UNIVERSITÀ DEGLI STUDI DI SIENA

QUADERNI DEL DIPARTIMENTO
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Appropriability and Incentives with Complementary Innovations

n. 603 – Novembre 2010

Abstract - This article analyzes the effects on ex ante incentives to invest in the development of complementary innovations of two alternative appropriability strategies: a strategy of exclusion of third parties from access (through active enforcement of IPRs or technical means) vis-a-vis an openness strategy, i.e. an ex-ante commitment not to exclude. Assuming that the complementary innovations constitute a common input and that agents make complementary investments in its private exploitation, we find that, when complementarities are sufficiently strong, a commitment to openness may provide greater incentives than an exclusion strategy. The theoretical framework is used to provide an interpretation of Open Source Software licenses and the "Open Science" system.

Keywords: incentives to innovation, complementarity, intellectual property rights, open source software, open science.

JEL classification: L17, O34.

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1. Introduction

In the past few decades, innovative activity has fundamentally changed. For a long time, the centralization of innovation within large firms has been rightly understood to confer critical advantages (for an early comment on this, see Nelson, 1959) and analyzing the division of innovative labour across firms (let alone across individuals) was not crucial to grasp the dynamics of knowledge creation. Now decentralized production of knowledge and innovation is the norm, rather than the exception. Changes in technology, market conditions as well as in the institutional environment where innovation takes place have led to a substantial increase of technological collaborations of various sorts and to the emergence of extreme forms of decentralization of innovative activity, such as for instance Open Source Software.

A somewhat striking feature of these developments is that decentralization is often accompanied by norms of "openness", i.e. by a commitment by each participant to the collective innovation effort not to exclude third parties from access to her contribution(s) that is reminiscent of the norms of Open Science. This is apparent in the context of software innovation (Maurer and Scotchmer, 2006; Rossi, 2006) as well as in a variety of other fields, including semiconductor process equipment (Lim, 2009) and sporting equipment (Franke and Shah, 2003).

The diffusion of this sort of commitments is, to some extent, surprising, since they appear to reduce the degree of private appropriation of the benefits generated by innovative activities and therefore incentives. If, as it is commonly assumed, the relationship between the extent of appropriability/excludability of knowledge and incentives to invest is a monotonically increasing one (more appropriability/excludability is invariably a good thing for incentives), we should expect a progressive reduction of the diffusion of these commitments. In fact, the opposite is the case. This suggests the possibility that a strategy of appropriability of the benefits from innovation that involves the explicit renounce to exclude from access may, under certain conditions, positively affect incentives—a possibility that constitutes the starting point for our paper.

This paper aims at clarifying through a formal model the conditions under which, in a context of decentralized knowledge production, a commitment to openness ("openness strategy") dominates in terms of incentives a strategy of appropriability based on the active enforcement of the right to exclude conferred by intellectual property rights ("exclusion strategy"). This constitutes a significant departure with respect to most accounts of the role of openness, as it places emphasis on ex ante incentives following from openness rather than on its well-known ex post advantages.

The paper considers a context of collective innovation by multiple independent agents whose innovative investments take the form of both the contribution to a common input and investment into its subsequent individual use/exploitation by the agent (to be understood in a broad sense, to include all individually beneficial activities that require access to the input). Within this framework, the paper shows that the standard result on the superiority of exclusion in terms of incentives need not hold in presence of: (a) complementarity among contributions, i.e. when the joint value of individual contributions is greater than the sum value of those contributions taken individually; and (b) complementarity between efforts exerted by each innovator for the development of the common input, on one side, and for its subsequent individual use on the other. The paper highlights that, when such complementarities are of some relevance, exclusionary mechanisms result in reduced incentives to invest as compared to a commitment by each contributor not to exercise her right to exclude third parties from her intellectual property.

The intuition for our result is as follows. Exclusion allows to charge a price for access to one's contribution to the common input. This, in principle, should increase appropriability and therefore incentives. However, when neither innovators' investments nor the quality of the innovation itself is contractible ex ante—as it is reasonable to assume—exclusion-based appropriability has two main drawbacks. The first is that, in presence of contractual incompleteness, each contributor's share of profit is determined by ex post bargaining. This, in turn, may result in insufficient reward of contributors for their efforts, given that the ex post value of a contribution is only imperfectly related to the bargaining power of its owner. More specifically, the greater the complementarity among the contributions to the common input, the weaker is the link between the value appropriable through ex post bargaining and ex ante investment. The second drawback concerns incentives for the contributor to undertake a complementary investment in the use of the common input. Ex post exclusion allows individuals to claim a share not only of the yields from the "public" dimension of the investment (the contribution to the advancement of the common input), but also on the return of the "private" dimension, i.e. the effect on its subsequent use by each developer. This is because continued access to the common input is essential to reap the benefits of the private dimension of the investment. Thus, exclusion will have adverse effects on the private dimension of the investment, and explains why the overall effect on incentives can be different than conventional wisdom suggests, and why, on the contrary, a commitment not to exclude others can be a better strategy to induce joint investments.

The two conditions under which openness dominates exclusion—complementarity among innovative efforts and cost complementarity between investment in the common input and investment in the subsequent use of the resulting innovation—are relevant in many instances of decentralized innovation.

Complementarity among contributions entails that the innovative process involves the joint effort of different innovators, which are not perfect substitutes one for another. This means that the combined effect of efforts x_i by i and x_j by j is not the same in terms of effects on innovation as the provision of effort $x_i + x_j$ by i alone. That this may be the case follows, on one side, from the very possibility of the division of innovative labour and, on the other, from the fact that different individuals or firms possess individual- or firm-specific human capital, knowledge, and resources by virtue of learning and previous innovative activities (Cohen and Levinthal, 1989). 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 investments. Hence, complementarity might simply reflect the advantages of specialization among different contributors, where each one invests in the production of a component which is complementary to others. If it is costly to specialize in one task or another, the joint effect of n contributors cannot be easily replicated by a n-fold investment by a single agent. Indeed, we think that perfect fungibility of contributions is more the exception than the rule in the innovation context.

The complementarity between investment in the common input and investment in the subsequent use of the resulting innovation, in turn, relates to the fact that the outcome of the collective project to which agents contribute may be an input in some profitable activity they engage in. When this is the case, the private benefit agents receive from using the innovation is often positively affected by the fact that they contributed to its development and, at the same time, their direct use of the technology may generate improvements to the common input.

Thus, there may be significant spillovers between the effort aimed at contributing to the common input and the effort aimed at increasing the value of the private dimension of the innovation. For example, by participating to a collective innovative project, contributors gain direct knowledge of a certain technology. The resulting increase in their technology-specific human capital allows them to derive a profit from activities requiring knowledge of and access to the technology developed as a common input. This is a frequent instance in circumstances in which agents market goods or services complementary to the common input, such as assistance to third parties in the use of the technology, customization of the jointly developed input to the needs of specific users and provision of complementary products and services.

Similarly, in many cases, the investment made in learning how to use a technology, while not directly aimed at developing it, may reveal limitations, flaws and bugs, suggest solutions to them or help identify improvements and further applications. Hence, investment in the private exploitation of a common knowledge input may increase the value of the input itself.

The paper is organized as follows. We present the model in section 2 and introduce two of its applications—Open Source Software and the production of scientific knowledge under the Open Science system—in section 3. Section 4 briefly concludes.

□ **Related literature.** Complementary innovations have been analyzed mostly from two angles. On one side, the literature on cumulative innovation (Green and Scotchmer, 1995; Matutes, Regibeau and Rockett, 1996; Scotchmer, 1996; O'Donoghue, 1998; Denicolò, 2000) has explored circumstances in which a basic invention constitutes the input to a subsequent complementary innovation, focusing on the issue of the division of profits that induces efficient ex ante incentives. On the other side, a number of contributions have analyzed complementary innovations that are not invented sequentially, disregarding the question of incentives to invest ex ante in their development; such contributions have focused on the negative effects of transaction costs and bargaining failures in terms of their ex post exploitation (Merges and Nelson, 1990; Heller and Eisenberg, 1998) and/or on the standard ex post inefficiency arising from monopolistic pricing and the associated inefficient exclusion of low demanders (Shapiro, 2001; Depoorter and Parisi, 2003; Lemley and Shapiro, 2007; Ménière, 2008). The present paper shares elements of both sets of contributions as it focuses on the issue of ex ante incentives to invest while analyzing complementary innovations none of which can be considered "basic", i.e. the foundation for any of the other innovations.

Closest in spirit to our paper is the recent contribution by (Gilbert and Katz, 2010), who study efficient incentives to produce complementary intellectual property (IP) assets. The two authors emphasize the relevance of the misalignment between an IP holder's bargaining power and the true contribution of her IP to the value of the final product—a point also stressed by (Lemley and Shapiro, 2007) and crucial to our model. However, their analysis differs from ours in many respects. In particular, in their model the complementary innovations are invented sequentially in the context of a Poisson discovery process, while in our model development of complementary innovations is simultaneous and does not involve stochastic elements. Most importantly, Gilbert and Katz's contribution does not take into account the possibility of a complementarity between investment in the common input and investment in the subsequent use of the resulting innovation.

The latter sort of complementarity—an aspect essential to the present paper—is emphasized in the literature on collective invention (for a seminal contribution, see Allen, 1983), and particularly on the phenomenon that von Hippel and von Kogh (2003) have defined as "private-collective innovation model"—a model whereby innovators publicly disclose innovations they have invested in. In this literature, however, the focus is on incentives to disclose existing innovations rather than on incentives to invest in their development, as it is the case in our paper. Moreover, no distinction is made between free revealing and the choice to make an explicit commitment not to exclude. Our paper, by contrast, stresses the importance of making an explicit ex ante commitment, echoing insights offered in this connection by the transaction cost literature, and particularly by the Williamsonian notion of *safeguard* (Williamson, 1983).

Finally, it is worth highlighting that, in the characterization of the innovation "production function", the paper draws on some insights from the stream of literature on public goods that emphasizes the role played by complementarity of contributions (Hirshleifer, 1983; Cornes, 1993).

2. Formal analysis

2.1. Model setup

We consider a group $N \equiv \{1, 2, \dots, n\}$ of individuals who can profit from the use of a common input X. Individual profit for $i \in N$ is $\pi_i = \theta_i X$.

Each individual can invest x_i in the development of X (the "technological quality" of the common input) and y_i in improving her private input θ_i, which can be interpreted as her ability to profit from X. Let $\theta_i = \theta(y_i)$ with $\theta(y_i) \geqslant 0$ for all $y_i > 0$, $\theta' > 0$ and $\theta'' < 0$. The effect of x_i on the public input X will be specified below, according to different hypotheses about the joint effect of individual investments.

The cost of the two investments is given by $\varphi(x_i, y_i)$, which is assumed to be increasing in its arguments and satisfies $\varphi_{xx} > 0$, $\varphi_{yy} > 0$ and $\varphi_{xy} \leqslant 0$. The latter property means that there is some cost complementarity between x_i and y_i, i.e. by investing in the development of the common input, the individual can increase her ability to use it and profit from it; conversely, the investment y_i can generate spillovers on the input used by all other individuals.

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

Individuals choose x_i (and y_i) independently, then merge their contributions, possibly making some payments to have access to others' 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 to their respective contributions.

We will indicate by $X(S)$ the quality of X when the contributions of individuals in the coalition S are used. A natural assumption is that additional contributions cannot reduce X, i.e. for given $(x_1, \ldots, x_n)$, $X(S) \geqslant X(R)$ if $R \subset S$. Assuming that $X(S)$ is twice differentiable,

$$\frac{\partial X(S)}{\partial x_i} \begin{cases} > 0 & \text{if } i \in S \\ = 0 & \text{otherwise} \end{cases} \qquad \frac{\partial^2 X(S)}{\partial x_i \partial x_j} \begin{cases} \geqslant 0 & \text{if } i \neq j \text{ and } i, j \in S \\ \leqslant 0 & \text{if } i = j \text{ and } i \in S \\ = 0 & \text{otherwise} \end{cases} \tag{1}$$

so that investments made by individuals belonging to the coalition increase X and are to a certain degree (to be specified below) complementary.

We will distinguish between two cases, or appropriability strategies, namely: (1) the case in which individuals retain and enforce a right to exclude others from access to their contribution, this ability to exclude being granted by technical means or by intellectual property rights (or both); (2) the case in which they agree at the beginning to give up this right and grant each other free access to their contributions. In the former case and only in that one, individuals can ask a price to grant access to their contribution: this will be named the *ex-post exclusion case.*

Since investments x_i and y_i are both assumed to have no value outside the activity that uses input X—i.e. investments are 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, on which we will come back below. The fact that the coalition includes all individuals does not mean that subcoalitions S play no role. Indeed, 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

$$\Pi(S) = \sum_{j \in S} \theta_j X(S) \tag{2}$$

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

$$\sum_{S \subseteq N | i \in S} \rho(S) \Big[\Pi(S) - \Pi(S \backslash \{i\}) \Big]; \tag{3}$$

where

$$\rho(S) = \frac{(|S|-1)!(|N|-|S|)!}{|N|!}. \tag{4}$$

This share can be thought of as a weighted average of the contribution of i's development to all possible subsets of developments[1]. 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[2].

The first order conditions identifying the optimal investment choices x_i^* and y_i^* for individual i are:

$$\theta_i'(y_i) \sum_{S \subseteq N | i \in S} \rho(S) X(S) - \varphi_{y_i}(x_i, y_i) = 0 \tag{5}$$

$$\sum_{S \subseteq N | i \in S} \rho(S) \sum_{j \in S} \theta_j(y_j) \frac{\partial X(S)}{\partial x_i} - \varphi_{x_i}(x_i, y_i) = 0 \tag{6}$$

The exclusion case will be compared with the case in which contributors agree in advance not to exclude each other from access to their respective contributions (openness strategy).[3] In this case, all contributions will be included in X, and the payoff of developer i will be:

$$\theta_i X(N). \tag{7}$$

[1] Note that $\sum_{S \subseteq N | i \in S} \rho(S) = 1$.

[2] 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 $S \backslash \{i\}$.

[3] This case can also be described as one in which contributors do not have access to any exclusion mechanism ex post, but this situation would be less relevant from a practical standpoint.

The first order conditions for the optimal choice x_i^{**} and y_i^{**}, are

$$\theta_i'(y_i)X(N) - \varphi_{y_i}(x_i, y_i) = 0 \tag{8}$$

$$\theta_i(y_i)\frac{\partial X(N)}{\partial x_i} - \varphi_{x_i}(x_i, y_i) = 0 \tag{9}$$

Both cases of exclusion and openness can be compared with the social optimum, which is reached when x_i and y_i of all individuals are chosen so that $\Pi(N)$ is maximized, or

$$\theta_i'(y_i)X(N) - \varphi_{y_i}(x_i, y_i) = 0 \tag{10}$$

$$\sum_{j\in N}\theta_j(y_j)\frac{\partial X(N)}{\partial x_i} - \varphi_{x_i}(x_i, y_i) = 0. \tag{11}$$

We can state the following:

Proposition 1. *For all i, the level of investment x_i and y_i in the two equilibria implied by exclusion and openness is lower than the socially optimal level.* □

Proof. The Proposition can be easily proved using results in monotone comparative statics. We first check that the interaction among contributors, both with exclusion and without exclusion, is a supermodular game: under the assumption that $\varphi_{xy} \leqslant 0$ and (1), expression (5) and (8) are nondecreasing in x_i, and expressions (5), (6), (8) and (9) are nondecreasing in x_j and in y_j (for all $j \neq i$).

Moreover, consider the game in which agents maximize social surplus $\Pi(N)$ ("social surplus game"), with optimal strategies characterized by (10) and (11) and representing the socially efficient level of investment. This is supermodular as well.

We know from Milgrom and Roberts (1990) that a sufficient condition for the highest equilibrium of a supermodular game to be not lower than the highest equibrium of another supermodular game is that the effect of an increase in i's strategies (x_i and y_i) on i's payoff is larger in the former game at each point in the strategy space.

We check that this is the case when we compare the exclusion game (conditions (5) and (6)) with the social surplus game (conditions (10) and (11)). Indeed, from $X(N) \geqslant X(S)$, and $\partial X(N)/\partial x_i > \partial X(S)/\partial x_i$ when $S \subset N$, follows that:

$$X(N) \geqslant \sum_{S\subseteq N|i\in S}\rho(S)X(S) \tag{12}$$

$$\sum_{j\in N}\theta_j(y_j)\frac{\partial X(N)}{\partial x_i} \geqslant \sum_{S\subseteq N|i\in S}\rho(S)\sum_{j\in S}\theta_j(y_j)\frac{\partial X(S)}{\partial x_i}. \tag{13}$$

Similarly, to compare the openness game with the social surplus game, we check that the expression in (9) is lower than the expression in (11), while (8) and (10) are equal.

Finally, note that a set of strategies cannot satisfy at the same time the first order conditions for the social surplus game *and* the first order conditions for the exclusion or the openness game. This allows us to conclude that the equilibrium level of investment must be strictly lower (in one or both dimensions) in the exclusion and in the openness games compared to the level in the highest equilibrium in the social surplus game, which corresponds to the socially optimal level (for a discussion on how to proof strict monotonicity, see Edlin and Shannon, 1998). □

This conclusion is by no means surprising. With regard to the openness case, the circumstance that contributors cannot appropriate the value of their contributions reduces incentives to invest in the common input X. This is the well known public good problem that is taken to justify the granting of intellectual property rights.

The fact that the incentive is reduced also in the case of exclusion should not be surprising either, since appropriation takes place through ex post bargaining, and this weakens the link between effort and profit.

Without exclusion, individuals have an incentive to free ride in their investment because they do not take into account the positive effect of their effort on others' profit. 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 part of the effect of x_i through exclusion comes at the cost of reducing the incentive to provide y_i: indeed, as it is clear from the first order conditions, for a given x_i, the marginal benefit from y_i is higher under openness than under exclusion. The possibility to exclude others from access to one's contribution results into the ability to appropriate part of their (complementary) private investment aimed at increasing θ. Hence, with respect to the social optimum, direct comparison of first order conditions shows that with exclusion the benefits from both y and x are reduced, while with openness it is the incentive to provide x which is affected. However, a direct comparison between the two cases is not possible without further assumptions about the interaction between x and y and about the degree of complementarity among different contributions. In the following sections we will consider some possible specifications of the model, reflecting different characteristics of the technology used to produce X.

2.2. Input quality as the sum of individual investments

The outcome of innovative activities is commonly described as a public good, because its use is nonrival. Moreover, it is often implicitly assumed, both with reference to public goods in general and to the outcomes of innovative activities, that their total available quantity is the sum of the quantities provided by the various contributors (this assumption underlies the so-called "summation" model of public good provision). This amounts to assuming 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.

We claim that this assumption is not 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

$$X(S) = \sum_{i \in S} x_i. \tag{14}$$

It follows that $\partial X(S)/\partial x_i = 1$.

We make the simplifying assumption that individuals are *symmetric*. In a symmetric equilibrium, where $x_i = x$ and $y_i = y$ for all i, $X(S)$ depends only on the size/numerosity of S ($|S| = s$), so that $X(S) = sx$. The equilibrium conditions (5) and (6) in the exclusion case become[4]

$$\frac{n+1}{2}\,\theta'(y)x = \varphi_y(x,y) \tag{15}$$

$$\frac{n+1}{2}\,\theta(y) = \varphi_x(x,y) \tag{16}$$

This must be compared to the case of openness, where the first order conditions are, under symmetry,

$$n\theta'(y)x = \varphi_y(x,y) \tag{17}$$

$$\theta(y) = \varphi_x(x,y). \tag{18}$$

In order to compare the optimal values of x and y in the two cases under different assumptions about the cost complementarity between x and y, we need to specify the functional form of $\theta(y)$ and $\varphi(x,y)$. We assume $\theta(y) = y^\beta$ with $0 < \beta < 1$, and

$$\varphi(x,y) = (x^b + y^b)^{\gamma/b} \qquad b \geqslant \gamma > 1 \tag{19}$$

where γ is the elasticity of cost with respect to an increase in both investments. Condition $b \geqslant \gamma$ is necessary to secure that $\varphi_{xy} \leqslant 0$ (i.e. a higher x does not increase the marginal cost of y and viceversa).

This formulation allows us to consider different degrees of complementarity between the two kinds of investment by changing the parameter b. At one extreme, when $b = \gamma$, we have $\varphi(x,y) = x^\gamma + y^\gamma$ and the marginal costs of investments x and y are independent. At the other extreme, as b tends to infinity, the cost function tends to $\max\{x,y\}^\gamma$, i.e. the marginal cost of increasing y when $x > y$ is zero.

Conditions (15) and (16) become

$$\frac{n+1}{2}\,\beta y^{\beta-1}x = \gamma y^{b-1}(x^b + y^b)^{\gamma/b-1} \tag{20}$$

$$\frac{n+1}{2}\,y^\beta = \gamma x^{b-1}(x^b + y^b)^{\gamma/b-1} \tag{21}$$

[4] Note that in the left hand side the sum across all $S \subseteq N$ containing i can be replaced by the sum across all coalition sizes, considering that the probability that i belongs to a coalition of size s is $1/n$.

so that the equilibrium investment with ex post exclusion (x^*, y^*) satisfies $y = x\beta^{1/b}$ and

$$\frac{n+1}{2}\,\beta^{\beta/b}x^{\beta} = \gamma(1+\beta)^{\gamma/b-1}x^{\gamma-1}. \tag{22}$$

Proceeding as above in the case of openness, from (17) and (18) we have that the equilibrium investments (x^{**}, y^{**}) must satisfy $y = x(n\beta)^{1/b}$ and

$$(n\beta)^{\beta/b}x^{\beta} = \gamma(1+n\beta)^{\gamma/b-1}x^{\gamma-1}. \tag{23}$$

In both the case of exclusion and of openness, from the second order conditions for an internal solution follows that $\gamma > 1+\beta$.

Proposition 2. *When $X(S) = \sum_{i\in S} x_i$, for $n > 1$, we always have $x^* > x^{**}$, i.e. the investment aimed at improving the public input X is higher under the exclusion regime than under the openness regime.* □

Proof. By comparison of (22) and (23) we have that $x^* > x^{**}$ as long as

$$\frac{2n^{\beta/b}}{n+1} < \left(\frac{1+\beta}{1+n\beta}\right)^{1-\gamma/b} \tag{24}$$

it can be easily verified that this inequality is satisfied for all $n > 1$ and for all $b \geqslant \gamma$. □

2.3. Complementarity among individuals' investments in input quality

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, cannot be easily reconciled with the coordination problems that afflict large development projects. 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, allowing for different degrees of complementarity among individual contributions.[5] Economic analysis has thus shown that, as we depart from the summation model, the incentive to contribute may be very different than in the standard case (Cornes, 1993).

We replace (14) with

$$X(S) = \Big(\sum_{i\in S} x_i^a\Big)^{1/a} \qquad 0 < a \leqslant 1 \tag{25}$$

[5] A case which is polar with respect to the summation model is the *weakest-link* (Hirshleifer, 1983): under a weakest-link technology, where complementarity among contribution is maximal so that the amount of the public good is the minimum among individual contributions.

this is the familiar expression for a constant elasticity of substitution (CES) production function; $(1-a)^{-1}$ is the elasticity of substitution, which is infinite in the case $a = 1$; note that in this case (25) reduces to (14). As a tends to zero, contributions become necessary for X to be valuable to the individuals. We restrict our attention to positive values of a, because for $a < 0$ the amount of the public good is always zero when the coalition N is not formed, i.e. when at least one individual decides not to participate,[6] hence the result is qualitatively the same we have with $a \to 0^+$. Note that the limiting case of a approaching zero corresponds to the O-ring production function, introduced by Kremer (1993). In Kremer's words (p. 551), such 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".[7]

We start from the case of openness. With the new expression for $X(N)$, under symmetry, the equilibrium conditions (8) and (9) are

$$n^{1/a}\theta'(y)x = \varphi_y(x,y) \tag{26}$$

$$n^{1/a-1}\theta(y) = \varphi_x(x,y) \tag{27}$$

Using the same specifications of the previous section for functions φ and θ, we have that $y^{**} = (n\beta)^{1/b}x^{**}$ while x^{**} satisfies

$$n^{1/a-1}(n\beta)^{\beta/b}x^{\beta} = \gamma(1+n\beta)^{\gamma/b-1}x^{\gamma-1}. \tag{28}$$

Consider now ex post exclusion. By substituting for $X(S)$ in (3), the equilibrium conditions (5) and (6) are

$$\lambda_n(a)n^{1/a-1}\theta'(y)x = \varphi_y(x,y) \tag{29}$$

$$\lambda_n(a)n^{1/a-1}\theta(y) = \varphi_x(x,y) \tag{30}$$

where $\lambda_n(a) = \sum_{s=1}^{n}(s/n)^{1/a} > 0$ is increasing in a and in n, with $\lambda_n(1) = (n+1)/2$ and $\lim_{a\to 0}\lambda_n(a) = 1$.

We observe that, as a decreases, the left hand size of conditions (30), expressing the marginal benefit from investment in the improvement of X in the case of exclusion, tends to coincide with (27), the marginal benefit in the case of openness. The latter is $(1/n)(\partial X(N)/\partial x_i)$, i.e. investment is made under the expectation that each contributor claims an equal share $(1/n)$ of the increase in the common input, regardless of her actual effort. Indeed, when individual contributions become essential to the innovation, the bargaininig power of the parties is not related to the intensity of individual effort; exclusion becomes less and less effective in reducing free riding in the production of the public input X. Moreover, when all contributions are equally essential, bargaining not only reduces the beneficial

[6] Note that, with $S = N$, as $a \to -\infty$ we have maximal complementarity, and $X(N) = \min\{x_1,\ldots,x_n\}$. This corresponds to the weakest-link technology mentioned in the previous footnote.

[7] Kremer refers to the case of labor skills. As he puts it (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."

effect of exclusion, it also has an adverse effect on the private incentive to invest, given by the effect of y on θ, as it is apparent from (29). With exclusion, each party is able to claim (expropriate) a share of each other party's private benefit, and the overall incentive is reduced.

By making the required substitutions for θ and φ in (29) and (30), we have that $y^* = x^* \beta^{1/b}$ and x^* satisfies

$$\lambda_n(a) n^{1/a-1} \, \beta^{\beta/b} x^{\beta} = \gamma(1+\beta)^{\gamma/b-1} x^{\gamma-1}. \tag{31}$$

We reach the following:

Proposition 3. *Let x^* and x^{**} be the symmetric equilibrium investments respectively when exclusion is possible and under an openness regime. Under the assumption (25), for all $n > 1$ and for all $b \geqslant \gamma$, there exists $a^*(b) > 0$, increasing in b, such that $x^* < x^{**}$ if and only if $a < a^*(b)$.* □

Proof. By comparing expressions (31) and (28), we find that a necessary and sufficient condition for $x^* \gtrless x^{**}$ is

$$\lambda_n(a) \gtrless n^{\beta/b} \left(\frac{1+n\beta}{1+\beta} \right)^{1-\gamma/b} \tag{32}$$

where the r.h.s. is always strictly larger than one for $n > 1$. Since $\lim_{a \to 0} \lambda_n(a) = 1$, the inequality is not satisfied for a small enough. From monotonicity and continuity of $\lambda_n(a)$ in a follows that there exist $a^* > 0$ such that the expression (32) is satisfied with equality at a^* and with '>' for $a < a^*$.

That a^* is increasing in b follows from the fact that the r.h.s. of (32) is increasing in b. This is verified by considering the logarithm of the r.h.s. and calculating the derivative w.r.t. b, which has the same sign as

$$\begin{aligned} \gamma \log \left(\frac{1+n\beta}{1+\beta} \right) - \beta \log n > (\beta+1) \log \left(\frac{1+n\beta}{1+\beta} \right) - \beta \log n = \\ = \log n + (\beta+1) \log \left(\frac{1+n\beta}{n+n\beta} \right) > \log n + \log(1/n) = 0 \end{aligned} \tag{33}$$

where we have used the fact that $0 < \beta < 1 - \gamma$ (the latter inequality follows from second order conditions). □

The proposition states that, provided that contributions are complementary enough, it is always possible that the openness regime induces higher investment in the development of the public input. Moreover, the higher the complementarity between x_i and y_i (i.e. the higher b), the lower the complementarity among individuals' contributions (i.e. the higher the value a^*) which is necessary to make openness advantageous.

To give an idea of the relation among parameters, we calculate a^* for different values of b and n, under the assumption that $\beta = .7$ and $\gamma = 2$:[8]

[8] Note that b is limited from below by γ.

	$b = 100$	10	5	3	2
$n = 5$	.73	.62	.52	.42	.32
10	.70	.55	.42	.30	.20
20	.68	.48	.34	.22	.13
50	.67	.41	.26	.15	.07

The first column ($b = 100$) identifies the case of maximum complementarity between the two dimensions of investment/effort, where $x_i = y_i$.

3. Applications

The model presented in the previous sections highlights that, if certain conditions hold, a reciprocal commitment not to exclude others from access to one's intellectual asset(s) can be a better strategy to induce investments than a strategy based on the active enforcement of IP and/or on technical exclusion. This conclusion holds under the twin hypotheses of the existence of (a) complementarity among the efforts made by different innovators at developing knowledge that has the nature of a common input to contributors' activities; and (b) complementarity between contributions to the common innovative input and investment in the subsequent (private) use of the resulting innovation.

As it was briefly mentioned in the introduction, both the adoption of an explicit ex ante commitment not to exclude third parties from one's IP and these conditions are more common than it may first appear. This section provides a concise analysis of two salient real-world examples of the sort of phenomena captured by our model, namely the system of Open Source Software licenses and the mechanics of production of scientific knowledge under the Open Science system.

3.1. Open Source Software

Open Source Software (henceforth 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. Once a given software is distributed under an OSS license, it becomes permanently accessible to all those willing to subscribe such licenses. Thus, this kind of licenses amounts to a developer's pre-commitment not to exclude third parties from access to their software contributions.

The strenght of this pre-commitment varies with the specific type of OSS license used, and particularly according to whether the license is "copyleft" or "non-copyleft". Copyleft licenses, such as the General Public Licence (GPL), are 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. Non-copyleft licenses (as the Berkeley Software Distribution - BSD), by contrast, preserve the freedom of subsequent developers to exercise ex post the right to exclude from their copyrighted improvements to the original software and therefore grant 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. Thus, copyleft licenses imply a much stronger commitment not to exclude than non-copyleft licenses.

In spite of their greater restrictiveness for licensors, copyleft licenses have by far the greatest diffusion in the OSS world and are adopted by more than 80% of OSS projects (Lerner and Tirole, 2005; Fershtman and Gandal, 2007; Comino, Manenti and Parisi, 2007). The quantitative prevalence of copyleft licenses appears puzzling in light of the standard view that more effective exclusion is invariably associated to greater incentives. According to this view, non-copyleft licenses should be preferred to copyleft licenses because, by ensuring greater appropriability through exclusion, they should be more highly valued by licensees. Perhaps for this reason, this empirical fact has mostly been rationalized by reference to ideology-based explanations, such as the need to attract ideologically-motivated contributors or an intrinsic (and unexplained) superior ability of copyleft licenses to prevent forking[9] or reduce free-riding (Lerner and Tirole, 2005; Maurer and Scotchmer, 2006; Gambardella and Hall, 2006). The model presented in this paper, by contrast, may provide an efficiency-based explanation to this phenomenon. It suggests that copyleft licenses tend to be most diffused exactly because they entail a more effective pre-commitment not to exercise exclusion rights and, as a consequence, greater incentives to invest.

The economic environment where OSS development takes place displays the main features captured by our model. Indeed, OSS software developers may both invest in an open source software program that has the nature of a publicly available common input and in the private exploitation of that input through activities such as the provision of complementary services in the form of software customization, support and assistance and the sale of the OSS software input in a bundle with other hardware or proprietary software. These investments are characterized by the crucial features highlighted by our model.

First, developers' investments in the jointly developed software program are complementary. The presence of complementarities among different developers' contributions to OSS collaborations may be understood to follow from the peculiar division of labour taking place within OSS projects. Indeed, the usual specialization benefits inherent to the division of labour tend to be particularly pronounced in OSS development because OSS developers may self-select for the tasks that best match their abilities (Benkler, 2002), so that contributions tend to be made by those that possess the best human capital and knowledge for a given task. Second, in a context of decentralized development, each of the separately developed software components tends to be co-specific to the other components making up a given program. This tends to be the case particularly when time to market is an issue, i.e. when lack of access to one of the components would significantly undermine profit opportunities by delaying market release of the program.

Second, developers benefit from advancement of the common input. Benefits

[9] Forking indicates the circumstance that a developer legally acquires a copy of a software source code and starts independent development of a distinct software program based on that code. The development of the original program thus forks in multiple directions.

may be intrinsic and/or extrinsic. Intrinsic benefits may take the form of 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)[10]. Extrinsic benefits may be in the form of reputation and signalling advantages (Lerner and Tirole, 2002), satisfaction of specific user needs (von Hippel, 2002), and monetary profits associated to the mentioned complementary activities.

Third, complementarities exist between investment in the common input and investment in its subsequent use for private purposes. On one side, investment in the common input enhances the value of investment in the private input since active participation to the development of OSS software code constitutes an essential precondition to engage in these private activities, which require first-hand knowledge of the software program that constitutes their input. On the other side, investment in the private input enhances the value of investment in the common input. Indeed, by using the innovation that incorporates the common input in complementary private activities, developers may identify bugs or possible improvements and applications, thus generating positive spillovers in terms of quality of the common input.

Finally, consistently with our model, the ability of developers to derive benefits from both the public and the private dimension of their investment depends on their having on-going access to the jointly developed OSS code.

Thus, our model provides a rationale for OSS licenses in general and more specifically for the quantitative prevalence of copyleft licenses over non-copyleft licenses, contributing to the limited theoretical literature on the matter.

3.2. Production of Scientific Knowledge under the Open Science system

Although the analysis has so far been developed by reference to decentralized *innovation*, i.e. to the commercial application of newly developed knowledge, it can also be applied to understand the framework within which the production of scientific knowledge has traditionally taken place. Indeed, the most extreme instance of ex ante commitment not to exclude third parties from access to one's intellectual assets can be identified in the rules that have for long disciplined "Open Science" production of scientific knowledge.

As is well known, the expression "Open Science" refers to the combination of norms and conventions that make up the ethos of scientific research, and particularly to the norms of the scientific community that facilitate disclosure and the diffusion of knowledge. For our purposes, the distinctive feature of such a system rests in the fact that individual appropriability of the benefits from research is not based on exclusion of third parties from access to scientific findings but rather on the widest possibile access to those findings, which feeds, in turn, a reputational system based on scientific publication and peer validation of research results (Dasgupta and David, 1994). The norms of the "Republic of Science" (Polanyi, 1962) thus amount to a pre-commitment not to exclude of the sort that interests us in

[10] Note that enjoyment of this sort of intrinsic benefits, depends on continued access to the common input.

this paper.

Most importantly, it appears that the rules of "Open Science" have emerged in a context characterized by features consistent with our model. Researchers may typically invest their time and intellectual resources both in contributing to the existing stock of scientific knowledge and in mastering and exploiting such body of knowledge through activities that use the latter as an input such as lecturing and providing consultancy services.

First, that the production of scientific knowledge results from the complementary efforts of different individuals is self-evident. Different individuals contribute to the scientific enterprise different intellectual resources, ingenuity and human capital. Also, to the extent that scientific research is characterized by serendipity, the outcomes achievable by multiplying the effort exerted by any single individual will never be the same as those achievable through multiple research efforts.[11] Indeed, the joint contribution to the same research endeavour by more than one scientist allows to attain results that are more valuable than those attainable by correspondingly increasing the effort exerted by a single scientist, among other things because reciprocal inspection allows to validate scientific findings. The scientific knowledge accepted by the community is reliable exactly because it is tested and developed by multiple scientists (Ziman, 1976).

Second, researchers benefit in many ways —again, both intrinsic and extrinsic— from the fact that their research findings may increase the relevance and recognition of the stream of research they are engaged in, which is a public good for a community of scientists/researchers.

Third, there is certainly no doubt that contribution to the advancement of science (x_i) and investment aimed at becoming an "expert" in that field (y_i) are complementary, to the point that they might coincide in many cases.

Finally, continued access to the existing stock of scientific knowledge is indispensable to engage in the above-described investment activities: absent access to existing knowledge, neither further advancement of the stock of scientific knowledge, nor its exploitation in the context of related activities would be possible.

The model presented in this paper may thus allow to explain the emergence of the system of "Open Science", contributing to the recent literature rationalizing this institution (see e.g. Stern, 2004; Aghion, Dewatripont and Stein, 2008). Moreover, it may provide insights on the implications of the emergence, within the scientific community, of a framework of rules alternative to the "Open Science" system and based on the active enforcement of IPRs over the results of scientific research.

The shift towards this alternative framework has been induced to a large extent by the progressive extension of patentability to the results of basic research[12] and the introduction of legislation that, following the U.S. Bayh-Dole Act of 1980,[13]

[11] The notion of serendipity refers to the fortuitous discovery of useful scientific results and to the associated perception of the unpredictability of the research areas with greater potential payoff.

[12] Scientific facts and principles and natural phenomena have traditionally not been patentable. However, given the blurry lines existing between natural substances and man-made ones, this limitation has not in practice been binding.

[13] The Bayh-Dole Act has allowed federally funded agencies, including universities, in the U.S., to claim title to the results of federally-funded scientific research on the basis of the presumption

has promoted the attribution of IPRs to universities and research institutions.[14]

As a consequence of these developments, scientists face a choice between publication and patenting (or between "openness" and "exclusion", in the terminology of this paper) since publishing research findings may compromise their right to patent. Indeed, a patent cannot be obtained if an invention was previously known or used by others in the country where patent protection is sought or patented or published anywhere in the world. Thus, presentations at conferences or seminars according to the rules of "Open Science" as well as publication on scientific journals are, to some extent, incompatible with patenting. In some jurisdictions, notably in the U.S., publishing and patenting may in principle be reconciled by submitting a provisional patent application that allows to obtain priority before publishing. However, even when this is the case, scientists interested in commercializing their discoveries will keep them confidential during the patent application process, which may take 5 to 7 years, and in any case will only disclose their findings in a way that is not sufficiently detailed to enable someone to reproduce the invention. This, of course, severely limits the possibility to exploit the complementarities among the multiple individual contributions to the public stock of scientific knowledge.

Thus, the alternative framework that is currently developing appears to be one where access to the complementary intellectual assets indispensable to the pursuit of scientific research requires ex-post contracting, as in the "ex-post exclusion case" considered in our model. The insights of the model may thus be regarded from a normative standpoint as suggesting caution with this kind of policies. Indeed, preserving the pre-commitment not to exclude from access to scientific findings that has for long been the distinguishing feature of Open Science appears more consistent with the characteristics of scientific knowledge.

4. Concluding remarks

The production of innovative knowledge is ever more frequently decentralized. Understanding the implications in terms of incentives of alternative arrangements disciplining access to each of the separately developed inputs to a collective instance of knowledge creation is thus important for both organizational decisions and policy-making. In this paper, we have provided a framework for analyzing the choice between a strategy of exclusion-based appropriability and an ex-ante commitment not to exclude third parties from one's own intellectual assets (openness strategy) in a context of contractual incompleteness. The framework's key advantage is that it allows to jointly consider two aspects of knowledge production that, though empirically relevant, tend to be neglected in most theoretical analyses, namely: (a) the complementarity among contributions to a common knowledge input; and (b) the complementarity between investment in the common input and

that government ownership would result in under-exploitation.

[14] Within this context, the U.S. Court of the Federal Circuit has concluded, in the well-known case *Madey vs. Duke*, that universities (and, of course, their scientists) are in the business of doing research and that therefore, as any other business, they should take out licenses on the patented material they are willing to use.

investment in a privately appropriable component. Our main conclusion is that, when the degree of complementarity is sufficiently high, an ex ante commitment not to exclude from access to one's intellectual assets may provide greater incentives than a strategy of exclusion. This conclusion on the relative ineffectiveness of IP-based exclusion as an incentive mechanism is reached under conditions that are particularly favourable to IP, namely the assumption that ex-post bargaining for one's share of surplus from the common input comes at no cost. Taking into account ex post transaction costs and monopoly deadweight losses would in all probability strenghten our result.

The two applications of the model presented in the paper—Open Source Software and the production of scientific knowledge under the Open Science system—do not exhaust the range of possible applications. By way of example, consider that many on-line collaborations of various sorts may fit the hypotheses of the model, as well as the allocation of IPRs within Research Joint Ventures[15]. Thus, the model has a number of empirical implications that it would be worth investigating.

Needless to say, the model suffers from some limitations. First, it does not address the issue of the comparison of the innovative performance of centralized and decentralized systems of knowledge production. In principle, within a centralized system, incentives for all of the agents making innovative investments could be appropriately adjusted to obtain results akin to those obtained through the combination of openness and decentralization. However, centralization also entails costs, and in many cases it is not a viable solution. The coexistence of large centralized companies and decentralized forms of organization in the same environment, e.g. OS and proprietary forms of software production, suggests that centralization and openness may represent alternative ways to coordinate individual efforts, characterized by strengths and weaknesses whose analysis is outside the scope of this paper.

Second, in considering the applicability of the model's results it should be stressed that they have been obtained in a setting characterized by symmetric agents. Considering asymmetric agents may bring further insights and it may possibly change some implications of the model.

The third, more relevant, limitation concerns the fact that we assume that the profits of the agents contributing to the common input are independent one from the other. Indeed, there are reasons to think that profits will actually tend to be negatively correlated. Contributors to the common input may, for instance, compete for a fixed amount of research funds or compete in the same final market. Considering the possibility of negative correlation of profits appears, *prima facie* to reduce the convenience of the "openness" solution. However, this is not at all

[15] In this regard, the model presented in the previous sections allows to compare the effects of two extreme alternative arrangements allocating the IPRs over the partnership's innovative outcomes and offers insights that may be regarded as both positive and normative. On the positive side, it suggests that we should observe the choice of an IPRs arrangement that implements a precommitment not to exclude when the two conditions identified in the model are verified. On the normative side, it suggests that the choice of this type of IPRs arrangement should be made if these conditions hold, so as to provide greater incentives to invest than it is the case under alternative IPRs arrangements.

obvious, as sufficiently strong offsetting factors such as, for instance, the existence of network externalities, may well come into play. To fully grasp the implications of modifying the assumption of independence of profits, a thorough analysis would be necessary.

In spite of these limitations, we think that this paper offers a valuable contribution to the understanding of decentralized forms of knowledge production.

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