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HIGHLIGHTS

- We analyze the R&D networks formed by either myopic or farsighted firms.
- Myopia leads to two minimally connected components of almost equal size.
- Farsightedness leads to two components of unequal size.
- The largest component comprises roughly three-quarters of firms.
- Farsightedness helps firms to better exploit the collaborative opportunities.

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ABSTRACT

We analyze the formation of bilateral R&D collaborations in an oligopoly when each firm benefits from the research done by other firms it is connected to. In contrast to myopic stability, farsighted stability leads to R&D networks consisting of two minimally connected components, with the largest one comprising three-quarters of firms.

1. Introduction

The objective of the paper is to analyze the R&D networks that would arise in the long run with either myopic or farsighted firms. We consider an n-firm industry, where initially identical firms produce a homogeneous good at a given marginal cost. Each firm is able to reduce its marginal cost by forming a link with another competitor. The cost reduction for one firm is proportional to the number of firms it is connected to. When a new link is formed between two firms already linked with others, all connected firms benefit in terms of cost reduction, but they are also adversely affected in terms of market competition since they face stronger competitors.[1] The collection of all the bilateral links defines the R&D network which in turn determines the marginal cost profile for the n oligopolists. Once the R&D network is formed, firms compete in quantities.

We find that firms add and delete links to form stable networks consisting of two components each of them minimally connected.

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[1] In Mauleon et al. (2008), the reduction in marginal costs also depends on the total number of connected firms, but the marginal effect of that reduction decreases with the distance. In Goyal and Joshi (2003), the reduction in marginal costs only depends on the number of direct links, as if each firm was able to isolate the knowledge coming from each firm to which it is linked. In Goyal and Moraga-Gonzalez (2001), firms even benefit, although imperfectly, from the research done by firms to which they are not connected. All these papers study the emergence of R&D networks among myopic firms.

The group of firms belonging to the largest component obtain a competitive advantage upon the other group. The difference in the number of firms between the two components is at most three if firms are myopic. However, if firms are farsighted, R&D networks consisting of two minimally connected components, with the largest one comprising roughly three-quarters of firms, become stable. Therefore, when firms are farsighted, the larger group of firms can derive from R&D collaborations a much greater competitive advantage relative to the other group.

2. The model

We consider a two-stage game in a setting with n competing firms that produce some homogeneous good. In the first stage, firms decide the bilateral R&D collaborations. Let $N = \{1, 2, \ldots, n\}$ be the set of firms. A network g is a list of which pairs of firms are linked to each other and $ij \in g$ indicates that i and j are linked under g. The network obtained by adding link ij to an existing g is denoted as $g + ij$ and the network that results from deleting link ij from an existing g is denoted as $g - ij$. Let $N(g) = \{i \mid \text{there is } j \text{ such that } ij \in g\}$ be the set of firms that have at least one link in g. A path in g between i and j is a sequence of firms $i_1, \ldots, i_K$ such that $i_k i_{k+1} \in g$ for each $k \in \{1, \ldots, K-1\}$ with $i_1 = i$ and $i_K = j$. A network g is connected if for all $i \in N(g)$ and $j \in N(g) \setminus \{i\}$, there exists a path in g connecting i and j. A nonempty subnetwork $h \subseteq g$ is a component of g, if for all $i \in N(h)$ and $j \in N(h) \setminus \{i\}$, there exists a path in h connecting i and j, and for any $i \in N(h)$ and $j \in N(g)$, $ij \in g$ implies $ij \in h$. The set of components of g is denoted by $C(g)$. A component h of g is minimally connected if h has $\#N(h) - 1$ links. Knowing the components of a network, we can partition the players into groups within which players are connected. Let $\Pi(g)$ denote the partition of N induced by g. That is, $S \in \Pi(g)$ if and only if either there exists $h \in C(g)$ such that $S = N(h)$ or there exists $i \notin N(g)$ such that $S = \{i\}$. We denote by $S(i)$ the coalition $S \in \Pi(g)$ such that $i \in S$.[2]

Let $N_i^k(g) = \{j \mid t(ij) = k\}$ be the set of firms that are connected to firm i by a path of at least k links. Each firm benefits both from its own R&D (reducing its marginal cost by 1) and from the R&D done by the firms it is connected to (reducing its marginal cost by $\sum_{j \neq i} \delta^{t(ij)-1}$).[3] Given a network g, the marginal cost for firm i is given by

$$c_i(g) = c_0 - 1 - \sum_{k=1}^{n-1} \#N_i^k(g)\delta^{k-1}$$

where c_0 is a firm's initial marginal cost and $\delta \in (0, 1]$. We focus on the case where each firm fully benefits from the research done by the firms it is connected to: $\delta = 1$.

In the second stage, firms compete in quantities in the oligopolistic market, taking as given the costs of production. Let $p = a - \sum_{i \in N} q_i$ with $a > 0$ be the linear inverse demand function. Thus, firm i's profits in g is given by $U_i(g) = (q_i(g))^2$ where the equilibrium output is

$$q_i(g) = \frac{1}{n+1}\left(a - c_0 + (n+1)\#S(i) - \sum_{S \in \Pi(g)} (\#S)^2\right). \tag{1}$$

In the first stage, network formation takes place. When firms are myopic, given there are small but positive costs to forming links, we use a strict version of Jackson and Wolinsky's (1996) notion of pairwise stability as in Goyal and Joshi (2003). A network g is pairwise stable if (i) for all $ij \in g$, $U_i(g) > U_i(g - ij)$ and $U_j(g) > U_j(g - ij)$, and (ii) for all $ij \notin g$, if $U_i(g) < U_i(g + ij)$, then $U_j(g) \geq U_j(g + ij)$. The proof of the following proposition is available upon request.

Proposition 1. *A network g is pairwise stable if and only if $C(g) = (h_1, h_2)$, h_1 and h_2 are minimally connected, $N(h_1) \cup N(h_2) = N$, and*

$$\#N(h_1) = \begin{cases} \text{int}((n+3)/2) & \text{if } n \text{ even} \\ (n+1)/2 & \text{if } n \text{ odd}. \end{cases}$$

3. Farsightedly stable R&D networks

We use a strict version of Herings, Mauleon and Vannetelbosch's (2009) notion of pairwise farsightedly stable set to determine the networks that emerge when firms are farsighted. A farsightedly improving path from g to $g' \neq g$ is a finite sequence of graphs $g_1, \ldots, g_K$ with $g_1 = g$ and $g_K = g'$ such that for any $k \in \{1, \ldots, K-1\}$ either (i) $g_{k+1} = g_k - ij$ for some ij such that $U_i(g_K) \geq U_i(g_k)$ or $U_j(g_K) \geq U_j(g_k)$, or (ii) $g_{k+1} = g_k + ij$ for some ij such that $U_i(g_K) > U_i(g_k)$ and $U_j(g_K) > U_j(g_k)$. If there exists a farsightedly improving path from g to g', then we write $g \to g'$. For a given g, let $F(g) = \{g' \in \mathbb{G} \mid g \to g'\}$. This is the set of networks that can be reached by a farsightedly improving path from g.

Definition 1. A set of networks G is pairwise farsightedly stable if

(i) $\forall g \in G$,
(ia) $\forall ij \notin g$ such that $g + ij \notin G$, $\exists g' \in F(g + ij) \cap G$ such that $U_i(g') \leq U_i(g)$ or $U_j(g') \leq U_j(g)$,
(ib) $\forall ij \in g$ such that $g - ij \notin G$, $\exists g', g'' \in F(g - ij) \cap G$ such that $U_i(g') \leq U_i(g)$ and $U_j(g'') \leq U_j(g)$,
(ii) $\forall g' \notin G$, $F(g') \cap G \neq \emptyset$.
(iii) $\nexists G' \subsetneq G$ such that G' satisfies Conditions (ia), (ib), and (ii).

Condition (ia) captures that adding a link ij to a network $g \in G$ that leads to a network outside G, is deterred by the threat of ending in g'. Here g' is such that there is a pairwise farsighted improving path from $g + ij$ to g', and g' belongs to G, which makes g' a credible threat. Condition (ib) is a similar requirement, but then for the case where a link is deleted. Condition (ii) requires external stability. From any network outside of G there is a farsighted improving path leading to some network in G. Condition (iii) is the minimality condition. A pairwise farsightedly stable set of networks always exists.

We now show that the set of all networks g consisting of two minimally connected components h_1 and h_2 such that $\#N(h_1) = \text{int}((3n+1)/4)$ and $N(h_1) \cup N(h_2) = N$ is a pairwise farsightedly stable set of networks.

Proposition 2. *The set $\widetilde{G} = \{g \mid C(g) = (h_1, h_2), h_1$ and h_2 are minimally connected, $\#N(h_1) = \text{int}((3n+1)/4)$ and $N(h_1) \cup N(h_2) = N\}$ is a pairwise farsightedly stable set.*

Proof. Take any $\widetilde{g} \in \widetilde{G}$. First, we show that condition (ia) is satisfied. The deviation from $\widetilde{g}$ to $\widetilde{g} + ij$ with $i, j \in N(h_1)$ or $i, j \in N(h_2)$ is deterred since the cardinality of h_1 or of h_2 does not change and forming links is costly. Moreover, from $\widetilde{g}$ firms $i \in N(h_1)$ and $j \in N(h_2)$ do not want to add the link ij to form a single component of size n. Indeed, comparing $U_i(g) = (a - c_0 + (n+1)(\text{int}((3n+1)/4)) - (\text{int}((3n+1)/4))^2 - (n - \text{int}((3n+1)/4))^2)^2/(n+1)^2$ with $U_i(g + ij) = (a - c_0 + n)^2/(n+1)^2$, we have $U_i(g) \geq U_i(g + ij)$ for all $n \geq 3$.

Second, we show that condition (ib) is satisfied. Since $\text{int}((3n+1)/4) > \text{int}((n+3)/2)$ if and only if $n > 5$, there is no profitable deviation from $\widetilde{g}$ to $\widetilde{g} - ij$ so that j is isolated in $\widetilde{g} - ij$ (i.e. $N_j(\widetilde{g} - ij) = \emptyset$) for $3 \leq n \leq 5$. For $n > 5$, the only profitable deviations from

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[2] We use the notation $\subseteq$ for weak inclusion, $\subsetneq$ for strict inclusion, # for the cardinality, and int(·) for the integer part.

[3] Two distinct ways of modeling knowledge externalities in the context of an oligopoly with cost-reducing R&D appear in the literature. Collaboration between firms either increases the effective marginal cost reduction (output spillovers) or increases the effective expenditure in research (input spillovers). Amir (2000) shows that the two approaches are not equivalent from a quantitative and qualitative point of view. The cost reduction approach appears to be of questionable validity for large values of the spillover parameter.

$\widetilde{g}$ to $\widetilde{g} - ij$ are such that j is isolated in $\widetilde{g} - ij$ (i.e. $N_j(\widetilde{g} - ij) = \emptyset$). We now show that such deviations are deterred because there is a farsightedly improving path from $\widetilde{g} - ij$ to some $g' \in \widetilde{G}$ and the initial deviator, firm i, is worse off at g'. Such a farsightedly improving path from $\widetilde{g} - ij$ looks as follows: first j adds a link jk with $k \in h_2$ forming the component h_2+jk, next $l \in h_1-jk$ cuts her link with $i \in h_1-jk$ so that l becomes isolated, next l adds a link lm with $m \in h_2+jk$ forming the component $h_2+jk+lm$, and so forth. That is, at each step, one firm belonging to the largest component in $\widetilde{g}$ becomes isolated and then this firm links to the smallest component in $\widetilde{g}$ looking forward to the end network $g' \in \widetilde{G}$ where the smallest component in $\widetilde{g}$ becomes now in g' the largest component with size $\text{int}((3n+1)/4)$. So, the end network $g' \in F(\widetilde{g}-ij) \cap \widetilde{G}$, and firm i that initially deleted the link ij is worse off in $g' : U_i(g') < U_i(\widetilde{g})$ (while j and firms in h_2 prefer g' to $\widetilde{g} - ij$).

Third, we show that condition (ii) is satisfied. Notice that we only need to show that there is a farsightedly improving path from any g consisting of minimally connected components to some $\widetilde{g} \in \widetilde{G}$. Indeed, if $\widetilde{g} \in F(g)$, then $\widetilde{g} \in F(g')$ for any $g' \supset g$ with $\Pi(g') = \Pi(g)$ because profits only depend on the cardinality of the components and forming links is costly. We consider three cases. (a) Take any g with $\Pi(g) = \{N\}$. If there is $ij \in g$ such that $g - ij \in \widetilde{G}$, then $g - ij \in F(g)$. Otherwise, we can build a farsightedly improving path from g to some $\widetilde{g} \in \widetilde{G}$ where first some firm i becomes isolated, next another firm j becomes isolated, next i and j form the link ij, next k becomes isolated, next k forms a link with either i or j, and so forth until we reach some $\widetilde{g} \in \widetilde{G}$ where firms that have isolated other firms along the path are in the largest component. (b) A similar farsightedly improving path can be built from any g containing one component of cardinality between n and $\text{int}((3n+1)/4)$. From g (in case g has at least three components), at each step, two firms belonging to the two smallest components form a link until we reach a network g' consisting of only two components (with one of them having cardinality larger than $\text{int}((3n+1)/4)$). From g', we proceed as in (a) by first isolating a firm of the largest component, next linking this firm with one firm of the smallest component, and so forth until we reach a network $\widetilde{g} \in \widetilde{G}$ where the firms that have linked the smallest components along the sequence are now in the component of cardinality $n-\text{int}((3n+1)/4)$, and the firms of the largest component in the initial network that have isolated some firms are now in the component of cardinality $\text{int}((3n+1)/4)$ in $\widetilde{g}$. (c) Consider now a network g containing only components of cardinality smaller than $\text{int}((3n+1)/4)$. From g, at each step, two firms belonging to the two largest components form a link until we reach a network g' with one component of cardinality greater or equal than $\text{int}((3n+1)/4)$ and some smaller components. From g', we proceed as in (b) by first forming links between the smallest components until reaching a network g'' with two components, next isolating a firm of the largest component and then linking this firm with one firm of the smaller component, and so forth until we reach a network $\widetilde{g} \in \widetilde{G}$. In $\widetilde{g}$, the firms that have linked the largest components along the sequence as well as the firms that have isolated some firms from the largest component once there were only two components in the network are now in the component of cardinality $\text{int}((3n+1)/4)$, which implies that they strictly prefer the end network to the network of the sequence from which they moved. Notice that the firms that have linked the smallest components once there was a component of cardinality larger than $\text{int}((3n+1)/4)$, are now better off in the component of cardinality $n - \text{int}((3n+1)/4)$.

Fourth, we show that condition (iii) is satisfied. Since $g \notin F(g')$ for all $g, g' \in \widetilde{G}$, any proper subset $G \subsetneq \widetilde{G}$ violates condition (ii). □

Since there is no farsighted improving path between any two networks in $\widetilde{G}$, the set $\widetilde{G}$ is also a von Neumann–Morgenstern farsightedly stable set.[4] However, the set of all pairwise stable networks, denoted by $\widehat{G}$, is neither a pairwise farsightedly stable set of networks nor a von Neumann–Morgenstern farsightedly stable set. Indeed, $\widehat{G}$ violates the external stability condition (ii) since $g \notin F(g')$ for all $g \in \widehat{G}$ and $g' \in \widetilde{G}$.[5]

Hence, we obtain that farsightedly stable R&D networks lead to a collaboration architecture similar to the equilibrium structure of Bloch's (1995) sequential group formation game for forming research associations where firms form two asymmetric alliances, with the largest one comprising roughly three-quarters of industry members.[6] In fact, by assuming that all connected firms in a network fully benefit from a new link, we recover Bloch's (1995) assumption that the benefits from cooperation increase linearly in the size of the association. However, the network approach differs from the group formation approach by focusing on bilateral relationships and allowing for a richer class of collaborations. It also differs in the decision making for establishing R&D collaborations. Mutual consent is needed for forming a new link between two firms, whereas the consent of all members of the association is usually required when a firm joins the association. Both approaches lead to similar conclusions only if firms are farsighted and anticipate the reactions of other firms to the decisions they take. Farsightedness helps firms to better exploit all the collaborative opportunities they face.

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4 With price competition and homogeneous goods, all networks give zero profits for all firms. Since forming links is costly, farsighted stability only supports the empty network, which is also the unique pairwise stable network.

5 Since $F(g) \neq \emptyset$ for $g \in \widetilde{G}$, the pairwise farsightedly stable set is not unique (see Theorem 5 in Herings et al. (2009)), and so, it could be that a set consisting of some pairwise stable networks together with other networks can be pairwise farsightedly stable.

6 Kamien and Zang (1993) consider an industry partitioned into symmetric competing alliances and show that when the spillover effects across alliances are not too large, splitting the industry's firms into exactly two competing alliances leads to the greatest level of industry wide effective research activity. See Bloch (2005) for a survey on group and network formation in industrial organization. Roketskiy (2012) studies collaboration between farsighted firms competing in a tournament and finds that stable networks consist of two asymmetric mutually disconnected complete components.

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