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Appropriability and incentives with complementary innovations

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# APPROPRIABILITY AND INCENTIVES WITH COMPLEMENTARY INNOVATIONS

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## Abstract

Most of the economic literature on patents and intellectual property rights considers that the ability to exclude third parties from access to one's own innovation is necessary to ensure appropriability of the benefits from investment and therefore to provide innovators with proper incentives to invest. However, when innovation requires complementary investments of a number of different innovators, and private benefits from such investment play a relevant role in motivating developers, this conclusion is not warranted. We show that, in this case, a commitment not to exclude other developers from the innovation can enhance incentives to invest. This conclusion may be useful in suggesting the appropriate allocation of IPRs over the results of symmetric technological collaborations and in explaining the prevalence of restrictive licenses (copyleft) over less restrictive licences (non-copyleft) in the case of open source software.

Keywords: intellectual property rights, open source, copyleft, incentives to innovation.

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# 1. Introduction

Innovative knowledge has long been described as possessing the characteristics of a public good—non-rivalness and non-excludability. As it is well known, these characteristics imply the emergence of an "appropriability problem": due to the possibility of free riding, incentives to invest in innovation are hampered by the difficulty of appropriating the benefits from such investment (Arrow, 1962; Nelson, 1959). From the identification of this problem follows almost self-evidently, in most of the literature on innovation, the prescription that increasing the extent of excludability from access to one's own innovative knowledge is necessary to restore incentives.

Intellectual property rights (IPRs), particularly patents and copyright, represent the most powerful legal means through which artificial excludability can be guaranteed and incentives enhanced. IP-based exclusion has its drawbacks, however. Recent literature has emphasized the limits to the effectiveness of IP in providing incentives in circumstances in which innovation is cumulative and/or products are complex, so that they require the assembling of many different pieces each of which may be patented (Boldrin and Levine, 2008; Bessen and Meurer, 2008; Jaffe and Lerner, 2006). At the same time, there is an increasing number of real-world examples of innovators that, in specific circumstances, voluntarily renounce to exercise exclusion rights over their creations. Open Source software development is the most prominent example of this general trend, which is by no means confined to the software domain.

These developments raise interesting questions: does the adoption of a strategy of appropriability of the benefits of innovation based on exclusion always ensure greater incentives to invest in innovation compared to a strategy that involves the explicit renounce to exclude from access? Under what conditions, if any, the latter strategy dominates exclusion in terms of incentives to invest?

In this article, we develop a theoretical approach to this problem that allows us to explore the relationship between different models of collective knowledge creation—including instances of collective innovation as diverse as *Research Joint* Ventures (RJVs) and Open Source Software—and the extent of incentives associated to exclusion. Our main conclusion is that the effectiveness of exclusion in providing incentives to invest depends on the extent of complementarity among the innovators' contributions, as defined by the characteristics of the knowledge production function. While exclusion provides greater incentives than a commitment not to exclude when contributions are complementary in a very weak sense, this can by no means taken as a general conclusion. When contributions are truly complementary in the sense that the value of each contribution depends on the availability of a given set of other contributions, each of which is essential to the final innovation, and private benefits play a role in motivating investment, a commitment not to exclude from access to one's intellectual creation enhances incentives to invest with respect to a situation in which each of the innovators can exercise her right to exclude third parties from her IP.

Our result depends on three characteristics of a collective innovative environment, which we consider relevant and whose interaction we analyse: first, innovation requires the joint effort of a number of innovators whose contributions are not fully interchangeable; second, the innovative effort exerted by each innovator generates both an innovative outcome which has the features of a public good and a private benefit for the innovator; third, neither innovators' investments nor the quality of the innovation itself is contractible ex ante.

As for the first feature, our focus is on circumstances in which innovation involves some form of coordination among different innovators, because it results from the integration of a number of different components, each developed independently. Innovation often requires the combination of complementary components developed by multiple innovators. This is most obvious in the context of complex product industries such as electronics, software and biotechnology (Grindley and Teece, 1997; Cohen, Nelson and Walsh, 2000), but may occur in any industry. Different individuals or firms possess individual- or firm-specific human capital, knowledge, and resources by virtue of learning and previous innovative activities. Therefore, although a single individual or firm may be able to invest in the development of all of the components of a given innovation or to acquire some of them in the market, there are generally gains to be made from the division of innovative labor and the coordination of complementary investment. These gains follow from the customization of the innovative effort or, more generally, from the specific nature of the innovative investment made by each of the contributors to a composite innovation.

The second feature of the innovative environment is given by the fact that innovative efforts, while giving rise to knowledge that can be analogized to a public good, generate also privately appropriable benefits. Innovative investments are in general valuable for those making them not only because they allow to obtain a specific innovative output, but also because they allow the innovator to accrue private benefits in the form of accumulation of individual- or firm-specific knowledge and of production of complementary goods of services; private benefit may include the ability to signal one's capability or enhancement of the returns from learning in future innovative activities (von Hippel and von Kogh, 2003) and, in some cases, intrinsic motivation. These private benefits can be obtained only through direct participation to innovation, so that free-riders obtain lower benefits from the innovation than those who have contributed to it.

Finally, the third relevant feature of the innovative environment we consider concerns the non-contractibility of the investments in innovation. Most of the innovation and intellectual property rights literatures adopts a complete contracting framework. However, the existence of complete binding agreements does not seem to be a sensible assumption to describe most real-word instances of collective knowledge creation or even simple exchange of IP-protected knowledge (Pagano and Rossi, 2004). This is because, among other things, it is difficult to evaluate ex ante the specific knowledge and know how that each innovator contributes to the collective innovation effort and to verify ex post the outcome of the innovative effort, if anything because it is difficult to specify in advance the exact nature of the innovation that is being developed. Moreover, in the case of Open Source software development, ex ante contracts are voluntarily incomplete, in the sense that they only specify the conditions of access to each others' contributions but do not imply any commitment to a specific level of contribution.

Non contractibility of investments in innovation means that, in case innovation is the result of joint effort and it is not possible to single out each one's contribution, individuals must rely on ex post bargaining in order to determine their share of profit. Ex post bargaining, which relies on some form of property right allocated ex ante among participating individuals, is an imperfect way to link individual investment effort to individual reward.

Our conclusion on the ineffectiveness of exclusion as an incentive device relies on the fact that, when different contributions to a final innovation are "truly" complementary, the link between the value appropriable through ex post bargaining and ex ante investment is weakened. Moreover, exclusion can have important drawbacks with regards to private benefits from investments. Ex post exclusion allows individuals to claim a share not only of the public benefit from investment, but also of the private effect. This implies that exclusion will have an adverse effect on the private incentive to invest, and results in the counterintuitive conclusion that a commitment not to exclude others can be a better strategy to induce investments.

In the paper, we consider different specifications of the innovation production function, reflecting different types and degrees of complementarity among innovative contributions. The first case—the summation model—it that of minimum complementarity: the value of each of the individuals contributions merged together is independent from the value of the other merged contributions. Innovation results, in this case, from the sum of the different contributions, and there is no possibility of duplication of innovation efforts. We can think of this case as one in which individual contributions are modular<sup>1</sup>.

The summation model of collective knowledge creation can accurately represent the mechanics of innovation only in very rare cases. The reason why we consider it is that it is the model of knowledge creation implicitly underlining most analyses of the implications of the public good nature of knowledge for the incentives to invest in innovation, irrespective of whether the collective innovation effort is centralized or decentralized. It is our contention that the summation model of innovation can be used to analyze incentives only in circumstances in which problems of coordination of the collective innovative effort are ruled out the analysis (for example because collective innovation is assumed to take place in a *centralized* organization, such as a firm; a hierarchical organization is able to assign different innovative tasks to different employees-contributors and to rule out the possibility of reciprocal hold-up, so that the value of the final innovation can be represented as the sum of individual contributions).

The remaining two cases we consider represent more accurately different instances of *decentralized* collective knowledge creation. The second case assumes a

<sup>&</sup>lt;sup>1</sup>The notion of modularity has a longstanding tradition in the innovation and management literature. According to Simon (1962), the attribute of modularity refers to the decomposable nature of a given technology: a complex system can be defined as modular if it is decomposable in a number of components or subsystems that are relatively independent but still concur to support the functioning of the whole, being connected through standardized interfaces. This notion does not necessarily imply that the value of innovation can be accurately described as the sum of the values of the different modules

production function which is multiplicative in individual contributions; it is meant to capture instances in which the value of a single contribution crucially depends on the availability of complementary and coordinated contributions. We claim that this case can accurately describe collective innovation through the formation of RJVs or through joint R&D projects. In this case there is an ex ante agreement to collaborate which restricts the number of possible contributors to the final innovation and assigns responsibility for the realization of the co-specific components to the n innovators selected ex ante. The value of the final innovation depends, in this case, from the availability of all of the contributions that have signed ex ante an agreement to collaborate.

The third case we consider takes into account both complementarity and the possibility of duplication of innovation efforts. It is meant to represent cases in which innovation efforts are still complementary in a strong sense (we assume indeed the strongest degree of technical complementarity between different "types" of contributions), but there is no ex-ante agreement identifying the innovators whose contributions will be merged into the final innovation. An example of innovation of this sort is given by Open Source software development in the case of a large complex project. The value of the final innovation depends, in this case, from the availability of a specific set of contributions, but each of the contributions can be provided by more than one innovator not necessarily identifiable in advance.

We will show that only in the first of the cases above exclusion is effective in enhancing investment. In the other two cases, a commitment not to exclude other contributors gives better incentives.

The rest of the paper is organized as follows: in the next section we develops the model and the three cases mentioned above. Section 3 discusses some application of these models, with special attention to the issue of Open Source Software licensing and Research Joint Ventures. Section 4 concludes.

## 2. Formal analysis

#### 2.1. Model setup

We consider a group N (of numerosity |N| = n) of individuals who can obtain a profit by using a common input X. Individual profit for  $i \in N$  is  $\pi_i = \theta_i X$ .

Each individual can affect both X (the "technological quality" of the input) and her private input  $\theta_i$  by making an investment  $y_i$ , whose cost is  $\varphi(y_i)$  ( $\varphi', \varphi'' > 0$ , this assumption is important only to secure an internal solution to the individual optimization problem). We can think of  $y_i$  as (1) an investment made by *i* in the development of X which at the same time increases her (X-specific) human capital, or in general increases the return from using X (e.g. via a signalling effect on the final market, see below the case of open source software); (2) the investment can improve the common input X in a developer-specific way, since developers can use "specialized" versions of X. In this sense, the effect of  $y_i$  on X must be thought of as the transferrable effect of  $y_i$ , which benefits the whole group N.

As mentioned in the introductory section, the presence of both a private and a public effect of  $y_i$  on  $\pi_i$  is very important in our explanation of the possible adverse effect of appropriability through exclusion.

Let the private input be  $\theta_i = \theta(y_i)$  with  $\theta(y_i) \ge 0$  for all  $y_i > 0$ ,  $\theta' > 0$  and  $\theta'' < 0$ ; the effect of  $y_i$  on the public input X will be specified below, according to different hypotheses about the joint effect of individual investments.

The amount of the investment  $y_i$  cannot be contracted in advance, hence no individual can commit to a specific value of  $y_i$ . This is reasonable if we think of  $y_i$  as an index of technological quality, which can be very difficult to measure in an objective way and specify in advance in a contract.

Once the investment is made, it contributes to the improvement of X with respect to a base version of quality  $X_0$ . However, we will consider that at least in principle each individual can exclude others from taking advantage of her contributions. We will use the language of cooperative game theory, and say that a *coalition* of individuals is made of all individuals who give each other reciprocal access their respective contributions.

Note that the investment  $y_i$  is assumed to be sunk, in the sense that it has no value outside the use of input X. However, we assume that all individuals have access to the base version of X, so that they are always able to get a profit  $\theta(y_i)X_0$ .

We will indicate by X(S) the quality of X when the contributions of individuals in the set S are used. A natural assumption is that  $X(S) \ge X(R)$  if  $R \subset S$ . Obviously,  $X(S) \ge X_0$  when S is nonempty.

Individuals choose  $y_i$  independently, then merge their contributions, possibly making some payments to have access to others' contributions. Finally, they use X and get a profit  $\pi_i = \theta_i X$ .

We will distinguish between two cases, namely: (1) the case in which individuals retain a right to exclude others from access to their contribution, and (2) the case in which they agree at the beginning to give up this right and grant each other free access to their contributions. The possibility of exclusion can be granted by technical means or by intellectual property rights (or both). In the case ex post exclusion takes place, individuals can ask a price to grant access to their contribution. This will be named the *ex-post exclusion case*.

Since ex post each contribution is specific to X, the price of access cannot be determined in a competitive market; instead, bargaining will take place among developers in order to allocate the surplus from innovations. Each developer's share in this surplus is determined by her bargaining power, which in turn is a function of how important is her own contribution to a group (or subgroup) of final users, and of its alternative uses outside of it.

We will make the assumption that bargaining is efficient, i.e. the coalition N will always be formed provided that X(N) > X(S) for all  $S \subset N$ . This is certainly a strong assumption, which will be discussed below. The fact that the coalition includes all individuals does not mean that subcoalitions S play no role. The fact that a contribution can have a value in coalitions different from N increases the bargaining power of the contributor.

In order to quantify the expected share of surplus accruing to each developer, we will make use of the concept of Shapley value. The use of this concept has an established tradition in the economic analysis of incomplete contracts and property rights (see, for instance, Hart and Moore, 1990). The Shapley value considers the share of a bargainer as a function of her contribution to the value of each possible coalition of bargainers  $S \subseteq N$ .

Let

$$\Pi(S) = \sum_{j \in S} \theta(y_j) X(S)$$
(1)

be the total profit obtained by coalition S.  $\Pi(S) - \Pi(S \setminus \{i\})$  is how much the profit of coalition S is reduced if *i* leaves it. The share for developer *i*—her Shapley value—is

$$\sum_{S \subseteq N \mid i \in S} \rho(S) \Big[ \Pi(S) - \Pi(S \setminus \{i\}) \Big];$$
(2)

where

$$\rho(S) = \frac{(|S|-1)!(|N|-|S|)!}{|N|!}.$$
(3)

As it is well known, this share can be thought of as a weighted average of the contribution of *i*'s development to all possible subsets of developments<sup>2</sup>. The formula is often justified by imagining that the coalition N is formed by adding one individual at a time, with each individual getting her contribution to the coalition (as if she could make a take-it-or-leave offer to the agents already in the coalition), and then averaging over the possible different permutations of individuals, i.e. all possible orders in which individuals can join the coalition<sup>3</sup>.

The case of exclusion will be compared with the case in which contributors have no access to any exclusion mechanism ex post or, perhaps more interestingly, agree in advance not to exclude each other from access to their respective contributions. All contributions will be included in X, and the payoff of developer i will be:

$$\theta(y_i)X(N). \tag{4}$$

The expressions above are very general, and they do not allow us to reach conclusions without further restrictions. We consider some possible specifications of the model, according to different assumptions about the technology used to produce X, in the following sections.

#### 2.2. Case I: sum of individual investments

As mentioned, the outcome of innovative activities is commonly described as a public good, because its use is nonrival. The assumption that is implicitly made when talking about a public good is that the total quantity of the public good constitutes the sum of the quantities provided by the various contributors (this assumption underlies the "summation" model of public good provision). This amounts to assume that the contributions of different individuals involve no duplications and a minimum degree of complementarity. They are perfectly modular, and the value of each individual contribution is independent of the value of others' contributions.

<sup>&</sup>lt;sup>2</sup> Note that  $\sum_{S \, \subset \, N \, | \, i \in \, S} \, 
ho(S) = 1.$ 

<sup>&</sup>lt;sup>3</sup> Taking all possible orderings of |N| agents as equally likely,  $\rho(S)$  represent the probability that i will be ranked just after the agents in the set  $S \setminus \{i\}$ .

We claim that this assumption is not very reasonable in most cases of innovation involving a plurality of individual contributions. However, it is useful to start from this specification, as it allows us to obtain the standard justification for exclusion as an effective response to free-riding.

We assume that

$$X(S) = \sum_{i \in S} y_i.$$
<sup>(5)</sup>

Substituting for X(S) in (2) and differentiating with respect to  $y_i$ , we find the marginal benefit to *i* from an increase in  $y_i$ :

$$\sum_{S \subseteq N \mid i \in S} \rho(S) \left[ \theta'(y_i) X(S) + \sum_{j \in S} \theta(y_j) \right].$$
(6)

We make the simplifying assumption that individuals are symmetric. In this case,  $\rho(S)$  and X(S) are uniquely defined by the numerosity of S. With s = |S|, it is

$$\sum_{\{|S|=s,S\subseteq N\}}\rho(S)=\frac{1}{n}, \tag{7}$$

and expression (6) becomes

$$\sum_{s=1}^{n} \frac{s}{n} \left[ \theta'(y_i) y_i + \theta(y_i) \right] = \frac{n+1}{2} \left[ \theta'(y_i) y_i + \theta(y_i) \right] \tag{8}$$

We compare this to the case in which there is no exclusion ex post, and the benefit is  $\pi_i(y_i, X(N))$  so that the marginal benefit is

$$n\theta'(y_i)y_i + \theta(y_i) \tag{9}$$

We reach the following

**Proposition 1.** When  $X(S) = \sum_{i \in S} y_i$ , for all values of n, the possibility of exclusion increases the investment  $y_i$  made by each contributor. The increase is higher the higher is the number of contributors n.

**PROOF.** The result follows from the fact that at given  $y_i$  the difference between the marginal benefit with and without exclusion (8) and (9) is

$$rac{n-1}{2}\left[ heta(y_i)-y_i heta'(y_i)
ight].$$
 (10)

From the assumption that  $\theta'' < 0$ ,  $\theta' > 0$  and  $\theta(y_i) \ge 0$  follows that this difference is positive and increasing in n.

We can compare both outcomes with the socially optimal level of  $y_i$ , i.e. the level of investment which maximizes aggregate profit net of the aggregate cost of investment

$$\sum_{i\in N} heta(y^i)\left(\sum_{i\in N} y_i
ight) - \sum_i arphi(y_i).$$
 (11)

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Coordinated by the Centre for Philosophy of Law – Université Catholique de Louvain – http://refgov.cpdr.ucl.ac.be WP–IFM-85 The first order condition for  $y_i$  implies that for each *i* the marginal cost  $\varphi'(y_i)$  should be set equal to the social marginal benefit, or

$$\sum_{k\in N} heta(y_k)+ heta'(y_i)\sum_{k\in N}y_k=arphi'(y_i)$$
 (12)

which, under symmetry, becomes

$$n\left( heta'(y_i)y_i+ heta(y_i)
ight)=arphi'(y_i).$$
 (13)

Therefore, social optimality would require an investment which is higher than both cases of exclusion and no exclusion. This result is not surprising given the public good nature of the innovation.

We can identify in expression (13) the term  $\theta'(y)X$  representing the private effect of an increase in  $y_i$  on profits, and the term  $n\theta(y)(\partial X/\partial y_i)$  representing the public effect, through an increase in X. Without exclusion, individuals have an incentive to free ride in their investment because they do not take into account the effect of their effort on others' profit through the latter effect. Exclusion can reintroduce some incentive, as individuals can "sell" the result of their effort ex post; in this way, they are able to appropriate at least in part their contribution to the improvement of the public input. Still, excludability is not enough to secure efficient incentives to invest, and individual investments are suboptimal even in this case. Moreover, the possibility to appropriate the public effect through exclusion comes at the cost of reducing the incentive coming from the private effect: exclusion allows other individuals to expropriate part of the latter too. We will see that under different assumptions on technology the second effect may dominate, and the result that exclusion is desireable can be reverted.

We finally note that, by assuming efficient ex post bargaining, we are not considering the standard ex post inefficiency arising from monopolistic pricing, which gives rise to inefficient exclusion of low demanders.

#### 2.3. Case II: individual investments are complementary

The assumption that individual efforts simply sum up, so that the output (in terms of quality improvement of X) is a function of the total effort of contributors, entails that the coordination problems that afflict large development projects are not taken into account. Usually, efforts by different individuals must fit together in a specific way, and the value of a single contribution depends on the availability of complementary and coordinated contributions. This aspect is particularly relevant when innovation investments are decentralized among a plurality of agents taking their decisions independently.

This implies that we should consider other specifications of the way individual contributions aggregate to determine an increase in X. The economic analysis of public goods has considered specifications of the "social composition function" other than the summation model; a different possibility, somehow extreme in the relevance it gives to complementarity among different contributions, is the case of the *weakest-link* (Hirshleifer, 1983): under a weakest-link technology, the amount of the public good is the minumum amount contributed by a group of individuals. It has been shown that under the weakest-link assumption the incentive to

contribute may be very different than in the standard summation case (Cornes, 1993).

We adopt here a variation of the weakest link case—Cornes (1993) labelled it the *weaker-link* case. It still implies that all contributions are essential to the development, though it allows some substitutability among the intensities of different contributions.

Let  $X_0$  be the quality of the common input when no innovation takes place, and assume that all individuals have access to this input. We assume that  $X(N) - X_0 = \prod_{i \in N} y_i$ . This kind of relation between input and output is also known as the O-ring production function, introduced by Kremer (1993). In Kremer's words (p. 551), this production function describes a situation "in which production consists of many tasks, all of which must be succesfully completed for the product to have full value".<sup>4</sup>

Note that by using this specification we are assuming that all agents will be forced to revert to  $X_0$  if at least one of the contributors does not agree to give access to her "piece".

We replace (5) with

$$X(S) = egin{cases} X(N) = X_0 + \prod_{i \in N} y_i & ext{if } S = N \ X_0 & ext{otherwise} \end{cases}$$

Considering exclusion under this assumption, expression (2) of individual i's payoff simplifies to

$$\rho(N)\left[\sum_{k=1}^{n}\left(\theta(y_k)X(N)-\theta(y_k)X_0\right)+\theta(y_i)X_0\right]+\left(1-\rho(N)\right)\theta(y_i)X_0.$$
 (15)

In a symmetric Nash equilibrium, the individual marginal benefit of  $y_i$  is

$$\left[\frac{1}{n} \theta'(y_i)y_i + \theta(y_i)\right] (y_i)^{n-1} + \theta'(y_i)X_0$$
(16)

(note that under symmetry  $\rho(N) = 1/n$ ).

This result must be compared with the case of no exclusion, which is represented once again by a payoff  $\theta(y_i)X(N)$ . Given the expression (14) for X(N), the marginal benefit from an increase of  $y_i$  is

$$\left[\theta'(y_i)y_i + \theta(y_i)\right](y_i)^{n-1} + \theta'(y_i)X_0 \tag{17}$$

We reach a conclusion which is very different from Proposition 1 above. Namely

**Proposition 2.** Under the assumption (14), for all values of n, the possibility of exclusion decreases the investment  $y_i$  made by each contributor. The decrease is higher the higher is the number of contributors n.

**PROOF.** It follows from simple comparison of expressions (16) and (17).  $\Box$ 

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<sup>&</sup>lt;sup>4</sup>Kremer refers to the case of labor skills. In his words (p. 553): "The O-ring production function differs from the standard efficiency units formulation of labor skill, in that it does not allow quantity to be substituted for quality within a single production chain."

Again, both results might be compared to the benchmark of the socially optimal level of investment. Here the social marginal benefit from an increase in  $y_i$  is

$$\left[ heta'(y_i)y_i+n heta(y_i)
ight](y_i)^{n-1}+ heta'(y_i)X_0$$
 (18)

A comparison of the three expressions (16), (17) and (18) for marginal benefit shows that in this case exclusion is not an effective way to reduce the gap of incentives due to the public nature of the input X. The reason is that when each contribution is essential to the innovation, the bargaininig power of the parties is not related to the intensity of contribution, hence to the effort. Each contributor can claim an equal share of the common surplus regardless of her effort. This not only reduces the beneficial effect of exclusion, it also has an adverse effect on the private incentive to invest, given by the effect of  $y_i$  on  $\theta_i$ . With exclusion, each party is able to claim (expropriate) a share of each other party private benefit, and the overall incentive is reduced.

# 2.4. Case III: multiple agents contribute to strictly complementary components

It may be claimed that for many practical applications the previous case is too extreme in that each contribution is essential to each other's improvement. The assumption that no investor is substitutable might overstate in most cases the role of coordination, in that it implies that the defection of any of those involved imposes a very high cost on others. Though this may be reasonable when the group of innovators is specified in advance and stable, such a framework provides a poor representation of cases (like for example open source development) in which more than one developer can in principle contribute to each task and participation is "open".

In this section, we modify the model of the previous section by assuming that the innovation requires that s different contributions are needed, but we assume that the task of providing each contribution is not assigned in advance to one individual. Namely, we assume that each contribution can be provided by either of two individuals; therefore, we are considering a population of n = 2s individuals of s different types. Note that this limits the veto power of each contributor, without eliminating the basic assumption that individuals are not completely interchangeable.

Let individual s + i be the same type as individual i, for  $i \in S \equiv \{1, \ldots, s\}$ . Given a set R of individuals, they will be able to produce an improvement only if at least one individual of each type belongs to R (i.e. either i or s + i must be in R, for all  $i \in S$ ). Moreover, we assume that contributions of the same type do not sum up (in this sense, they are one a substitute for the other). The latter assumption reminds of the so called *best-shot* social composition function in which only the largest contribution counts.<sup>5</sup>

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<sup>&</sup>lt;sup>5</sup> The example provided by Hirshleifer (1983, p. 373) is that of a number of anti-missile batteries defending a city from a single nuclear-armed intercontinental ballistic missile: only the best defensive shot will count in this case.

We additionally modify the composition rule among different "types" in the direction of more complementarity: we assume a *weakest-link* production function for the common input. This assumption is extreme, but it has the advantage of givin us a neat result, and simplifying the analysis of the equilibrium. Under this technology, the total amount X is equal to the minimum of all s required contributions. In formal terms:

$$X(R) = X_0 + \min\left\{\max\{y_1, y_{s+1}\}, \dots, \max\{y_s, y_{2s}\}
ight\}$$
 (19)

with X(R) = 0 when nobody in the coalition provides one of the *s* necessary types of contributions. Note that no benefits comes from adding contribution when the same type of contribution—of the same or larger quality—has already been provided.

Individual payoff for individual i (2) as a function of her own investment  $y_i$ , under the assumption of symmetry so that  $y_j = y$  for all  $j \neq i$ , can be written as follows (see Appendix):

$$(1-eta) heta(y)+eta heta(y_i)\min\{y,y_i\}+ heta(y_i)X_0$$
 (20)

where the parameter  $\beta$  is decreasing in s and satisfies  $0 < \beta < (s+1)/2s$  (note that the upper limit is always less than one for s > 1).<sup>6</sup> The individual marginal benefit from investment  $y_i$  is computed by differentiating (20):

$$egin{cases} heta(y)+eta heta'(y)y+ heta'(y)X_0 & ext{for } y_i\leqslant y \ heta'(y)X_0 & ext{otherwise} \end{cases}$$

It turns out that this game has a continuum of symmetric Nash equilibria in pure strategies, the highest being such that

$$\theta(y) + \beta \theta'(y)y + \theta'(y)X_0 = \varphi'(y_i).$$
 (22)

We turn now to the case of no exclusion. This case involves multiple equilibria, too, but no symmetric equilibrium; since what counts is  $\max\{y_i, y_i + s\}$  there is no incentive for a contributor *i* to invest if another contributor i + s of the same type has invested. Indeed, the game between two individuals of the same type involves two Nash equilibria, in which one of the two provides no investment. Hence, there are  $2^s$  possible Nash equilibria for the overall game with 2s individuals.

This multiplicity might be a problem if individuals are not able to coordinate to one of the Nash equilibria. However, given that one equilibrium is reached, the investment necessary to the innovation will be done. In equilibrium, s individuals (one for each type) will choose  $y_i$  so that

$$heta(y_i)\min\{y,y_i\} - \varphi(y_i)$$
 (23)

<sup>6</sup> Here is the value of  $\beta$  computed for several sizes *s*:

S	2	5	10	20	100
β	.666	.406	.284	.199	.088

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is maximized. Their individually optimal level of investment will be given by the first order condition

$$heta(y)+ heta'(y)y=arphi'(y_i)$$
 (24)

while the remaining s individuals will maximize their payoff taking the investment of the former group of individuals as given, so that their  $y_i$  will satisfy the following first order condition:

$$\theta'(y_i)y^s = \varphi(y_i) \tag{25}$$

corresponding to a lower level of investment.

We conclude that

**Proposition 3.** Under the assumption (19), the quality of X will be lower under exclusion.

Moreover, exclusion will involve higher costs for given level of development, because of investment duplication.  $\hfill\square$ 

**PROOF.** The conclusion on the adverse effect of exclusion follows from simple comparison between expressions (22) and (24).

The conclusion on effort duplication follows from the fact that the Nash equilibrium with exclusion is symmetric while all equilibria without exclusion are asymmetric and involve that s individuals contribute only a reduced amount of investment.

Hence, provided that complementarity among different types of contributions is sufficiently strong, the conclusion of the previous case carries on to the current case, in which no individual is strictly necessary to the production of the innovations.

## 3. Applications

The model presented in the previous section allows to analyze within a single analytical framework very different instances of collective knowledge creation. It can be used to evaluate incentives created by exclusion of individuals or firms participating to a technological collaboration. Exclusion can be exercized on the outcome of each innovator's investment, either through IP or through technological means. The analysis thus encompasses joint R&D projects, Research Joint Ventures involving different firms as well as rather loose forms of technological collaboration involving independent individuals such as Open Source Software development.

The primary contribution of the model resides in the emphasis it places on the effect that a *commitment not to exclude* might bring about on incentives to invest when investment by independent contributors are made in a decentralized fashion.

The possibility that committing ex ante not to exclude from access to the outcome of one's innovative investment may enhance appropriability of the benefits from such investment, and therefore incentives, is generally overlooked in the innovation and intellectual property rights literatures. Greater effectiveness of exclusion appears almost self-evidently to be associated to greater incentives to invest. Moreover, the implications of the existence of complementarities in innovative activities for the effectiveness of exclusion as an appropriation device has not been thoroughly explored.

We consider in turn different cases.

## 3.1. Collaborative R&D and RJVs

Collaborative R&D may take many forms, involving different degrees of communication of background and foreground knowledge across firms, different degrees of coordination of innovative activities and different degrees of structural integration among firms. On one side, research partnerships may simply involve an ex-ante agreement to pursue a coordinated research endeavour and a "division of labour" that implies the separate realization of R&D projects. In this case, the extent of communication of knowledge across firms participating to the partnership is reduced to a minimum and does not exceed standard market spillovers among firms. On the other side, research partnerships may involve a much higher degree of coordination and complete communication of research results across partners, with many intermediate possibilities lying in between these two extreme cases.

A relevant question concerning the formation of technological collaborations in general, and of Research Joint Ventures in particular, concerns the allocation of the intellectual property rights over the innovative results obtained by the R&D partners. IPRs play a key role within research partnerships, both in the phase of constitution of the venture and in the phase of its dissolution. Indeed, IPRs allow to clearly identify the foreground knowledge that partnering firms contribute to the venture and to define the boundaries of the rights that the technological collaboration enjoys with respect to foreground knowledge (the knowledge created by the research partnership). The allocation of IPRs on the innovative output of the research collaboration has, of course, a relevant impact on the partners' incentives to invest.

The model presented in section 2.3 allows to compare the effects of two extreme alternative arrangements allocating the IPRs over the partnership's innovative outcomes. On one side, partners may decide at the outset that IPRs over each of the results will be separately assigned to the partners that have developed them. In this case, partners agree ex ante on the research trajectories they pursue independently but contract ex post for access to each other's innovations. The other extreme IPRs arrangement we examine is given by an ex ante commitment by the research partners to give reciprocal access to each other's innovative results. The model suggests that the presence of complementarities among the investment efforts of the various research partners implies that the latter IPRs arrangement dominates the former in terms of the incentives to invest in innovation that it is able to generate.

Complementarity of R&D resources constitutes a well-documented and prominent factor motivating recourse to technological collaborations and the formation of joint ventures. Hagedoorn and Schakenraad (1990), for instance, analyze a very large sample of cooperative agreements worldwide (more than 7000) and find that complementarity is one of the primary motives for the formation of joint ventures and research corporations in information technologies, biotechnology, and new materials. Therefore, the implications of our model are likely to hold in a range of relevant real-world circumstances. However, in considering the applicability of the model's results it should be stressed that they have been obtained in a setting characterized by symmetric firms, and under the assumption that firms participating to the collective innovation effort obtain private benefits from innovative investments.

# 3.2. Open Source software development and restrictive licenses

The perspective we propose allows, among other things, to shed light on an aspect of the OSS phenomenon that would appear puzzling if examined in light of the standard view tha more effective exclusion is invariably associated to greater incentives. We refer to the fact that the form of licensing that has by far the greatest diffusion in the OSS world—copyleft licenses such as he General Public Licence (GPL), adopted by more than 80% of OSS projects (Lerner and Tirole, 2005)—is also the most restrictive in terms of the freedom of developers to exercise the right to exclude from their copyrighted contributions to the OSS project to which they participate<sup>7</sup>.

The defining feature of OSS is given by the kind of license under which it is distributed. OSS licenses grant to licensees (a) free access to the program source code, i.e. to the human-readable instructions expressing the different tasks that have to be performed by the computer, and (b) the freedom to use (run) the program, to study how it works, to modify and improve it, to redistribute it with or without modifications. Of course, the first condition (free access to the source code) is a precondition for the second in that no improvement is possible in absence of access to the source code<sup>8</sup>. The two elements of OSS licenses described above constitute essential preconditions for the working of a decentralized form of collective knowledge creation such as OSS development.

Within OSS licenses, however, a distinction should be traced between copyleft and non-copyleft licenses. The former impose more stringent constraints relative to the latter. From our point of view, the most relevant of such additional constraints concerns the obligation to license future developments under the same terms. Thus, developers of contributions to a given copylefted software retain copyright over their creations but they must distribute them under the terms of the initial license<sup>9</sup>

<sup>&</sup>lt;sup>7</sup> It should be emphasized that, although OSS software is generally freely available on the web, it is not in the public domain. Each of the developers contributing to an OSS project does retain copyright over her contribution, which is then licensed to the users/developers of OSS software.

<sup>&</sup>lt;sup>8</sup>Note that OSS software is to be distinguished from software whose license allows to use it freely, but not to modify it (e.g. Acrobat). In this case the software is free, in the sense that is it distributed at no cost, but it is not open source.

<sup>&</sup>lt;sup>9</sup>This constraint is imposed, among others, by the General Public Licence, or GPL. Section 2(b) of the GPL reads:

You must cause any work that you distribute or publish, that in whole or in part contains or is derived from the Program or any part thereof, to be licensed as a whole at no charge to all third parties under the terms of this License.

The alternative available to OSS developers is to adopt a non-copyleft license, such as for instance the Berkeley Software Distribution (BSD) license, which preserves the freedom of subsequent developers to exercise ex post the right to exclude from their copyrighted improvement to the original software. In other words, the BSD, differently from the GPL, grants developers the possibility to exclude other users and developers from access to an improved version of the software or from a software using the original one as a component. This implies that the BSD opens up the possibility to charge a price for access.

Given the difficulty of reconciling the prevalence of the more restrictive copyleft licenses with the standard relationship between exclusion and incentives, most of the existing explanations offered for why copyleft licenses are most diffused have to do with ideology, either in the sense that the GPL constitutes a means to ensure that the expectations of ideologically-motivated contributors are not frustrated by the commercialization of the result of their effort (see, for instance, Frank and Jungwirth, 2001) or in the sense that the GPL allows to attract ideologicallymotivated contributions when other sources of motivation are weak (Lerner and Tirole, 2005). Other reasons have to do with GPL's ability to prevent forking<sup>10</sup> (Maurer and Scotchmer, 2006) or to reduce the extent of free-riding, particularly in the form of the privatization of existing OSS projects (Gambardella and Hall, 2005).<sup>11</sup>

The argument put forward in this paper suggests to interpret copyleft licenses as an ex ante commitment of developers not to exclude ex post other actual or potential contributors from access to their copyrighted improvements on the original software. As shown above, this commitment protects developers from the possibility that their *private* return from investment is expropriated through exclusion from improved versions of the software. In this perspective, a restricted licence such as the GPL constitutes a *safeguard* in Williamsonian terms (Williamson, 1985) against the possibility of ex post expropriation of the value of each party's contributions in circumstances in which such contributions are complementary (*co-specific*, to remain with Williamson's terminology).

We think that the case of OSS software fits perfectly with the three characteristics of the innovative environment we consider in the paper. First, the technology of decentralized software production involves relationships of complementarity and substitutability among the contributions provided by different developers. The presence of complementarities may be understood to follow from the fact that each of the separately developed software components is co-specific to a given program that requires each of the components to be run or from the fact that the innovative outputs of different contributors to a software are linked through indirect network externalities. Moreover, when software innovation is pursued in

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<sup>&</sup>lt;sup>10</sup> The notion of "forking" refers to the possibility for an OSS developer to start a new OSS project on the basis of an existing OSS project when disagreement emerges in relation to the appropriate direction of development of the original project.

<sup>&</sup>lt;sup>11</sup>The comparison of the costs and benefits of these two forms of licensing from an economic viewpoint has so far received scant attention—with the exception of Gaudeul (2005) and Bezroukov (1999). Indeed, while the literature highlights a number of reasons why recourse to the GPL may make sense, it does not explore the question whether the GPL may make more or less sense than the BSD and under what circumstances this is likely to be the case.

a collective and decentralized fashion, as in the OSS production model, there may be some extent of redundancy of development efforts. Absent ex ante coordination of the type ensured by the centralized organization of the firm, more than one contribution by different developers may perform the same functionality. In other words, there may be some degree of substitutability among different contributions.

It follows that decentralized software innovation cannot be adequately represented as the sum of individual contributions.

Second, by contributing to an OSS project that has, indeed, the features of a public good in that it is made freely available on the web, software developers also derive private benefits. These can be in the form of reputation and signalling benefits (Lerner and Tirole, 2002), satisfaction of specific user needs (von Hippel, 2002; Johnson, 2002), intrinsic benefits including the enjoyment of programming *per se* (Moglen, 1999) and the satisfaction following from respect of an ideological commitment to the norms of OSS communities (Bergquist and Ljungberg, 2001). In addition to this, private benefits may be obtained also by for-profit firms adopting an OSS business model. In this case firms cannot profit from the *direct* sale of the software, but derive benefits from the provision of complementary services, such as for instance software customization, support and assistance. Of course, active participation of firms adopting an OSS business model to the developement of OSS software code constitutes an essential precondition to derive the private benefits deriving from the possibility to charge for complementary services.

Third, innovative investments are non-contractible almost by definition in the context of OSS projects because there is no ex ante agreement (and, *a fortiori*, no binding agreement) specifying the level of each contributor's investment. Indeed, although OSS projects are far from the anarchic and caotic world described by Raymond's romantic view of the "bazaar" production model (Raymond, 1998), coordination of innovative activity is not achieved through contracts. Moreover, even if it was, such contracts would be necessarily incomplete given the nature of their object, i.e. hard-to-verify innovative effort.

Additionally, the case of OSS is typically that of "open" access in the sense that who contributes to each "module" is not determined in advance. From this point of view, the model described in section 2.4 is particularly relevant to describe the situation of decentralized software development. The conclusion reached in Proposition 3 implies that a commitment not to exclude other developers from ex post access may improve incentives. This provides an economic based rationale for restrictive licences limiting exclusion, i.e. copyleft licenses enhance incentives relative to non-copyleft licenses. This may contribute to explain why they are most diffused.

## 4. Conclusions

In this paper we have shown that, in the presence of complementarities among joint investments in innovation, the conclusion that appropriability of one's contribution through exclusion (via IPR or other devices) does not necessarily enhance incentives to invest.

This conclusion has been reached by building a model that considers the inter-

play of some dimensions of collective innovation and knowledge production that we think are important: namely, the fact that the innovative effort exerted by each innovator, beside improving a common input with the nature of a public good, generates a private benefit for the innovator; and the fact that investment in innovation is not contractible in advance. Under these assumptions, we have shown that, when the production function for the innovation involves complementarity among contributions, agreeing ex ante not to exclude others from access to one's contribution can give better incentives than relying on ex post bargaining on the surplus as made possible by exclusion. Such conclusion is true even assuming ex post efficient bargaining, i.e. even disregarding other costs associated with the possibility of exclusion, such as monopoly pricing or the inability to reach an agreement.

Our model can be improved and developed in more than one direction: in particular, it should be checked whether our conclusion is robust when we combine complementarity with different assumptions about the possibility that more than one individual can contribute to a specific task; in our model, the analysis of this possibility has been limited to the strongest case of complementarity (see case III above). Moreover, the whole analysis has been made under the assumption of symmetry among contributors; the effect of asymmetry should be considered as well.

In addition to this, empirical analysis may be used to test whether our model can provide an economic rationale for the popularity of copyleft (restrictive) licences in the case of Open Source software. The perspective presented in this article suggests to take explicitly into account in the analysis of the implications of different licenses for incentives a "technological" dimension, namely the degree of complementarity among innovation tasks, which is at present not explicitly considered by existing empirical studies such as Fershtman and Gandal (2007). Indeed, our analysis implies that, absent other coordination devices, restrictive licences like the GPL should be more common when coordination among complementary tasks is important to the success of the project.

## Appendix

## Derivation of expression (20)

We calculate the symmetric Nash equilibrium. Under the assumption of symmetry, individual *i*'s payoff as a function of her own investment  $y_i$ , the investment of her "rival"  $y_{s+i}$  and the investment of the generic individual  $y_j$ , which we assume to be the same  $(y_j = y)$  for all  $j \neq i, s+i$ , is

$$\begin{aligned} \frac{1}{2s} \sum_{k=1}^{2s} \left\{ &\alpha(k) \big[ (k-1)\theta(y) + \theta(y_i) \big] \min\{y, y_i\} \\ &+ \hat{\alpha}(k) \Big[ (k-1)\theta(y) \big( \min\{y, \max\{y_{s+i}, y_i\}\} - \min\{y, y_{s+i}\} \big) \\ &+ \theta(y_i) \min\{y, \max\{y_{s+i}, y_i\}\} \Big] + \theta(y_i) X_0 \right\} \end{aligned} \tag{26}$$

European FP6 – Integrated Project Coordinated by the Centre for Philosophy of Law – Université Catholique de Louvain – http://refgov.cpdr.ucl.ac.be WP–IFM-85 where

$$\alpha(k) = \binom{s-1}{k-s} \binom{2s-1}{k-1}^{-1} 2^{2s-k-1} = \binom{k-1}{s} \binom{2s-1}{s}^{-1} \frac{2s-k}{k-s} 2^{2s-k-1}$$
(27)

represents the probability that individual in position k is pivotal to complete the minimum coalition, while

$$\hat{lpha}(k) = {{s-1} \choose {k-s-1}} {{2s-1} \choose {k-1}}^{-1} 2^{2s-k}$$
 (28)

is the probability that the minimum coalition has been already formed by the k-1 individuals preceding k. These probabilities are multiplied by the corresponding contributions of the individual to a coalition of k-1 members as she joins it as kth member. In other words, the expression in braces in (26) can be interpreted as the payoff the individual receives if she joins as kth and makes a take-it-or-leave offer to the k-1 individuals preceding her. By averaging over all possible positions in the population of numerosity 2s we have i's expected payoff.

Note that the addendum in the second line in (26) takes into account that the contribution to a coalition already containing the minimum coalition depends on  $y_i$  being higher than the investment made by the "rival" individual providing the same type of contribution.

Note also that  $\alpha(k) = 0$  for k < s; moreover,  $\alpha(k)$  is increasing and then decreasing for k going from s to 2s, with  $\alpha(2s) = 0$ ;  $\hat{\alpha}(k) = 0$  for  $k \leq s$ ,  $\hat{\alpha}(k)$  is nondecreasing in k and  $\hat{\alpha}(2s) = 1$ . The probability  $1 - \alpha(k) - \hat{\alpha}(k)$  is equal to one for k < s - 1, then it decreases as k increases, and is zero for k = 2s.

Let

$$eta = rac{1}{2s}\sum_{k=1}^{2s}ig(lpha(k)+\hat{lpha}(k)ig).$$
 (29)

Clearly  $\beta > 0$ , while from  $\sum_k \alpha(k) = 1$  and from the fact that  $\hat{\alpha}(s) > 0$  only for k > s follows that  $\beta < (s+1)/2s \leq 1$  (the latter inequality is strict for s > 1). Since

$$\frac{1}{2s}\sum_{k=1}^{2s}(k-1)\alpha(k) = 1 - \beta$$
(30)

substituting from (29) and (30), and considering that in a symmetric Nash equilibrium  $y_{s+i} = y$ , the payoff (26) can be written as in (20).

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