the intensity of information trading will be chosen such that the winner's share  $\sigma$  of the value of the innovation maximizes the firms' profits. From the first order condition of the profit maximum at the symmetric Nash equilibrium (4) we have for the optimal winner's share

$$\sigma^* = \frac{Ph'(x) + M - 1}{MPh'(x)}, \quad (34)$$

where  $x$  and  $h'$  have the values of joint optimality. Substituting for  $P$  from the first order condition to determine the optimal level of research expenditures we have

$$\sigma^* = \frac{h - h'x + \iota}{M(h - h'x) + r}, \quad (35)$$

with all endogenous values evaluated at optimal levels of the industry equilibrium. As was shown by Stewart (1983), expected profits are an increasing function of the number of participants in the innovation race up to some  $M^{**}$  and a decreasing function of  $M$  for higher values. With free entry the number of participants will increase up to a point where expected profit are equal to zero, unless we would introduce a mechanism which allows firms at a single location to deter entry beyond a total number of researchers of  $M^{**}$ .

To show that there will be only one agglomeration of researchers assume to the contrary that the geographic concentration of researchers occurs at two locations. Assume further that the researchers at one location consider whether to differentiate with respect to the intensity of information trading between the two locations. Following the above argument on the optimal  $\sigma$ , it can be shown that regardless of the relative sizes of the two centers the optimal  $\sigma$  is always smaller than one. That is, it is always optimal to share information with all other researchers who have the same research interest..

This, in turn, requires that all researchers move to the same location: If firms agglomerate at different points in geographical space without increasing the networking costs, a system of non-overlapping networks emerges, as the researchers would confine

networking to costless links at their own location. If so, the second incentive compatibility constraint of the sequential cooperative equilibrium ceases to hold: It is then possible to cheat all fellow researchers who are not member of one's own network without running the risk of a spread of the bad reputation to all members of the population. Therefore, the informal trade of technical know how will be confined to a single location when there are no relocation costs.

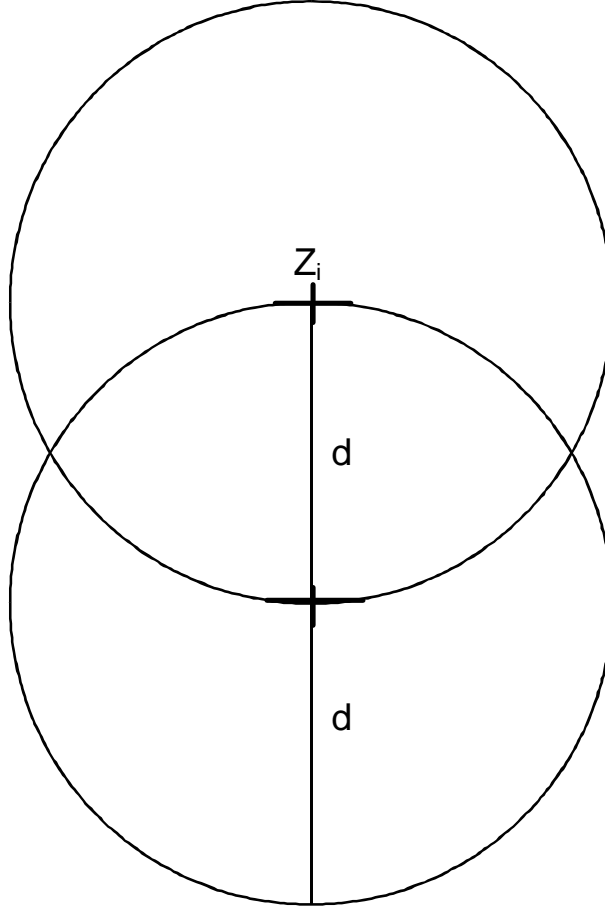
All of them will network as there are no costs of networking. The condition for cooperation in the repeated game then reduces to

$$\frac{1}{1-\delta} \geq (1+g), \quad (36)$$

as a single defection becomes known to all members of the network. The defector would then be isolated for all further rounds of matching and have no possibility to switch to cooperative behavior. If the total number of researchers  $M$  exceeds  $M^{**}$ , the expected profits of firms will decrease. If there is no further entry to the industry firms will enjoy positive profits due to the saving of the networking costs in the agglomerative equilibrium.

### 3.2.2 *Relocation of firms with distance dependent relocation costs*

Assume now that there relocation costs which are linearly dependent on the distance of relocation. Let the relocation costs per unit of distance be denoted by  $c^*$ . We consider a geographical configuration with a location  $Z$  being the point of the highest density of researchers at the center of a circle with radius  $2d$ :

**Figure 3: Localization of Technical Knowledge and Relocation Costs**

Let  $N_1$  firms be located in  $Z_i$  and  $N_2$  firms within the circle around  $Z_i$  with radius  $d$ . We assume that for distances  $d_{iZ_i} < d$  between a firm  $i$  and the center  $Z$  the relocation costs are smaller than the present value of the costs of maintaining the network at the initial location with the minimal size to prevent competitors from cheating:

$$c * d_{iZ_i} < \frac{C_i^{\min}}{1 - \delta} \quad (37)$$

**Proposition 3:** *With relocation costs  $c^*$  per unit of distance, a center  $Z_i$  with  $N_1$  innovators and  $N_2$  innovators within the circle around the center  $Z_i$  with radius  $d$ , all  $N_1 + N_2$  firms will locate in the center  $Z_i$  under the following conditions:*

$$M^* < N_1 + N_2 \quad (38)$$

$d = \max d_{iZ_i}$  such that



$$\frac{P[\sigma^* h + a_{z_i}(1 - \sigma^*) / (N_1 + N_2 - 1)] - x_{z_i}}{\sum_{z_j \neq z_i \in Z} a_{z_j} + (N_1 + N_2)h + \iota} - F - c^* d_{iz} \geq 0 \quad (39)$$

$$g < \frac{\delta}{1 - \delta}. \quad (40)$$

**Proof:** We assume that  $N_1$  is larger than the minimum number of members of a network which protects its members from being cheated. By the same arguments as those we put forward to argue for a single agglomeration in the case without relocation costs, all of the  $N_2$  firms will move to  $Z_i$ . Outside the circle with radius  $2d$  around  $Z_i$  other agglomerations of research firms may emerge. The set of agglomerations is then a collection of disjoint networks. The networks being disjoint the second incentive compatibility constraint of the cooperative sequential equilibrium is again violated. As a consequence there will be no cooperation between researchers at different locations.

The expected profit function  $V'$  of an individual firm after relocation when there are relocation costs reduces to

$$V' = \frac{P[\sigma^* h + a_{z_i}(1 - \sigma^*) / (N_1 + N_2 - 1)] - x_{z_i}}{\sum_{z_j \neq z_i \in Z} a_{z_j} + (N_1 + N_2)h + \iota}. \quad (41)$$

The indices  $z_i$  and  $z_j$  now refer to agglomerations. All endogenous variables are evaluated at the local symmetric equilibrium. Each firm optimizes research expenditures sharing optimally technical know how with all researchers in the location  $Z_i$  and taking account of the rival hazard rates  $a_{z_j}$  of other agglomerations  $Z_j$ . All firms around  $Z$  within the radius  $d$  which can cover the fixed costs of participating in the innovation race and the relocation costs will move to the center. For these firms equation (39) must hold. The radius  $d$  in Figure 3 is defined by the maximal value of  $d_{iz}$  for which the equality sign holds in equation (39).

#### 4 Conclusions

We have studied the clustering of researchers or research firms in geographical space to facilitate the beneficial sharing of information in the course of the research process. The inability to commit to the truthful revelation of proprietary know-how is overcome by

local networking of researchers. The networks serve to communicate on the reputation of potential partners of cooperation. We identify the conditions under which such a networking leads to a general cooperation among researchers. If the costs of maintaining network links depend on the distances between the locations of any two researchers the localisation of specialised technical knowledge results. Depending on whether relocation costs are distance dependent one or more centers of technical know how will form.

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