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Knowledge Sharing and Cumulative Innovation in Business Networks

Gilles Saint-Paul

Paris School of Economics (ENS-PSL), 75014 Paris, France; gilles.saint-paul@psemail.eu

Abstract: How can we explain the success of cooperative networks of firms which share innovations, such as Silicon Valley or the Open Source community? This paper shows that if innovations are cumulative, making an invention publicly available to a network of firms may be valuable if the firm expects to benefit from future improvements made by other firms. A cooperative equilibrium where all innovations are made public is shown to exist under certain conditions. Furthermore, such an equilibrium does not rest on punishment strategies being followed after a deviation: it is optimal not to deviate regardless of another firm's actions following a deviation. A cooperative equilibrium is more likely to arise the greater the number of firms in the network. When R&D effort is endogenous, cooperative equilibria are associated with strategic complementarities between firms' research effort, which may lead to multiple equilibria.

Keywords: R&D; cooperation; innovation; growth; technical progress; information sharing; open source; Silicon Valley; cumulative knowledge

JEL Classification: O3

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1. Introduction

There are several examples of the emergence of business networks or communities where firms exchange strategic information, or even share important innovations, with competitors.

One traditional example is Silicon Valley. Accounts of its success insist on the role of information sharing between firms. Information sharing allows a firm to easily improve on an innovation by another firm, thus stimulating the growth process. Employee mobility and the low enforcement of trade secrets by courts implied that many innovations were shared by firms in the network. While such a process does not seem to rely on a voluntary policy of information sharing from firms, there is evidence that the culture of Silicon Valley penalizes those entrepreneurs who do not share enough information and/or sue departing employees for violations of trade secrets. Thus, Hyde (1998) writes that "enforceability [of trade secrets] is limited because firms that litigate in defense of their trade secrets face substantial informal social and economic sanction from other firms (whose cooperation is necessary to accomplish many projects), venture capitalists, and incumbent and prospective employees". This suggests that while the instrument of information sharing was employee mobility between firms, entrepreneurs recognized that they had an interest in cooperating with other members of the network by not blocking such mobility by litigation or other means. Another more recent example is the emergence of the "Open Source" community in the software industry. As described by its proponents (Raymond 1999), open source software allows very fast growth for a project, as improvements that different users implement cumulate. This is especially true with respect to debugging, where users who have access to the source have an interest in finding and fixing bugs, and, with enough good will, will make their fixes public.[1]

This thematic is also present in the knowledge management literature, which, based on the insights of Michael Polanyi (1962), recognizes the role of inter-organizational cooperation in the production of innovation.[2] Similarly, Chesbrough (2003) and Chesbrough et al. (2014) developed the managerial concept of "open innovation" and showed that this encompasses a variety of practices that are in no way limited to software communities but are pervasive in manufacturing as well. Chesbrough's insights has stimulated a vast empirical literature which documents the existence of business networks that openly share knowledge in a variety of sectors.[3] In the 1980s, Piore and Sabel (1986) had already documented a similar knowledge-sharing and open innovation culture in the industrial districts of SMEs in northern Italy.[4]

To an economist, a simple question is: why do such networks function at all? Why do individual firms not just free-ride by using other participants' public information while hoarding their own valuable information? To be sure, the literature on dynamic games has highlighted a number of cooperation mechanisms: "trigger strategies", "reputation", etc.[5] However, these mechanisms rely on free riding being detected, which is problematic in a context where cooperation is about information revelation, since one may well play cooperative while having nothing valuable to reveal.

In this paper, I describe another, far more robust, cooperation mechanism which applies to the revelation of innovations and captures part of the incentives underlying the open source movement. I assume innovations are cumulative, i.e., an innovation opens the door for further innovations. An individual firm then has an incentive to make its innovations public, because this will increase the number of firms heading toward the next step in the technological ladder. If it is expected that the next innovation will also be made public, sharing one's invention with other members in the network will shorten the time until the next innovation arrives, which benefits the individual firm. As is shown below, this benefit may outweigh the short-run cost of lower profits for the innovating firm.

This mechanism does not rely on cheating being detected nor on the sustainability of a punishment strategy. By not revealing its information, the firm punishes itself, since it will have to wait longer for the next innovative step. In other words, the losses from non-cooperation are genuine and do not rely on the other players' strategic responses to one's deviation. However, given that the benefits from information sharing rely on future innovations also being public, the argument does rest on the horizon being infinite and a "Nash" equilibrium where information is kept private always exists. Nevertheless, for a range of parameters, a cooperative equilibrium also exists. Another interesting result is that the cooperative equilibrium is more likely to exist the larger the number of firms in the network. This contrasts with traditional arguments, which suggest that free-riding is more likely the greater the number of agents. Here, more firms mean a much greater benefit of making one's innovation public, because a much larger number of firms will work toward the next step.

I also show that the cooperative equilibrium has faster growth than the non-cooperative equilibrium. In some sense, when innovations are cumulative, the case for public innovations is stronger than when they are not, when it can be shown that public innovations may reduce long-run growth on net because they depress the profitability of private innovation (Saint-Paul 2003).

Finally, the model is extended to allow for an endogenous research and development (R&D) effort. It is shown that the results are robust to introducing such endogeneity. Furthermore, as the cumulative benefits of an innovation depend on improvements by other firms, and thus on their R&D effort, research efforts by different firms are now complementary, which may lead to multiple equilibria.

Since the seminal work of Schumpeter (1942), the endogenous growth literature has paid a lot of attention to the effect of competition on innovation and growth (see Romer (1990); Aghion and Howitt (1992); Grossman and Helpman (1993)). A subset of that literature has analyzed the value of R&D cooperation between firms when there are spillovers. The value of technology sharing is well recognized by that literature. Hence, Baumol (1992) writes that "in an industry with, say, ten firms similar in output and investment in R&D, each member of a nine-firm technology cartel can expect to obtain immediate access to nine times the number of innovations that the remaining enterprise can anticipate on the average" . However, to my knowledge, this is the first paper to analyze how that advantage can be turned into a cooperation mechanism when innovation is cumulative. The literature, instead, typically relies on traditional trigger strategy mechanisms, exogenously assumes cooperation, or uses a cooperative game framework.[6] Furthermore, most of it deals with cooperation in setting R&D levels rather than in the decision to make an innovation public.[7] For example, Cozzi (1999) analyzes the consequences for growth of switches between cooperative and non-cooperative equilibria, but cooperation is enforced by a standard trigger-strategy mechanism, and cooperation is about the R&D level. Another strand of the literature (d'Aspremont and Jacquemin 1988; Leahy and Neary 1997) compares outcomes with and without R&D cooperation when there are spillovers, but again, it does not ask the question of how cooperation is enforced and focuses on investment rather than information. Finally, a series of works by Scotchmer (1991, 1996, 2004) discusses conflicts over intellectual property rights when innovation is cumulative and the efficiency properties of different patent systems in this case.

The paper which is most related to the current one is Bessen and Maskin (2008). In that paper, as in here, a given innovation exerts positive spillovers on further innovations. Bessen and Maskin perform a welfare analysis of intellectual property regimes and show that under sequential innovation, no patents may be preferable to IP protection. But, in their paper, if IP exists, it is always privately optimal to use it. In the present paper, it is actually an equilibrium outcome for firms to voluntarily disclose their innovation regardless of the IP regime.

2. The Model

2.1. The Intratemporal Profit Function

We consider a specific sector of an economy, which is homogeneous enough and where firms are large enough relative to the total size of the sector, for the economic effects analyzed here to be relevant. Such a sector could be, say, Silicon Valley, the agroforestry sector in Brazil, or flexible manufacturing garment firms in the Bologna area. In that sector, there are N firms, competing with each other by producing differentiated goods. Each firm i is characterized by a level of technological advancement captured by an integer number n_i. The profit of firm i is given by a function

$$\pi_i(n_1, \ldots, n_i, \ldots n_N).$$

We assume that technical progress in a given firm increases its profits:

$$\frac{\partial \pi_i}{\partial n_i} > 0,$$

while technical progress in another firm decreases profits:

$$\frac{\partial \pi_i}{\partial n_j} < 0, j \neq i. \tag{1}$$

Finally, the progression of all firms by one step in the technological ladder increases the profits of any given firm:

$$\sum_{j=1}^{N} \frac{\partial \pi_i}{\partial n_j} > 0.$$

We shall assume that if all firms other than i have the same technical level n, while firm i has technical level $\hat{n}$, then firm i's profit can be expressed in the following way:

$$\begin{aligned} \pi_i(n, \ldots, n, \hat{n}, n, \ldots, n) &= \pi(\hat{n}, n) \\ &= A^n f(\hat{n} - n), \end{aligned} \tag{2}$$

where by assumption, $A > 1$, $f(.) > 0$, and

$$f(q+1)/f(q) > A. \tag{3}$$

The latter inequality is needed for (1) to hold.

Equation (2) expresses the firm's profit as an increasing function of the other firm's overall technological level, as captured by n, and the gap between firm i and the other firms, as captured by $\hat{n} - n$. For competitive effects to dominate, firm i has to suffer when other firms innovate, which will be true if the second effect is stronger than the first effect, as captured by our assumption that $f(q+1)/f(q) > A$. In economic terms, this condition sets a lower bound on the value of climbing the technological ladder. In Proposition 1 below, an upper bound is assumed and shown to be a sufficient condition for an "open innovation" equilibrium to exist.

Example 1. *The demand curve for firm i is isoelastic and given by $y_i = Yp^{-\alpha}(p_i/p)^{-\sigma}$, where $\sigma > 1$, Y is an index of demand for the whole sector and p is a sectoral price index given by*

$$p = \left(\sum_{i=1}^{N} p_i^{1-\sigma}\right)^{\frac{1}{1-\sigma}}.$$

Firm i's unit cost is c/B^{n_i}, with $B > 1$; thus, each step in technical progress represents a geometric reduction in unit costs. Firms set their price so as to maximize their profit $\pi_i = y_i(p_i - c/B^{n_i})$. They neglect the impact of their decision on the sectoral price level and thus set $p_i = (\sigma-1)/\sigma \cdot c/B^{n_i}$. Thus, we find that the equilibrium $\pi_i(\ldots)$ function is given by

$$\pi_i(n_1, \ldots, n_N) = KB^{(\sigma-1)n_i}\left[\sum_{i=1}^{N} B^{(\sigma-1)n_j}\right]^{\frac{\sigma-\alpha}{1-\sigma}},$$

where K is a constant given by $K = Y\left[\frac{\sigma c}{\sigma-1}\right]^{\frac{\sigma-\alpha}{1-\sigma}} \frac{c^{1-\sigma}}{\sigma-1}\left(\frac{\sigma}{\sigma-1}\right)^{-\sigma}$. If $n_j = n, j \neq i$, and $n_i = \hat{n}$, we obtain

$$\pi_i = KB^{n(\alpha-1)}\left[B^{(\sigma-1)(\hat{n}-n)}\left(N-1+B^{(\sigma-1)(\hat{n}-n)}\right)^{\frac{\sigma-\alpha}{1-\sigma}}\right];$$

thus we have

$$A = B^{\alpha-1}$$

and

$$f(q) = K\left[B^{(\sigma-1)q}\left(N-1+B^{(\sigma-1)q}\right)^{\frac{\sigma-\alpha}{1-\sigma}}\right].$$

The properties $A > 1$ and $\partial\pi_i/\partial n_j < 0, j \neq i$ hold if $1 < \alpha < \sigma$. One can then check that the property $f(q+1)/f(q) > A$ then holds, since

$$\frac{f'(q)}{f(q)} - \ln A = (\sigma-\alpha)\ln B - \frac{(\sigma-\alpha)B^{(\sigma-1)q}\ln B}{\left(N-1+B^{(\sigma-1)q}\right)} > 0,$$

which is positive if $\sigma > \alpha$.

This example shows how a functional form like (2) can be derived from monopolistic competition among differentiated goods. As the whole sector climbs the technological ladder (i.e., the n_i values grow), it grows in terms of output and, as long as $\alpha > 1$, in terms of profits.

Without loss of generality, we shall normalize $f(0)$ to 1 (in the previous example, this amounts to picking the right value of Y, so that $K = N^{\frac{\sigma-\alpha}{\sigma-1}}$).

Remark 1. *Going back to (2), note that A is the proportional effect on a firm's profit of an increase in the technological level of all firms by one step provided all other firms have the same technical level. Conversely, the effect on a firm of a unit increase of its technical level, holding that of other firms constant, is $f(\hat{n}+1-n)/f(\hat{n}-n)$, which is greater than A. Growth in a single firm must increase that firms' profits by more than growth in all firms; otherwise, it would not be harmed by growth in other firms and there would not be any coordination problem. However, in the example we just constructed, we have*

$$\lim_{q\to+\infty} \frac{f(q+1)}{f(q)} = B^{\alpha-1} = A. \tag{4}$$

In other words, this mathematical property means that asymptotically, if a firm become infinitely productive relative to the others, thus covering the whole market, each innovation will increase its profits by the same factor A, which increases a firm's profits when an innovation is implemented by all firms. This property is quite natural: if a firm becomes infinitely productive relative to others, it is as if one has a single firm in the market. The property should therefore hold in any model where, asymptotically, the proportional effect of an innovation which is adopted by all firms on profits does not depend on the number of firms. In other words, property (4) is not a knife-edge case but should be expected to generally hold. As shown below, property (4) plays an instrumental role in making the upper bound on individual innovation gains, that delivers the cooperative outcome in Proposition 1, compatible with Assumption (3).

2.2. The Dynamics of Innovation

The preceding subsection has introduced the intratemporal profit function. We now describe the dynamics of innovation.

Time is continuous; firms maximize the expected present discounted value of their profits given by

$$V_i(t) = E_t \int_t^{+\infty} \pi_i(n_1(u), \ldots, n_i(u), \ldots, n_N(u)) e^{-ru} du, \tag{5}$$

where r is the discount rate, assumed fixed and exogenous. In order for the value of a firm to be well defined, we shall assume that r is larger than a firm's maximum potential growth rate. That is,

$$\lambda N(A-1) < r \tag{6}$$

The technical level available to a given firm jumps from n_i to $n_i + 1$ according to a Poisson process with arrival rate λ. At this stage of analysis, this process is assumed exogenous, and, therefore, so is parameter λ. Despite that, growth remains endogenous because the technical level of a given firm is transferable to other firms. Firm i has the option of revealing its level to other firms, in which case they can jump to level n_i, i.e., in some sense, adopt its technology. Therefore, with probability λ per unit of time, a given firm's technology level improves by one step, which allows it to increase it from n_i to $n_i + 1$, and it has two options:

1. Do not share its innovation with other firms, in which case they all remain at level n_j.
2. Share the innovation, in which case all firms such that $n_j < n_i + 1$ can upgrade to level $n_i + 1$.

To fix ideas, we shall assume that an innovation can be released only at the time it occurs and not after, although this is immaterial and only simplifies the analytics.

Thus, the only decision to be made by firms in this setting is whether or not to make an innovation public at the time it arrives. We will relax it in Section 4, where the R&D effort and the arrival rate of innovations are made endogenous.

2.3. The Nash Solution

Clearly, there always exists an equilibrium where firms do not share innovations. If I anticipate that other firms will never share their innovations with me, giving away my innovations to them will increase their technological level forever, which reduces my own profits, by virtue of the fact that $\partial\pi_i/\partial n_j < 0$. Thus, it is a subgame perfect equilibrium to never release information. In such an equilibrium, the average speed of innovation for any given firm is λ. As in the literature on repeated games (see Fudenberg and Tirole 1991), this subgame perfect equilibrium is the repeated Nash equilibrium of the static game where players ignore the future consequences of current outcomes.

3. Cooperative Equilibria

We now construct an equilibrium such that it is profitable for firms to reveal their innovations to their competitors, despite the fact that it reduces their profits upon impact. The equilibrium concept is again the standard subgame perfect equilibrium.[8]

We construct an equilibrium where an innovation is shared every time it occurs. Thus, in the equilibrium path, all firms have the same technological level. Situations with a dispersion in technological levels only occur off the equilibrium path.

To construct such an equilibrium, we compute the value of a firm along the equilibrium path and an upper bound of the value of deviating by not releasing information; we then show that the former is greater than the latter for a given range of parameters. This yields the following proposition:

Proposition 1. *Assume $f(.)$ satisfies*

$$\sup_{k=0,1,\ldots} A^{-k} f(k) \leq \frac{r + \lambda N}{r + \lambda(A-1) + \lambda N(2-A)} \tag{7}$$

Then, there exists a equilibrium where each innovation is instantaneously made public.

Proof. Along the equilibrium path which we seek to construct, all firms have the same technological level n. Furthermore, all firms upgrade to level $n+1$ with a flow probability equal to λN, since the day any given firm innovates, its innovation spreads to the whole sector. Consequently, the value of a firm when the whole sector is at technical level n is determined by

$$V_C(n) = \frac{\pi(n,n) + \lambda N V_C(n+1)}{r + \lambda N}.$$

The numerator is equal to the sum of the profit flow at technical level n, $\pi(n,n)$, and of the flow probability of any one firm innovating, equal to the product of the arrival rate for innovations λ and the number of firms N, times the value of the firm when all firms upgrade to the next level, $V_C(n+1)$. Iterating forward allows for computing the value of a firm along the equilibrium path:

$$V_C(n) = \sum_{i=0}^{+\infty} \left(\frac{\lambda N}{r + \lambda N}\right)^i \frac{\pi(n+i, n+i)}{r + \lambda N},$$

which, using (2), is equivalent to

$$V_C(n) = \frac{A^n}{r - \lambda N(A-1)} \tag{8}$$

For this formula to be meaningful, it must be that $\lambda N(A-1) < r$, i.e., that the growth rate of profits be lower than the interest rate; otherwise, the value of a firm would be infinite.

Let $\bar{f} = \sup_{k=0,1,\ldots} A^{-k} f(k)$. Then:

$$\begin{aligned} \pi_i(n_1, \ldots, n_i, \ldots n_N) &\leq \pi_i(0, \ldots, n_i, \ldots 0) \\ &= f(n_i) \\ &\leq A^{n_i} \bar{f}. \end{aligned} \tag{9}$$

Let $\vec{n} = (n_1, \ldots n_N)$ denote a vector of firm's technological advancements, and $V_i(\vec{n})$ denote the maximum value of firm i, over all possible courses of action, if $\vec{n}$ is the current state of technology level[9].

Let

$$\bar{V}_i(n, p) = \max_{\substack{\vec{n}=(n_1,\ldots,n_N) \\ n_i = n \\ n_j \leq p, j \neq i}} V_i(\vec{n})$$

Note that We define operator T_j as follows. If $\vec{n} = (n_1, \ldots, n_N)$, then

$$T_j \vec{n} = (\max(n_1, n_j), ., \max(n_k, n_j) \ldots, \max(n_N, n_j)).$$

Operator T_j tells us how the state vector is transformed if firm j releases its technical level: all firms with a lower technical level are lifted to level n_j. We also define U_j, which tells us how the state vector is transformed upon a shock hitting firm j, before it has decided whether to make it public or not:

$$U_j \vec{n} = (n_1, \ldots, n_{j-1}, n_j + 1, n_j, \ldots, n_N).$$

The value function $V_i(\vec{n})$ then obeys the following recursive condition:

$$V_i(\vec{n}) = \frac{\pi_i(\vec{n}) + \lambda \sum_{j=1}^{N} \max(V_i(T_j U_j \vec{n}), V_i(U_j \vec{n}))}{r + \lambda N}.$$

For any $\vec{n} = (n_1, \ldots, n_N)$ such that $n_j \leq p < n_i = n$, $j \neq i$, we have, for $j \neq i$, $V_i(T_j U_j \vec{n}) \leq \bar{V}_i(n, p+1)$ and $V_i(U_j \vec{n}) \leq \bar{V}_i(n, p+1)$, while $V_i(U_i(\vec{n})) \leq \bar{V}_i(n+1, p)$ and $V_i(T_i U_i(\vec{n})) \leq \bar{V}_i(n+1, n+1)$. This, along with (9), implies

$$V_i(\vec{n}) \leq \frac{A^{n_i} \bar{f} + \lambda(N-1)\bar{V}_i(n, p+1) + \lambda \bar{V}_i(n+1, n+1)}{r + \lambda N},$$

consequently:

$$\forall p < n, \bar{V}_i(n, p) \leq \frac{A^n \bar{f} + \lambda(N-1)\bar{V}_i(n, p+1) + \lambda \bar{V}_i(n+1, n+1)}{r + \lambda N}. \tag{10}$$

To proceed, we now show that for $\vec{n} = (n_1, \ldots, n_N)$ such that $n_j \leq p \leq n_i = n$, it must be that

$$V_i(\vec{n}) \leq \frac{A^n \bar{f}}{r - \lambda N(A-1)}.$$

To see this, write

$$V_i(\vec{n}) = \max_{\vec{n}(.) \in \Phi} \int_0^{+\infty} \int_{\Omega_t} \pi_i(\vec{n}(\omega)) dF(\omega, t) e^{-rt} dt,$$

where ω is a state of nature representing the whole history of shocks between date 0 and date t, $\vec{n}(\omega)$ is the corresponding state vector (which depends on the strategies followed by firms), and $dF(\omega, t)$ is the probability distribution of ω at date t. Φ is the set of feasible strategies, which is represented by a mapping defining the current state vector as a function of the whole history of shocks. Clearly, regardless of which strategy is followed, the most advanced firm climbs by at most one step every time a firm is hit by a shock. Thus, if $\vec{n}(\omega) = (n_1(\omega), \ldots, n_N(\omega))$, then $\max_k n_k(\omega) \leq n + S(\omega)$, where $S(\omega)$ is the total number of shocks that has occurred to any firm between 0 and t. In other words, $\Phi \subset \{\vec{n}(.), \max_k n_k(\omega) \leq n + S(\omega)\}$. $S(\omega)$ follows a Poisson distribution with arrival rate λN (that is, $P_t(S(\omega) = k) = \frac{(\lambda N t)^k}{k!} e^{-\lambda N t}$). Consequently, we have in particular that $n_i(\omega) \leq n + S(\omega)$ so that $\pi_i(\vec{n}(\omega)) \leq A^{n+S(\omega)} \bar{f}$. Hence:

$$\begin{aligned} V_i(\vec{n}) &\leq A^n \bar{f} \int_0^{+\infty} \int_{\Omega_t} A^{S(\omega)} dF(\omega, t) e^{-rt} dt \\ &= A^n \bar{f} \int_0^{+\infty} \left(\sum_{k=0}^{+\infty} A^k \frac{(\lambda N t)^k}{k!} e^{-\lambda N t} \right) e^{-rt} dt \\ &= A^n \bar{f} \int_0^{+\infty} e^{-(r - \lambda N(A-1))t} dt \\ &= \frac{A^n \bar{f}}{r - \lambda N(A-1)}. \end{aligned}$$

Note that this inequality holds regardless of the strategies that are followed by firm i or any other firms with respect to revealing their technologies upon being hit by an innovation.

A corollary is that

$$\bar{V}_i(n, p) \leq \frac{A^n \bar{f}}{r - \lambda N(A-1)} \text{ for } p \leq n. \tag{11}$$

Substituting that inequality into the second term in the numerator of the right-hand side (RHS) of (10) (which we can do since in (10) one assumes $p < n$), we obtain:

$$\bar{V}_i(n, p) \leq \frac{A^n \bar{f} + \lambda(N-1) \frac{A^n \bar{f}}{r - \lambda N(A-1)} + \lambda \max \frac{A^{n+1} \bar{f}}{r - \lambda N(A-1)}}{r + \lambda N}. \tag{12}$$

Rearranging, we get that

$$\bar{V}_i(n, p) \leq \frac{A^n \bar{f}}{r - \lambda N(A-1)} \frac{r - \lambda N A + 2\lambda N - \lambda + A\lambda}{(r + \lambda N)}.$$

Now, if inequality (7) holds, then $\bar{V}_i(n, p) \leq V_i(n, \ldots, n) = V_C(n) = \frac{A^n}{r - \lambda N(A-1)}$. Consequently, releasing innovation always dominates hoarding it when other firms are expected to follow the equilibrium path, which shows that it is indeed an equilibrium. □

An important aspect of proposition 1 is that a cooperative equilibrium is more likely to exist the greater the number of firms participating in the network (holding the $f()$ function invariant). This effect runs counter to the usual analysis of free rider problems, where cooperation is made more difficult by a greater number of players. Here, the greater the number of players, the quicker one will be paid back for sharing one's innovations with others, as the next technological step is discovered by one participant.

Since $A > 1$, it is also clear that the RHS of (7) is an increasing function of λ: the greater the frequency of innovations, the more likely it is that a cooperative equilibrium exists. Clearly, a greater arrival rate of innovations brings ahead in time the benefits of further innovations from other firms. Perhaps this explains why open innovation plays an important role in infant industries with a steep learning curve such as electric vehicles (see Purificato 2014; Cabigiosu 2023).

Note also that the proof relies on using an upper bound for the value of deviating for any response of other players to the deviation. Consequently, cooperation is not sustained by a trigger punishment strategy, as deviation is deterred even in the case where all other firms continue to release their innovations at all nodes following the deviation. The loss from other firms being one step backwards relative to cooperation is enough to deter opportunistic behavior. In some sense, the feedback effects of benefitting from other's future improvements on one's innovation generates gains from cooperation that are more robust—in that a firm contemplating deviations can ignore what others would do following its deviation—than those coming from punishment strategies. Thus, even if for some reason a deviation was undetected[10], incentives to cooperate would still remain.

Note that for inequality (7) to hold and be compatible with the restriction that $f(q+1)/f(q) > A$[11], it must be that $\lim_{q \longrightarrow +\infty} f(q+1)/(f(q)A) = 1$. Otherwise, the left-hand side (LHS) of (7) could not be bounded and (7) would not be satisfied. However, as argued above, $\lim_{q \longrightarrow +\infty} f(q+1)/(f(q)A) = 1$ is a rather plausible condition[12]; if $\lim_{q \longrightarrow +\infty} f(q+1)/(f(q)A) > 1$, then a single firm would grow faster than N firms for the same arrival rate of innovation, and we are not able to put a bound on the value of deviating from cooperation, although such a bound, and a cooperative equilibrium, may still exist.

Going back to the isoelastic example discussed above, in that special case, we have

$$\begin{aligned} \sup A^{-k} f(k) &= \lim_{k \longrightarrow +\infty} A^{-k} f(k) \\ &= \lim_{k \longrightarrow +\infty} K B^{(\sigma-\alpha)q} (N - 1 + B^{(\sigma-1)q})^{\frac{\sigma-\alpha}{1-\sigma}} \\ &= K \\ &= N^{\frac{\sigma-\alpha}{\sigma-1}}, \end{aligned}$$

where the last equality comes from the normalization $f(0) = 1$.

Thus, a sufficient condition for a cooperative equilibrium to exist is

$$N^{\frac{\sigma-\alpha}{\sigma-1}} < \frac{r + \lambda N}{r + \lambda(A-1) + \lambda N(2-A)}. \tag{13}$$

A first point to be made is that the RHS grows with N and is equal to 1 for $N = 1$. Therefore, for any given N, condition (13) is always satisfied for $(\sigma - \alpha)/(\sigma - 1)$ to be low enough. At face value, it seems that when N becomes large, the inequality is violated. This suggests that taking into account the effect of N on $f()$ may reverse the result that large values of N favor cooperation. This is due to an additional effect: with a larger number of differentiated firms, having an edge on the others is more valuable for a single firm, as the effect of decreasing marginal revenues at the sector level (captured by parameter α) is less severe. However, too large values of N are not possible, because (6) must hold. For intermediate values of N, it is difficult to show whether or not (13) holds analytically, but numerical computations suggest that it is more likely to hold for large, acceptable values of N than for small values of N. A typical example is given in Table 1. Therefore, the conclusion that larger networks make cooperation easier remains true despite the countervailing additional effects that were ignored when $f()$ was treated as exogenous.

Table 1. Cooperation range, A = 1.8, λ = 0.015, σ = 2, α = 1.8.

r	Maximum Value of N	Range over Which (13) Holds
0.04	3	2–3
0.05	4	2–4
0.06	5	2–5
0.07	5	2–5
0.08	6	4–6
0.1	8	6–8
0.13	10	9–10
0.16	13	13–13
0.18	15	–

We can also establish a necessary condition for cooperation to hold, which has similar determinants as the sufficient one derived in Proposition 1.

Proposition 2. *A necessary condition for a cooperative equilibrium to exist is*

$$f(1)/A \leq \frac{r - \lambda(A-1)}{r - \lambda N(A-1)}. \tag{14}$$

Proof. Assume a cooperative equilibrium exists and consider a firm which deviates by not releasing its innovation. Assume it releases its innovation the next time it has one. Then, this strategy yields a value given by

$$\tilde{V}(n+1,n) = \frac{A^n f(1) + \lambda(N-1)\frac{A^{n+1}}{r-\lambda N(A-1)} + \lambda \frac{A^{n+2}}{r-\lambda N(A-1)}}{r+\lambda N}.$$

The middle term in the numerator reflects the fact that if another firm is hit by an innovation, it will release it, and all firms will be at technical level $n+1$.

For a cooperative equilibrium to exist, this strategy must yield a lower value than releasing the innovation, i.e., one must have

$$\tilde{V}(n+1,n) \leq \frac{A^{n+1}}{r - \lambda N(A-1)}.$$

One can straightforwardly check that it is equivalent to (14). □

Condition (14) becomes satisfied very easily as N grows. Therefore, it rules out cooperative equilibria only for fairly low values of N. In the case of our isoelastic example, for the parameter values of Table 1, it always holds. The following table (Table 2) shows the range of values of N where it does not hold, for a different set of parameters, that differ from Table 1 only in that α is lower. It confirms the general message that cooperation is more likely with more firms.

Table 2. Non-cooperation range, A = 1.8, λ = 0.015, σ = 2, α = 1.3.

r	Maximum Value of N	Range over Which (14) Is Violated
0.04	3	—
0.05	4	2–2
0.06	5	2–2
0.07	5	2–3
0.09	7	2–4
0.1	8	2–5
0.12	10	2–6
0.14	11	2–8

4. Endogenous R&D Effort: The Role of Strategic Complementarities

In the preceding analysis, the only decision made by a firm is whether or not to release its innovation. The arrival rate of innovations λ is entirely exogenous. It is relatively straightforward to extend the model to allow for an endogenous λ and to compute its equilibrium value in a cooperative equilibrium. The cost is that the sufficient condition that I am able to establish for such an equilibrium to exist is more stringent than in the previous section.

Endogenizing λ yields two key insights. First, one may believe that the previous result that an increase in the network's size boosts growth and is good for sustaining cooperation can be overturned with an endogenous λ. As N is greater and innovations arrive at a higher rate, an individual firm might be tempted to spend less on R&D and reduce λ. In fact, that intuition is incorrect: at a cooperative equilibrium[13], an increase in N increases λ locally. The reason is that the total arrival rate of innovations is additive in each firm's specific λ, so that an increase in the number of firms does not reduce the marginal gain from increasing one's λ. On the contrary, a greater value of N increases the incentives for R&D via a capitalization effect. The greater the N value, the faster the rate at which the increments in profits from a given innovation grow, and the greater the incentives to innovate. Or, to put it otherwise, the greater the N value, the greater the speed at which my innovation is improved by other firms, and the greater my incentive to innovate.

Second, there exist strategic complementarities between the R and D effort of different firms. The increase in R&D by one firm tends to increase R&D by another firm. The reason is again the capitalization effect. If other firms increase their R&D effort, improvements on my innovation will come faster, and my incentive to innovate is larger. As a result, there may in principle be several cooperative equilibria with different arrival rates of innovation.

To endogenize the arrival rate of innovations, I assume that at each point in time a firm i can choose its own value of λ at a cost equal to $\pi_i c(\lambda)$, where π_i is its current profit. That the cost is proportional to π_i ensures that it will not become negligible relative to benefits as the economy grows. As cooperative equilibria are symmetrical, it is easy to compute the equilibrium common value of λ in such an equilibrium. Denoting again the value of a firm when all have a technical level equal to n by $V_C(n)$, the Bellman equation for an individual firm can be written as

$$V_C(n) = \max_{\lambda} \frac{\pi(n,n)(1-c(\lambda)) + \hat{\lambda}(N-1)V_C(n+1) + \lambda V_C(n+1)}{r + \lambda + \hat{\lambda}(N-1)},$$

where $\hat{\lambda}$ is the common value of λ of other firms, which is taken as given by the firm. We assume that $c(\lambda)$ is concave, differentiable, and increasing over $[\underline{\lambda}, \bar{\lambda}]$, with $c'(\underline{\lambda}) = 0, c(\bar{\lambda}) = 1$. If there is an interior solution for λ, it is given by the first-order condition:

$$c'(\lambda)\pi(n,n) = V_C(n+1) - V_C(n). \tag{15}$$

This equation has the usual straightforward interpretation. The LHS is the marginal cost of increasing λ by one unit. The RHS is the marginal benefit, which is equal to the capital gain made when all firms climb one step in the technological ladder. In a symmetrical equilibrium, we have $\lambda = \hat{\lambda}$, and the equivalent of Equation (8) holds, i.e.,

$$V_C(n) = \frac{A^n(1-c(\lambda))}{r - \lambda N(A-1)}. \tag{16}$$

Substituting that along with (2) into (15), and normalizing again $f(0)$ to 1, we obtain an equation determining the equilibrium value of λ, which is denoted by λ^* :

$$c'(\lambda^*) = \frac{(A-1)(1-c(\lambda^*))}{r - \lambda^* N(A-1)}. \tag{17}$$

If $(\frac{r}{N(A-1)}) > 1$, then this equation always has at least one solution, which is indeed interior and satisfies (15).[14]

While the LHS is a increasing function of λ, the RHS may be either increasing or decreasing. This is because a rise in λ has two conflicting effects on the capital gains from an innovation. Because R and D costs are proportional to profits, a higher λ compresses the difference in income flows between two consecutive technological levels: one can call that a revenue effect. On the other hand, a higher λ increases the growth rate of that difference, which tends to increase its expected present discounted value: this is the capitalization effect. If the capitalization effect is strong enough, then multiple equilibria may arise, as illustrated in Figure 1.

In such a case, as in the general analysis of Cooper and John (1988), multiple equilibria come from a strategic complementarity between a firm's research effort and the effort of other firms, as discussed above. Following Cooper and John, we can check that equilibria are Pareto rankable from the point of view of the firms[15]. Consider two equilibria, denoted by subscripts 0 and 1, such that $\lambda_1^* > \lambda_0^*$. Using the value function (16), we see that Equilibrium 1 dominates if

$$\frac{(1 - c(\lambda_1^*))}{r - \lambda_1^* N(A-1)} > \frac{(1 - c(\lambda_0^*))}{r - \lambda_0^* N(A-1)}.$$

Substituting the first-order condition (17), we see that this is equivalent to $c'(\lambda_1^*) > c'(\lambda_0)$, which clearly holds. Equilibria with higher R&D effort clearly dominate.

The preceding discussion does not tell us, however, whether a cooperative equilibrium exists. But, as shown in Appendix A, Proposition 1 can be extended and a non-empty sufficient condition for a cooperative equilibrium can be established, although this condition is much less tractable than the one derived in Proposition 1.

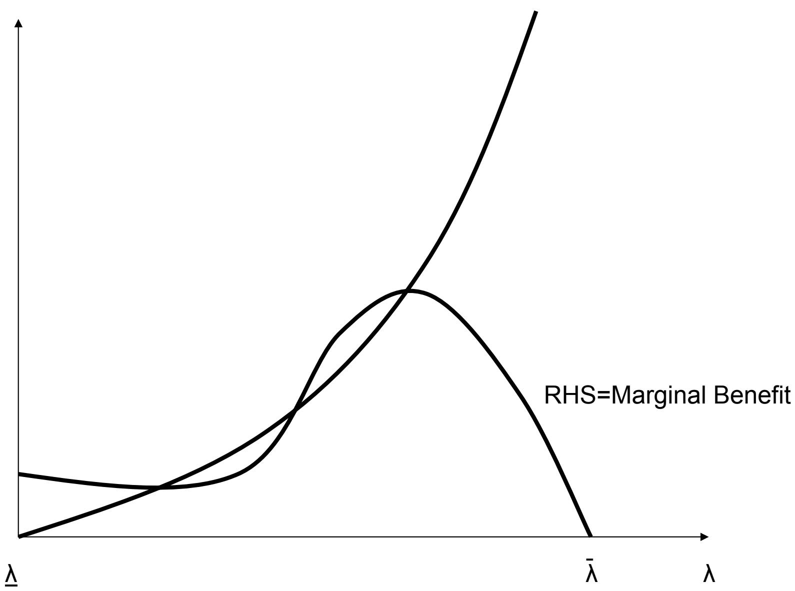

Figure 1. Multiple equilibrium R&D effort.

5. Conclusions

We hope the present paper has shed some light on the viability of public innovation when technical progress has a cumulative dimension. We have shown the existence of a "co-operative" equilibrium in which it is a subgame perfect strategy for firms in a given industry to share their innovations with others, because they expect to benefit from the incremental innovations that other firms will make, building on its own knowledge. Meanwhile, as in the literature on cooperation in dynamic games, there also exists a non-cooperative equilibrium in which innovation is not shared; here, the cooperative equilibrium is somewhat more robust than generally in that literature. Cooperation does not rely on other players coordinating on a punishment trajectory following deviation by a given player. Instead, the deviator punishes itself by foregoing the benefits of the future incremental innovations that its contribution would have generated among its competitors if it had been made public. Our theoretical analysis sheds light on the pervasiveness of "open innovation", as theorized by Chesbrough, and predicts that open innovation is enhanced when the number of innovative firms in the relevant industry goes up.

Further research could focus on more specific aspects. For example, in Silicon Valley, worker mobility has been an important vector of innovation sharing. It could be valuable to further analyze the role of the labor market in the diffusion of knowledge, which has been a largely untouched topic until now.[16] In principle, such research avenues could deliver insights as to why Silicon Valley emerged in an economy with a flexible labor market as opposed to a European country where collective bargaining and labor regulation hamper labor mobility. Another potential avenue of further research would be the analysis of an incomplete information network in which firms would release innovations only to a subset of firms to which it is 'connected': the incentive for a firm to make its innovations public would then depend on its position in a network.

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Appendix A

Proposition A1. *Assume λ remains between bounds $\underline{\lambda}$ and $\bar{\lambda}$, such that $c(\underline{\lambda}) = 0, c(\bar{\lambda}) = +\infty$. Let*

$$\alpha = \bar{f}\left[\frac{1}{r+N\underline{\lambda}} + \frac{(N-1)\bar{\lambda}}{\left(r+(N-1)\bar{\lambda}+\underline{\lambda}\right)\left(r-\bar{\lambda}N(A-1)\right)}\right];$$
$$\beta = \frac{\bar{\lambda}}{r+(N-1)\underline{\lambda}+\bar{\lambda}}.$$

Assume the following inequality holds:

$$\alpha + \beta\frac{A\bar{f}}{r-\bar{\lambda}N(A-1)}) \leq \frac{1-c(\lambda^*)}{r-\lambda^* N(A-1)},$$

then there exists a cooperative equilibrium where all firms constantly set $\lambda = \lambda^*$ and make all innovations public.

We follow the same steps as in the proof of Proposition 1. At each conceivable point in time, there exists a vector of $\vec{n} = (n_1, \ldots, n_N)$ of technological levels and a vector $\vec{\lambda} = (\lambda_1, \ldots, \lambda_N)$ of R&D efforts. Assume we restrict λ_i to be a sole function of the state vector $\vec{n}$, $\lambda_i = \lambda_i(\vec{n})$. That is, we only consider "Markov strategies" that depend on the current vector of state variables. Clearly, if all agents consider that along any path Markov strategies are followed, it is indeed optimal for them to follow such a strategy. Then, the value of a firm i can be recursively written as

$$V_i(\vec{n}) = \frac{\pi_i(\vec{n})(1-c(\lambda_i(\vec{n}))) + \sum_{j=1}^N \lambda_j(\vec{n})\left[\max(V_i(T_j U_j \vec{n}), V_i(U_j \vec{n}))\right]}{r + \sum_{j=1}^N \lambda_j(\vec{n})}$$

Defining, as previously,

$$\bar{V}_i(n,p) = \max_{\substack{\vec{n}=(n_1,\ldots,n_N) \\ n_i = n \\ n_j \leq p, j \neq i}} V_i(\vec{n}),$$

we again have the property that for any $\vec{n} = (n_1, \ldots, n_N)$ such that $n_j \leq p < n_i = n$, $j \neq i$,

$$V_i(\vec{n}) \leq \frac{A^n \bar{f}(1-c(\lambda_i(\vec{n}))) + \sum_{j\neq i}\lambda_j(\vec{n})\bar{V}_i(n,p+1) + \lambda_i(\vec{n}), \bar{V}_i(n+1,n+1))}{r + \sum_{j=1}^N \lambda_j(\vec{n})}. \tag{A1}$$

We can again prove that for $n = \max(n_i)$,

$$V_i(\vec{n}) \leq \frac{A^n \bar{f}}{r - \bar{\lambda}N(A-1)},$$

along the same lines as in the proof of Proposition 1. An implication is that for $p \leq n$

$$V_i(n,p) \leq \frac{A^n \bar{f}}{r - \bar{\lambda}N(A-1)} \tag{A2}$$

Plugging into (A1) yields

$$V_i(\vec{n}) \leq \frac{A^n \bar{f}(1 - c(\lambda_i(\vec{n}))) + \left(\sum_{j \neq i} \lambda_j(\vec{n})\right) \frac{A^n \bar{f}}{r - \bar{\lambda}N(A-1)} + \lambda_i(\vec{n}) \frac{A^n \bar{f}}{r - \bar{\lambda}N(A-1)}}{r + \sum_{j=1}^{N} \lambda_j(\vec{n})}. \tag{A3}$$

Then, observe that the following inequalities hold:

$$\frac{\sum_{j \neq i} \lambda_j(\vec{n})}{r + \sum_{j=1}^{N} \lambda_j(\vec{n})} \leq \frac{(N-1)\bar{\lambda}}{r + (N-1)\bar{\lambda} + \underline{\lambda}}.$$

$$\frac{\lambda_i(\vec{n})}{r + \sum_{j=1}^{N} \lambda_j(\vec{n})} \leq \frac{\bar{\lambda}}{r + (N-1)\underline{\lambda} + \bar{\lambda}}.$$

Therefore, we have that

$$\begin{aligned} V_i(\vec{n}) \quad \leq \quad & \frac{A^n \bar{f}}{r + N\underline{\lambda}} + \frac{(N-1)\bar{\lambda}}{r + (N-1)\bar{\lambda} + \underline{\lambda}} \frac{A^n \bar{f}}{r - \bar{\lambda}N(A-1)} \\ & + \frac{\bar{\lambda}}{r + (N-1)\underline{\lambda} + \bar{\lambda}} \frac{A^{n+1} \bar{f}}{r - \bar{\lambda}N(A-1)}. \end{aligned} \tag{A4}$$

Since this holds for all vectors such that $n_j \leq p < n_i = n$, $j \neq i$, we have, for $p < n$:

$$\begin{aligned} \bar{V}_i(n,p) \quad \leq \quad & \frac{A^n \bar{f}}{r + N\underline{\lambda}} + \frac{(N-1)\bar{\lambda}}{r + (N-1)\bar{\lambda} + \underline{\lambda}} \frac{A^n \bar{f}}{r - \bar{\lambda}N(A-1)} \\ & + \frac{\bar{\lambda}}{r + (N-1)\underline{\lambda} + \bar{\lambda}} \frac{A^{n+1} \bar{f}}{r - \bar{\lambda}N(A-1)} \\ = \quad & A^n(\alpha + \beta \frac{A\bar{f}}{r - \bar{\lambda}N(A-1)}) \end{aligned} \tag{A5}$$

where

$$\begin{aligned} \alpha \quad &= \quad \bar{f}\left[\frac{1}{r + N\underline{\lambda}} + \frac{(N-1)\bar{\lambda}}{\left(r + (N-1)\bar{\lambda} + \underline{\lambda}\right)\left(r - \bar{\lambda}N(A-1)\right)}\right]; \\ \beta \quad &= \quad \frac{\bar{\lambda}}{r + (N-1)\underline{\lambda} + \bar{\lambda}}. \end{aligned}$$

Note that if we can prove that $\bar{V}_i(n, n-1) \leq V_C(n)$ regardless of the strategies followed in a deviation, then clearly there exists a cooperative equilibrium. Given (A5) and that

$$V_C(n) = \frac{A^n(1 - c(\lambda^*))}{r - \lambda^* N(A-1)},$$

a sufficient condition is

$$\alpha + \beta \frac{A\bar{f}}{r - \bar{\lambda}N(A-1)}) \leq \frac{1 - c(\lambda^*)}{r - \lambda^* N(A-1)}, \tag{A6}$$

where λ^* is the equilibrium value of λ in a cooperative equilibrium, that is any solution to (17).

The condition in Proposition A1 is non-empty, since it collapses to that in Proposition 1 for $\bar{\lambda} = \underline{\lambda} = \lambda$ and $c(.) = 0$. By continuity, one can then construct examples where both sides of that inequality are arbitrarily close to the corresponding expressions in Proposition 1.

Notes

1. See also Curley and Salmelin (2017) for a survey of the innovative culture of the software industry.
2. See Nonaka and Nishiguchi (2001); Nonaka et al. (2001), and, in that same volume, the case studies of Nishiguchi (2001); Nishiguchi and Caspary (2001); Lincoln and Ahmadjian (2000), and de Michelis (2001).
3. See, for example, Carvalho Vieira et al. (2021); Hitchen et al. (2017); Rexhepi et al. (2019), and Seyfettinoglu et al. (2020).
4. On the other hand, obviously, many firms avoid making their innovations open and rely instead on patents or even trade secrets. A famous example is the Coca-Cola beverage formula (see Crittenden et al. 2015). Clearly, revealing such a secret would be of little interest to the firm, as it is likely to lead to imitation instead of cumulative process innovation (see Morikawa 2014 for a discussion of the effect of trade secrets on product vs. process innovation). Another famous example is the Google search algorithm. Here, the explanation is likely to be different. While revealing that algorithm is likely to lead to a wave of improvements that Google could benefit from, provided they were made public, the firm's market share is so big that it loses too much in the short term by making its algorithm public. In terms of the model, this is similar to a case where the number of firms is too small for the cooperative equilibrium to exist.
5. See Tirole (1990) for a survey.
6. This is the option in Aloysius (1999). See also Brod and Shivakumar (1997). Petit and Tolwinski (1999) assume away any problem in enforcing cooperation.
7. An interesting paper by Dutta and Seabrigh (2002) looks at the impact of the extent to which knowledge is explicit on growth and at its cross-impact with competition. However, the degree of explicitness of knowledge is exogenous, whereas it can be viewed as endogenous in the current paper. Katz and Ordover (1990) discuss informally how improvements in intellectual property rights may enhance incentives to share information by licensing. Licensing is not considered in the present paper.
8. We can simply assume that firms do observe whether one competitor is struck by an innovation even though they need not benefit from the innovation. Thus, there is no asymmetry of information as far as the structure of the game is concerned. The asymmetry of information with respect to the contents of the innovation are summarized by the payoffs and play no further role in the determination of the equilibrium strategies.
9. One has to check that V_i exists, i.e., is finite. That is actually an implication of the derivations that follow.
10. In the model's setting, a deviation would be detected as other firms would observe a fall in profits without an innovation being released, but that would change if profits were subject to shocks.
11. This restriction implies that $A^{-k}f(k)$ goes up with k, so that $\lim_{k \longrightarrow +\infty} A^{-k}f(k) = \sup A^{-k}f(k)$.
12. It is slightly weaker than (4).
13. Note that we rule out any cooperation on λ, which may be unobservable, and continue to focus on the incentive to make one's innovation public.
14. Furthermore, this restriction prevents degenerate solutions where the growth rate is greater than the interest rate.
15. The model is clearly silent about consumer surplus. One may conceive of innovations that reduce the elasticity of demand and may thus harm consumers.
16. Lerner and Tirole (2002), though, deal with the role of career concerns in the development of open source software.

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