Bureau
d'économie
théorique
et appliquée
(BETA)
UMR 7522

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Document de travail n° 2005–**10**

Mai 2005

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Open knowledge disclosure, incomplete information and collective innovations

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This draft: April 2005

Abstract

Why do firms decide sometimes to disclose widely part of their knowledge while they could have kept it secret ? We attempt to provide an original answer to this question by combining the literature in economics of innovation and in economics of incomplete information. We suggest that such practices of open knowledge disclosure can be deliberate strategies aiming at solving adverse selection problems that arise when firms try to find partners with whom to cooperate in R&D. Competent firms can sometimes think it a profitable strategy to disclose knowledge because this disclosure may allow them to display their differences with less competent firms, thus making it easier to start a profitable collaboration with other competent firms. We illustrate this intuition with the help of a signalling game under incomplete information.

Key-words : open knowledge disclosure, signalling, adverse selection, innovation network, R&D collaboration, collective invention.
JEL classification : L0

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I. Introduction

Although the firm is central to economics and has been the focus of a tremendous number of studies, many questions regarding firms' behaviours remain unanswered. In particular, it is still unclear why firms sometimes choose to disclose widely some of their knowledge that, once disclosed, benefits other firms including competitors. Yet, it is indisputable that behaviours of knowledge disclosure occur in reality and that firms often prefer to voluntarily release their knowledge rather than to keep it secret. The objective of this paper is to investigate the motivations that may induce rational profit-seeking agents to disclose knowledge. We insist specifically on the reputation that stems from knowledge disclosure and that can ease the formation of R&D collaborations with other firms and with public institutions, thus increasing the R&D performances of disclosing firms.

Our interest in this paper lies in a particular kind of knowledge disclosure, namely open knowledge disclosure, which we distinguish from closed knowledge disclosure[1]. We define open knowledge disclosure as a situation in which a firm chooses deliberately to disclose part of her knowledge, without receiving any direct compensation (monetary or not) for this disclosure and without being able to prevent a given agent from accessing the disclosed knowledge. In other words, three dimensions count to characterise open knowledge disclosure: The disclosure must be voluntary (i.e. the firm could have kept the disclosed knowledge secret during some time), it must be free (i.e. not directly remunerated) and it must be open (i.e. not restrained to some well-specified recipients). The distinction between open and closed knowledge disclosure is essential because the motivations that induce firms to adopt these two kinds of behaviours are completely different. Behaviours of closed knowledge disclosure are usually based on exchanges and reciprocal agreements and therefore are closer to patterns of informal cooperative R&D and of knowledge trading than to pure knowledge disclosure.

Open knowledge disclosure are frequent behaviours: Firms allow their researchers to publish in scientific journals and to present their work in conferences, they apply for patents

[1] Basically, the difference between these two concepts deals with the terms of access to the disclosed knowledge. When the sender can choose exactly to whom he wants to disclose his knowledge (i.e. when he can prevent some agents from accessing the disclosed knowledge) then the disclosure is said to be closed. Conversely, when the sender cannot exclude a given agent from learning the disclosed knowledge then the disclosure is considered as open. Closed knowledge disclosure may occur through common practice, training of employees of other firms, exchange of employees, meetings, visits of factories, exchange of materials (software for instance), etc.

without planning to use the property rights associated with patents[2], they release information on their web sites, etc. The fatherhood of the literature on open knowledge disclosure is usually granted to Allen (1983), who noticed that many knowledge exchanges occurred within the blast furnace industry in the district of Cleveland (UK) between 1850 and 1875. Allen explained that new innovations and their degrees of performance were made available to other firms of the district (hence including rival firms) in scientific publications and during conferences and meetings organized by the engineering association. Since Allen's pioneer study, many other authors have emphasized the fact that firms often let their researchers publish in scientific reviews (Koenig, 1983; Henderson and Cockburn, 1994; Hicks, Ishizuka, Keen and Sweet, 1994; Hicks, 1995; Hicks, Isard and Martin, 1996; Cockburn and Henderson, 1998; Lim, 2000).

Firms are, by definition, not directly remunerated by openly disclosing knowledge. Furthermore, open knowledge disclosure is a costly activity, mostly because it means providing competitors with helpful knowledge that will enable them to improve their technology and to compete more fiercely with the disclosing firm. This sole cost may frequently deter firms from openly disclosing knowledge. Other costs involve the codification of the disclosed knowledge (which must be articulated and expressed into a language) or the fact that the support through which the diffusion is operated may not be free.

At first sight common wisdom suggests therefore that firms will not release precious information to competitors for free but will rather try to protect their new innovations by keeping them secret as much as possible. In the past open knowledge disclosure was often misunderstood by industrial economists, who attributed knowledge flows essentially to spillovers, i.e. to undesired knowledge leakages, to altruism or even to a kind of lack of rationality from the disclosing firms, thus considering that, from an economic point of view, disclosing firms make a mistake by releasing their knowledge for free. But nowadays it is no

[2] When firms apply for a patent they must provide a detailed description of the innovation they want to patent, which must be detailed enough to allow a person aware of the state-of-the-art to reproduce the patented innovation. Once the patent is granted, and in some countries even if the patent is not granted, this description is published, meaning that everybody has free access to it. Hence patents admit a disclosure dimension. What is more controversial is that firms apply for patents because they want to disclose knowledge. It is indeed usually assumed that firms consider the fact that the knowledge underlying their patented innovation must be revealed as a constraint that they must accept in order to be granted a monopoly right. Yet, recent empirical studies provide several insights tending to support that the knowledge disclosure property of patents may not always be viewed as a constraint (Levin *et al.*, 1987; Mazzoleni and Nelson, 1998; Cohen, Nelson and Walsh, 2000; Jaffe, 2000; Hall and Ziedonis, 2001).

longer possible to argue, as Allen did 20 years ago[3], that economists have neglected the fact that rational firms may benefit from disclosing their knowledge. In the last two decades open knowledge disclosure has been the topic of notable economic studies and wide ranges of indirect mechanisms that can make a strategy of open knowledge disclosure profitable for disclosing firms have been investigated (Pénin, 2003).

For instance, it has been suggested that firms may be induced to reveal widely some of their knowledge in order to provide motivation to their researchers. Indeed, for firms, the only way to attract famous researchers is often to allow them to publish because these researchers value as much their reputation than their salary. Open knowledge disclosure may also be a device aiming at controlling researchers' productivity.

von Hippel (1987) used a very basic result of game theory in order to explain behaviours of open knowledge disclosure. He showed that open knowledge disclosure may be rational in a game infinitely repeated, even though it is not if the game is not repeated. The repetition of events allows therefore explaining open knowledge disclosure behaviours like tacit agreements of reciprocity. Notice however that Eaton and Eswaran (2001) tempered slightly von Hippel's optimistic conclusions by showing that in repeated games the properties of indivisibility of the innovations and of stochasticity of the innovation process undermine the existence of disclosure behaviours. In other words, the less divisible the knowledge and the more stochastic the innovation process, the less firms are encouraged to reveal.

De Fraja (1993) considered the problem of knowledge disclosure by using the framework of a patent race in which the winner does not take all (meaning that laggards also profit from the innovation). Within such a framework, and given the uncertainty and the cost of the race, De Fraja showed that there exists a non-cooperative Nash equilibrium for which one firm or more may decide to disclose some knowledge in order to shorten the race and to decrease the costs that it involves.

Knowledge disclosure may also be encouraged by the willingness to trigger network effects either by increasing the use of a given technology (which may be profitable if the value of this technology increases with the number of firms using it; for instance, more user firms may allow those firms to benefit from cheaper inputs) or by allowing compatibility for a

[3] Allen explained that: "Essential feature of collective invention was the release of technical information to actual and potential competitors […] To the degree that economists have considered this behaviour at all, it has been regarded as an undesired "leakage" that reduces the incentives. That firms desire such behaviour are possibilities not yet explored. They should be." (Allen, 1983, p. 21).

given product (which may be profitable if the value of this product increases with the number of consumers) (Boivin, 2000).

Harhoff (1996) suggested that firms in upstream sectors may be induced to openly disclose valuable information with the purpose to expand the production in downstream sectors and therefore to enhance the demand of production factors addressed to suppliers in upstream sectors, which in turn may increase the profitability of the firm who disclosed.

Using a similar, but reverse, reasoning, Harhoff, Henkel and von Hippel (2003) suggested that innovators in downstream sectors may also benefit from openly disclosing their knowledge. Indeed, the knowledge disclosed by firms in downstream sectors may profit to suppliers in upstream sectors, who can then use it to improve their products. If these improvements are then sold to users in downstream sectors, the firm who disclosed may be largely rewarded under the form of better quality, and/or better adapted, inputs at a lower price, i.e. under the form of pecuniary spillovers.

Finally, Maret (2003) gave an original explanation to behaviours of open knowledge disclosure by assuming that the process of knowledge codification both increases knowledge disclosure and allows to increase the firm own absorption capacity (since codification is a learning process). It follows that firms may have incentives to codify and hence to disclose their knowledge because this codification means more ability to absorb external knowledge[4].

This paper is path breaking with the existing literature that explores the rationales of open knowledge disclosure in that it explains open knowledge disclosure by combining the literature on economics of information (and more specifically of incomplete information) and the literature on economics of innovation. The innovation process is worth being examined under the light of the literature on incomplete information because it is widely considered by scholars as a collective process, i.e. it is likely to be impeded by adverse selection problems. Innovation is a collective process in the sense that one single person or one single firm hardly has the ability to innovate alone. Economic agents (firms, universities, banks, patent offices, etc.) must cooperate, must set up formal research joint ventures (RSV) or more informal collaborations in which they have the possibility to exchange some of their knowledge and to

[4] Notice that the assumption of Maret that knowledge codification automatically implies disclosure is still vividly debated among scholars. Many authors believe indeed that codification does not mean to break secrecy. It is even argued sometimes that to codify knowledge is a way to improve the appropriation of this knowledge. Hence, conversely to what is assumed by Maret, it is also possible that firms decide to codify knowledge in order to improve their absorption capacity, without necessarily implying a disclosure of this knowledge.

share specific competences. R&D collaborations are especially important to access sticky knowledge held by partners and which would not be available otherwise. Indeed, far from being a public good available to everybody, as traditionally argued in economic textbooks, knowledge usually flows only within clubs and is accessible only to members of the club. Therefore, firms who want to access particular pieces of knowledge must develop collaborations with the owners of these pieces of knowledge, they must be granted access to the network of agents in which knowledge is flowing[5].

Yet, as many processes that involve exchange, cooperation and human interactions, knowledge production is likely to be subject to problems of incomplete information. An important question that firms involved in the collective process of innovation have to address is finding the most appropriate partners. Firms do not know exactly the competences of potential partners and therefore they may not be able to infer whether or not a partnership is profitable. For instance, how can a firm localise potential successful partnerships? How (based on which criteria) can she distinguish profitable partnerships from less profitable ones?[6] These problems of adverse selection may severely damage the collective process of innovation (Akerlof, 1970).

In order to solve those problems of adverse selection, firms may therefore be induced to implement strategies aiming at decreasing the risk of cooperating with inappropriate partners. And it is well-known in economics of information that "signalling" may be an efficient strategy to solve adverse selection problems (Spence, 1973). Consequently, competent firms who are looking for partners with whom to cooperate in R&D can sometimes think it a profitable strategy to disclose some of their knowledge, even the most valuable, in order to signal their know-how to the industrial and academic communities, thus breaking the adverse selection problems and facilitating R&D collaborations with other firms or with public institutions. Firms who reveal knowledge may be able to find partners more easily because the disclosure reduces the uncertainty regarding their competences. In other words, we argue in this paper that, by openly disclosing knowledge, firms may want to signal to other

[5] Gibbons (1994, p. 165) explained that: "knowledge production and knowledge appropriation converge. The outcomes are likely to be commensurate with the degree of involvement. Only those who take part in knowledge production are likely to share its appropriation". Johnson and Lundvall (2001, p. 12) added: "Reality is complex and most knowledge is neither completely public nor completely private. The knowledge base is fragmented and constituted by semi-public "pools" to which access is shared regionally, professionally and through networking".

[6] Foray (2000, p. 99) argued that: "The abundance of knowledge leads to a problem of localisation of relevant knowledge for firms. If the probability that this knowledge exists and is stocked somewhere is high, the probability that firms do not find where it is stocked is also very high" (quotation originally in French. The translation is mine).

firms that they hold specific competences, thus indicating that it is worth collaborating with them[7]. This explanation of open knowledge disclosure in terms of signalling is similar to the one proposed by Hicks (1995, p. 411) who argued that: "publications aid networking and facilitate collaboration […] they help to raise the image in the academic and scientific community […] they are a ticket to an information network".

We illustrate our point by using a formalisation taken from the literature on game theory under incomplete information that goes back to the works of Akerlof (1970), Spence (1973), Selten (1975) and Kreps and Wilson (1982). We consider a model with three firms who must choose a partner with whom to collaborate in R&D but who do not know the competences of their potential partners. We assume also that during the process of finding a partner firms can disclose some of their knowledge in order to provide indication about their level of competences. We solve this signalling game of incomplete information by using the concept of perfect Bayesian equilibrium (PBE). Among other results, we are able to show that under specific conditions PBE that support the existence of behaviours of open knowledge disclosure exist and we can identify some conditions under which those behaviours may arise.

The remaining of this paper is structured as follows. In the next part we present the model which, although far too simple to pretend describing the complex reality of things, may provide useful insights about the basic forces at work when knowledge is openly disclosed. Then we discuss the economic implications of this model and we draw comparisons with results obtained in other works. We conclude with extensions for future studies.

II. A model of signalling with three firms

Consider three firms *A*, *B* and *E*. Firms *A* and *B* are rival firms (i.e. are competitors in the same product market) whereas firm *E* does not compete with them (firm *E* is therefore supposed to be located in another product market). Yet, firm *E* must decide whether or not to collaborate in R&D either with firm *A* or with firm *B*[8]. Furthermore, we assume that firms *A* and *B* can be of two different types: They can be competent in the technological domain that

[7] The following metaphor may help the understanding of the point we make here. Mansfield and Mansfield (1993) argued that building an absorption capacity is equivalent, for firms, to open a window on the outside world in order to see what other firms are doing. To this respect, firms may openly disclose knowledge in order to be seen by the people who watch through the window.

[8] We assume that a collaboration between the three firms is not possible due, for instance, to antitrust regulations that prevent the two firms that are in the same market from being member of the same venture. Notice further that firm *E* can also choose to refuse to collaborate with both firms.

interests firm *E* (type 1) or not competent, or rather less competent, in the technological domain that interests firm *E* (type 2)[9]. For simplicity, we assume that one firm is of the competent type and one is of the less competent type, that firm *E* knows this fact but does not know which firm is competent. The a priori probability that each firm is of the competent type is ½. Finally, we assume that for firms *A* and *B* profits without collaboration with firm *E* are the following:

If firm *i* is of the competent type: $\pi_i = \pi_1 = \delta_1 k_1 - \alpha\delta_2 k_2 \quad (i=A,B)$,

If firm *i* is of the less competent type: $\pi_i = \pi_2 = \delta_2 k_2 - \alpha\delta_1 k_1 \quad (i=A,B)$,

in which $\alpha \geq 0$ reflects the intensity of competition between firms *A* and *B*, $\delta > 0$ reflects firms' ability to transform knowledge into cost reductions and hence into profits and k stands for the overall stock of knowledge held by firm *i*. We do not assume any knowledge spillovers, which would imply that the stock of knowledge of one firm has a positive effect on other firms' profits.

Benefits arising from R&D cooperation among firms come from an increase of their knowledge stock[10]. As firm *i* cooperates with firm *j* we posit that her knowledge stock becomes $k_i^j \geq k_i$. Indeed, although firm *E* is not in the industry of firms *A* and *B*, the three firms may nevertheless share some technological characteristics, i.e. by collaborating they may acquire some new knowledge[11]. On the other hand, cooperation between firms *i* and *j* is also likely to involve some costs c_i^j , to acquire compatibility, for instance. Hence, whatever the type of firms *A* and *B*, if firm *i* cooperates with firm *E* her profits become:

$$\pi_i^E = \delta_i k_i^E - \alpha\delta_j k_j - c_i^E ,$$

And if firm *i* cooperates with firm *E*, firm *j* profits become:

$$\pi_j^{E,i} = \delta_j k_j - \alpha\delta_i k_i^E < \pi_j .$$

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[9] The adjective "competent" does not refer to an absolute level of competence. Rather, it is meaningful only relatively to cooperation with firm *E*, i.e. firms of type 1 are competent in the technological domain that interests firm *E* in the sense that cooperation with this type of firm is better for firm *E* than cooperation with firms of the other type. Hence, it is quite possible that some firms, who are qualified as not competent in our model, are, all technologies accounted for, more competent than firms, who are qualified as competent.

[10] R&D collaboration allows increasing firms' stock of knowledge because *(i)* it opens access to sticky knowledge held by other firms and which requires common practice to be transferred and *(ii)* it increases research efficiency by allowing a more efficient division of labor and by decreasing both the risks and the costs of doing research.

[11] The fact that firms *E*, *A* and *B* are not rival firms but use similar technologies and thus work on similar research projects can hardly be considered as surprising. It is usual to observe firms from different sectors sharing the same technology: For instance, IBM and Airbus both use electronic technology; Bayer, Aventis and Total-Elf-Fina all use chemical technology, etc.

Where π_i^j stands for firm *i*'s profit if she cooperates with firm *j* and $\pi_i^{E,j}$ stands for firm *i*'s profit if firm *j* cooperates with firm *E*. For simplicity, we assume further that profits after collaboration satisfy the following restrictions:

For firm *E*: $\pi_E^1 > \pi_E > \pi_E^2$,

For both firms *A* and *B* and whatever their type: $\pi_i^E > \pi_i$

In other words, we consider a situation in which firm *E* must decide whether or not to cooperate in R&D with firms *A* or *B*, who are possibly of two types: Either competent or less competent. Firms *A* and *B* whatever their type have an interest to cooperate with firm *E* but firm *E* has an interest to cooperate only with a firm of the competent type. Yet, firm *E* does not know the type of the two firms she is facing (does not know whether firm *A* or firm *B* is competent but knows the probability that each firm is competent) and hence she does not know with whom cooperation is profitable (while we assume that firms *A* and *B* know that cooperation with firm *E* is profitable[12]). Therefore, the problem for firm *E* is to infer the type of firms *A* and *B*. Here we can already stress a very basic result of the economics of incomplete information (Akerlof, 1970):

Lemma 1: Compared to a situation of complete information in which firm *E* knows the type of firms *A* and *B*, the existence of incomplete information in the cooperation process tends to:

(1) Penalize firm *E* (the non-informed firm), since under incomplete information there is a risk that firm *E* accepts to cooperate with a firm that is of the less competent type (i.e. it would have been more profitable to refuse cooperation) or, conversely, there is a risk that she refuses to cooperate with a firm that is of the competent type (i.e. it would have been profitable to accept cooperation).

(2) Penalize the firm of the most competent type, since under incomplete information this firm, although more competent than her rival and perfectly informed, may be driven out of the cooperation process if she cannot prove to firm *E* that she is of the competent type. Furthermore, the presence of incomplete information within the process of R&D cooperation may also allow cooperation between firm *E* and less

[12] For sake of simplicity we still assume that, although firm *E* does not know firm *A*'s competences, firm *A* knows firm *E*'s competences. This assumption holds, for instance, if firm *E* has been the leader in her industry for years, if firm *E*'s researchers are famous or if firm *E* has been granted several important patents. Examples of this kind of situation in which there is an asymmetry of information between two firms who are looking to cooperate in R&D are many: As big-pharmaceutical firms try to cooperate with small biotechnology firms, as firms such as Microsoft or IBM try to cooperate with small start ups, etc.

competent rivals, who otherwise would not have been given an opportunity to cooperate.

(3) Favour the firm of the less competent type, since under incomplete information this firm may be given a chance to cooperate with firm *E*, which could hardly happen if the latter was perfectly informed about her competences. Furthermore, incomplete information may also prevent rival firms of the competent type from cooperating with firm *E*.

Proof: very straightforward.

When information is incomplete it is hence likely that firm *E*, who is penalized by this situation, tries to restore a situation close to complete information. One way to do so would be to require, before accepting to collaborate with firms *A* or *B* that the latter send a signal of their competences in order to prove to firm *E* that they are of the competent type. The question we attempt to answer now is thus the following: Does it exist an opportunity for the most competent firm to be distinguished by firm *E* from firms of the less competent type? More specifically, we explore whether or not the possibility to openly disclose knowledge can help to solve those problems of incomplete information.

Assume therefore that firms *A* and *B* whatever their type, can choose to send a signal S_i to firm *E* prior that the latter decides whether or not to cooperate with one of them. For simplicity, we assume that firms have only two possible signalling strategies: Either they send a signal S_i or they do not send a signal (i.e. firms cannot choose the intensity of the signal). This signal of competences can take the form of scientific publications, patents or presentations in conferences. Furthermore, the signal sent by firm *i* must contain valuable knowledge in order to convince firm *E* that the sender is competent. Let us note k_i^s the knowledge disclosed by firm *i*[13].

The main cost that arises from openly disclosing knowledge is to provide useful knowledge to rival firms. If firm *i* decides to send a signal S_i , the disclosed knowledge k_i^s

[13] The signal must contain valuable knowledge even when it is emitted by less competent firms because publications in scientific reviews, presentations in conferences or patents must pass through a referring process, which should ensure the quality of the disclosed knowledge. Hence, if firm *i* wishes to publish, she is forced to reveal at least to some extent valuable knowledge in order to obtain the agreement of the referees. This referring process warrants, in some sense, that a minimal amount of knowledge is embodied in the signal. Therefore, we have here a potential lever for policy makers who could decide to ease or to take a harder line regarding the requirements to publish in scientific reviews or to be granted a patent.

embodied in this signal benefits the other firm who, depending on her absorption capacity, has the opportunity to use this disclosed knowledge in order to improve her technology and to reduce her production cost. When firm *i* chooses to send S_i , the stock of knowledge of her rival firm becomes therefore: $k_j+\beta_j k_i^s$, in which β_j reflects firm *j*'s $(i=1,2, j\neq i)$ absorption capacity (Cohen and Levinthal, 1989)[14, 15]. In other words, to send a signal is costly because the disclosed knowledge benefits rival firms. To openly disclose knowledge also involves other costs due, among others, to the necessity to codify knowledge prior to openly disclosing it (Pénin, 2003). Yet, those expenditures are often marginal compared with the cost that stems from the communication of helpful knowledge to competitors and hence they can be neglected without too much damage.

Before we go any further, two important assumptions of the model need to be underlined: First, we assume that firm *E* cannot absorb the knowledge disclosed by firms *A* and *B* ($\beta_E=0$). This assumption allows dismissing cases for which firm *E* would be able to improve her technology merely by observing the signal and thus would decide not to cooperate even if the observed signal is high. Second, we make the hypothesis that the knowledge disclosure is open, in the sense that firm *i* cannot prevent her rival firm from accessing the disclosed knowledge. At first sight, this hypothesis may not appear realistic in a model with only two agents, since in this case it is likely that firm *i* can communicate directly and exclusively with the firm to whom she wants to signal her knowledge (firm *E*). Yet, this assumption of openness is important because, in some sense, it is a way to give credibility to the signal in case of the eventual partner is not able to assess himself the value of the disclosed knowledge. The fact that everybody can access the disclosed knowledge ensures that the signal is not a fake.

To summarize, we have now a dynamic game with incomplete information in which firms *A* and *B* can eventually prove to firm *E* that they are of the competent type by disclosing some of their competences. The sequence of the game is the following: In the first period, firms *A* and *B* decide whether or not to reveal some knowledge (S_i or *0*). In the second period

[14] β_j reflects the fact that the extent to which the disclosed knowledge benefits other firms depends strongly on the ability of these firms to understand and manage the information embodied in the signal. Indeed, the signal provides only information about the technology but does not allow an immediate use of this technology. And there is still a long way to go from the reception of an information about how to solve a problem to the understanding of how to solve it oneself.

[15] The fact that knowledge released by a given firm may always benefit other firms means that firms *A* and *B* knowledge sets are considered as perfectly disjoined.

firm *E* observes firms *A* and *B* decisions of the first period and then chooses whether or not to cooperate with one of them (C_A, C_B or $\overline{C}$).

Technically, this signalling game of incomplete information can be solved by using the concept of perfect Bayesian equilibrium (PBE) introduced by Spence (1973), Selten (1975) and Kreps et Wilson (1982)[16]. In our problem of R&D cooperation, a PBE requires that: *(i)* Firm *E* has some beliefs regarding the type of the firm who emits a signal *S*; *(ii)* Firm *E* takes her decision to cooperate according to these beliefs; *(iii)* Firms *i* signalling decisions correspond to firm *E*'s beliefs.

Let us consider the following beliefs for firm *E*: If firm *i* plays *S* and firm *j* does not then firm *E* believes that firm *i* is of the competent type. Hence, if firm *i* plays *S* and firm *j* does not firm *E* will choose to cooperate with firm *i*. Otherwise, if neither firm *A* nor firm *B* or if both firms *A* and *B* disclose their knowledge, firm *E* believes that they are competent each with a probability of one half and she chooses either to cooperate with firms *A* and *B* each with probability ½ or not to cooperate at all (this decision is function of the comparison of π_E with $\frac{1}{2}\pi_E^1+\frac{1}{2}\pi_E^2$). In other words, we assume that from the viewpoint of firm *E* all the observed signals are identical. Firm *E* does not make any distinction between k_1^s and k_2^s[17]. This assumption is consistent with our former hypothesis that firm *E* cannot absorb knowledge openly disclosed by firms *A* and *B* $\left(\beta_E=0\right)$.

Building over this framework, which is summarized in the figure in appendix 4, it is possible to stress the following propositions (we are only interested in PBE for which behaviours of open knowledge disclosure may arise):

Proposition 1: Consider firm *E*'s beliefs as described above. Under *conditions 1* and *2* below, there exists a separating PBE for which firm *i* decides to disclose knowledge if and only if she

[16] For an introduction to signalling game under incomplete information see Tirole (1988), Fudenberg and Tirole (1991), Gibbons (1992) and Salanié (1994).

[17] The fact that firm *E* cannot make any distinction among the disclosed knowledge allows interpreting k_i^s as the minimal amount of knowledge required to publish in a scientific review or to be granted a patent. Indeed, given firm *E*'s beliefs, firms *i* have no interest to disclose a higher amount of knowledge than k_i^s since this would be costly and this would have no impact on firm *E*'s decision to cooperate or not with them.

is of the competent type and for which firm *E* chooses to cooperate with firm *i* only if the latter discloses her knowledge[18].

(condition 1) $k_1^S \leq \frac{\delta_1\left(k_1^E - k_1\right) + \alpha\delta_2\left(k_2^E - k_2\right) - c_1^E}{2\alpha\delta_2\beta_2}$

(condition 2) $k_2^S > \frac{\delta_2\left(k_2^E - k_2\right) + \alpha\delta_1\left(k_1^E - k_1\right) - c_2^E}{2\alpha\delta_1\beta_1}$

Proof: Given in Appendix 1.

Condition 1 ensures that, given firm *E*'s beliefs, firm *i* chooses to play *S* if she is of the competent type. *Condition 2* ensures that, given firm *E*'s beliefs, firm *i* does not play *S* if she is of the less competent type. Hence, under both *conditions 1* and *2* firm *i* chooses to disclose knowledge if and only if she is of the competent type, i.e. we have a separating PBE. Firm *E*, by observing the signal, can infer whether firm *i* is competent or not. This situation, in which firms can send a signal of their competences, always favours firm *E*, but it may not always benefit firms *A* and *B* even if they are of the competent type. When the signal is costly the competent firm may sometimes prefer a situation of incomplete information without signalling possibility.

To summarize, there may exist a PBE for which only competent firms disclose knowledge, thus enabling other firms to infer the competences of disclosing and non disclosing firms. Moreover, proposition 2 below states that, in our model, there does not exist a possibility for less competent firms to be the only firms to disclose knowledge. Finally, proposition 3 stresses that there also exists a PBE for which both types of firms disclose their knowledge.

Proposition 2: There does not exist a separating PBE for which only the firm of the less competent type discloses her knowledge.

Proof: Given in Appendix 2.

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[18] Conditions 1 and 2 have been computed under the assumption that $\frac{1}{2}\pi_E^1 + \frac{1}{2}\pi_E^2 \geq \pi_E$. If we assume that this restriction is not fulfilled then we have the two following conditions:

(condition 1') $k_1^S \leq \frac{\delta_1\left(k_1^E - k_1\right) - c_1^E}{\alpha\delta_2\beta_2}$ (condition 2') $k_2^S > \frac{\left(k_1^E - k_1\right)}{\beta_1}$

Proposition 3: Under the three conditions below there also exists a pooling PBE in which firms *A* and *B*, whatever their type, choose to disclose their knowledge and in which firm *E* decides to cooperate with firms *A* and *B* each with a probability ½[19].

(condition 1) $k_1^S \leq \frac{\delta_1\left(k_1^E - k_1\right) + \alpha\delta_2\left(k_2^E - k_2\right) - c_1^E}{2\alpha\delta_2\beta_2}$

(condition 3) $k_2^S \leq \frac{\delta_2\left(k_2^E - k_2\right) + \alpha\delta_1\left(k_1^E - k_1\right) - c_2^E}{2\alpha\delta_1\beta_1}$

(condition 4) $\frac{1}{2}\pi_E^1 + \frac{1}{2}\pi_E^2 \geq \pi_E$

Proof: Given in Appendix 3.

This proposition stresses that, under specific conditions, there may exist a PBE in which both competent and less competent firms choose to disclose knowledge, i.e. the presence of incomplete information may lead all types of firms to openly disclose knowledge in order to prove or to try to dissimulate their type to the principal. In this case the signal is not informative. It is of little utility for firm *E* who cannot infer the type of firms *A* and *B* by observing their decision in the former period.

III. Discussion and economic implications

The main result stressed by our model is that there exist parameter values that support the existence of PBE, either pooling or separating, in which open knowledge disclosure occurs, i.e. strategies of open knowledge disclosure aiming at breaking adverse selection problems may pay in an environment of incomplete information and it may be fully rational for firms to openly disclose knowledge in order to ease collaborations with other firms. This finding is in line with several empirical observations.

Von Hippel (1988, p. 77), for instance, explained that: "[knowledge] trading networks appear to be formed and refined as engineers get to know each other at professional

[19] Conditions 1, 3 and 4 have been computed under the assumption that $\frac{1}{2}\pi_E^1 + \frac{1}{2}\pi_E^2 \geq \pi_E$. If we assume that this restriction is not fulfilled then we have the three following conditions that must hold to ensure the existence of a PBE in which both firms *A* and *B* disclose knowledge. In this case both firms *A* and *B* disclose their knowledge even though they know that firm *E* will not collaborate with them.

(condition 5) $\frac{1}{2}\pi_E^1 + \frac{1}{2}\pi_E^2 < \pi_E$, *(condition 6)* $k_1^S \leq \frac{\left(k_2^E - k_2\right)}{\beta_2}$, *(condition 7)* $k_2^S \leq \frac{\left(k_1^E - k_1\right)}{\beta_1}$

conferences and elsewhere. In the course of such contacts, an engineer builds his personal informal list of possibly useful expert contacts by making private judgments as to the areas of expertise and abilities of those he meets". This clearly points out the role of conferences, and other meetings in which firms disclose knowledge, in order to improve firms' awareness of the competences of other firms and, *in fine*, in order to develop collaborations with other firms.

The role of open knowledge disclosure in the collaboration process was also emphasised by Grossetti and Bès (2002), who explored the ways through which 110 R&D collaborations were initiated in France between firms and public labs. They consider basically that there are three main ways through which R&D collaborations can start[20]: The first is called the "logic of market". It is when collaboration results from a link established through scientific publications or public conferences, meaning that partners have heard about each other following a publication or a conference. The second is called "the logic of personal network". It is when collaboration results from former existing personal relationships between the two parties (see for instance, the work of Granovetter, 1973 and 1974, dealing with the importance of weak ties to connect people)[21]. The third way to initiate collaboration is the "logic of institutions". In this case collaboration is initiated by a public institution that puts the different actors in touch[22]. Overall, the empirical inquiry done by Grossetti and Bès indicates that for 42 collaborations out of 110 the contact resulted from a "logic of market", for 48 collaborations it stemmed from a "logic of network" and for the 20 remaining collaborations from a "logic of institutions". The "logic of market" to initiate collaborations is specifically important when firms and labs are not located in the same region. Indeed, when the partners are located in the same region "the logic of network" works in 60% of collaborations and "the logic of market" in only 20%. Conversely, when partners are not located in the same region

[20] It is possible to draw an analogy between the different ways to initiate R&D partnerships and those to match employers and workers on the job market. In the latter case, it is also usually considered that there are three main ways to match employers and workers: *(i)* The signalling way, which was formalized by Spence (1973) in its seminal paper and in which employers hire employees on the basis of a signal, such as higher studies for instance; *(ii)* The network way in which workers and employers are matched through network relationships (a common friend, a family member, etc.) (Sylos Labini, 2004); *(iii)* The institutional way, in which public institutions (like ANPE in France) match employers and workers.

[21] Notice that in this case the personal network is already structured and nothing is said about how it was formed. It is however quite likely that open knowledge disclosure, i.e. the logic of market, played an important role in developing the personal network of the firm.

[22] It is possible to add to this list a fourth way to initiate R&D collaborations that was not considered by the authors and that we may call the logic of chance. Indeed, it must not be neglected that in every process of search there is an important part of chance that plays in order to match partners.

the logic of market works in 59% of cases and the logic of network in 24%. This study tends therefore to give some strength to the hypothesis we defend here, since it suggests that participation to conferences or publications can be efficient devices to initiate R&D collaborations.

Hicks (1995) stressed that publishing signals the existence of un-publishable resources, meaning that open knowledge disclosure may indicate to potential partners that the sender possesses competences that have not been disclosed. Hicks (1995, p. 401) wrote that: "Publishing mediates links with other organizations, serving to signal the presence of tacit knowledge and to build the technical reputation necessary to engage in the barter-governed exchange of scientific and technical knowledge". Gambardella (1992) also noticed that successful pharmaceutical firms are like academic departments in the sense that they implement a policy of open science by allowing their scientists to publish their work. He added that this openness is viewed as a necessary condition to gain access to valuable sources of external knowledge by entering inner circle of scientific communities (see also Callon, 1998; Cockburn and Henderson, 1998). Finally, the positive impact of strategies of open knowledge disclosure on the formation of collaborations was raised recently by Fontana, Geuna and Matt (2004) in an econometrics study.

At this step, a central question remains open: What are the conditions that support the emergence of behaviours of open knowledge disclosure? Even if the greatest care must be adopted, our model can provide some insights to answer this question.

For instance, a separating PBE in which only competent firms choose to reveal requires that, all other things being held equal, the degree of competition among firms must be bounded upward and downward. If competition is too sharp then competent firms may choose to keep their knowledge secret whereas if it is too low then less competent firms may also choose to reveal, which will undermine the existence of the equilibrium. For the same reason, it also requires that, all other things being held equal, the absorption capacity is not too strong for less competent firms but is strong for competent firms. The technology (the extent to which firms transform their knowledge into costs reduction and profits) must also not be too efficient for less competent firms while it must be efficient for competent firms. Moreover, the extent to which cooperation with firm E is profitable to competent firms must remain relatively high while it must be relatively low for less competent firms (in particular, this implies that the cost of acquiring compatibility with firm E remains acceptable for competent firms but is high for less competent firms in order to deter them to reveal). Last, but not least, k_1^s, which may be interpreted as the minimum level of knowledge that the competent firm

must accept to disclose in order to be allowed to publish in a scientific journal or to be accepted in a conference, must remain low. Conversely, k_2^s must be relatively high. Indeed, the higher the requirements about the disclosure the less firms are encouraged to reveal, all other things being held equal, since this disclosure has no positive effect while it is costly. In terms of policy implications, this means that editors must be careful to keep the requirements to get published in scientific journals not too high nor too low.

Our results can be compared with those stressed by other studies that deal with knowledge disclosure. For instance, the effect of competition on the emergence of disclosing behaviours was already raised by Allen (1983), who argued that knowledge disclosure may often be triggered by the fact that competition is weak and hence that to provide other firms with relevant information is not damaging for disclosing firms. Overall, this competition effect was raised by most of the studies on the topic. Our model adds to this analysis the fact that if competition is too weak then all firms may decide to disclose their knowledge thus undermining the existence of a separating equilibrium. In this case the signal looses its primary role, which is to allow disclosing firms to be distinguished from other firms.

Harhoff *et al.* (2003) considered a simple model of open knowledge disclosure with one manufacturer firm and two user firms, in which the latter may decide to openly disclose knowledge in order to trigger pecuniary spillovers from the manufacturer firm. In this framework they identify three variables that have an impact, either positive or negative, on users' decision to disclose or not their knowledge. All other things being held constant, the degree of competition between user firms and the cost to adopt the improved input play negatively on the decision to reveal while the extent to which the manufacturer firm improves the product affects positively the decision to reveal. Finally, the degree of generality of the new technology, which reflects the extent to which the revealed technology is specific to the firm who discloses, has an undetermined effect on the decision to reveal or not.

Eaton and Eswaran (2001) focused on the effect of the indivisibility of knowledge and of the stochasticity of the innovation process on the decision whether or not to disclose knowledge. They found out that the less divisible the knowledge and the more stochastic the innovation process, the less firms are encouraged to reveal. The effect of the indivisibility of knowledge can also be underlined in our model. Indeed, as we emphasised earlier k_i^s is the minimal level of knowledge that must be disclosed in order to be published or accepted in a conference. We made so far the assumption that each agent can disclose exactly the amount of knowledge $k_i^s \ (i=1,2)$, i.e. that knowledge is a perfectly divisible good. This assumption can

be softened, which enables us to concur with the conclusions reached by Eaton and Eswaran. For instance, let us assume that firm *A* does not have the opportunity to disclose an amount of knowledge exactly equal to k_i^s because knowledge is not a perfectly divisible good. In such a case, firm *i* must reveal an amount of knowledge $k_i^{s'}$ such that $k_i^{s'} = \min_{k_i \geq k_i^s}(k_i)$. This means that the less divisible the knowledge, the higher the probability that firm *i* must send a signal far above k_i^s, i.e. the higher the probability that firm *A* decides not to disclose it.

Finally, it is worthwhile noticing that our work suggests that the disclosure must remain, if possible, a signal that is hardly exploitable by other firms but that indicates clearly that the sender possesses other resources that have not been disclosed. Conversely to most studies on the topic in which disclosing firms want other firms to use the disclosed knowledge (De Fraja, 1993; Harhoff, 1996; Harhoff *et al.*, 2003), in our model disclosing firms only aim at signalling their knowledge. It is hence likely that firms choose to reveal only knowledge that is not applicable by other firms. The difficulty of the exercise consisting for firms to disclose enough knowledge in order to send a strong signal but not as much knowledge as to enable other firms to reproduce the innovation. Yet, our explanation of open knowledge disclosure in terms of signalling does not exclude the disclosure of very valuable knowledge. It is indeed possible that firms decide to disclose core competences if they expect that the cooperation that may be triggered by this disclosure is worth it.

IV. Conclusion

This paper was a first attempt to provide an explanation to open knowledge disclosure behaviours by using the literature on incomplete information. It was proposed that the presence of adverse selection problems during the early stage of R&D cooperation may induce firms to openly disclose part of their knowledge in order to convince other firms or public institutions that it is worth beginning a collaboration in R&D with them.

We first established that, since innovation is a collective process, it is essential for firms who want to remain innovative to develop R&D collaborations. Specific emphasis was put on the importance of collaborations to access knowledge held by other firms. However, a major challenge for firms involved in this collaborative process is to identify appropriate partners. Indeed, we argued that since the process of finding competent partners with whom to cooperate in R&D occurs in an environment of incomplete information, firms may not be able to identify the partners that fit them best. This conclusion led us to focus on the role that open

knowledge disclosure may play in order to solve these problems of incomplete information. We showed, by using a signalling game under incomplete information, that due to adverse selection problems firms may be induced to disclose widely parts of their knowledge in order to signal their competences to potential partners (who would wonder whether or not to cooperate with the disclosing firm) and to facilitate cooperation in R&D. Indeed, to openly disclose knowledge constitutes unquestionably a way to enhance firms' reputation. Therefore open knowledge disclosure may be a powerful device to improve firms' position on the 'market to find R&D collaborations'.

We can therefore draw a link between open knowledge disclosure and the concept of closed knowledge disclosure or knowledge trading that was introduced at the beginning of this paper. It appears clearly in the above discussion that, due to the presence of adverse selection problems, open knowledge disclosure is a prerequisite to knowledge trading because it eases the entrance within clubs in which firms trade knowledge. Firms who openly disclose knowledge may increase their probability of developing R&D collaborations with other firms.

Several extensions of this model have not been considered here for sake of simplicity but may be worth investigating in future studies: For instance, we assumed that the principal's absorption capacity is always equal to zero. This assumption was convenient since it allowed dismissing cases for which a given firm reveals an important amount of knowledge but for which firm *E* has nevertheless no interest to cooperate with this firm because she can use alone the disclosed knowledge. To soften this hypothesis may enable to take into account situations in which firms would have to be careful not to reveal a too important amount of their knowledge to firm *E*.

We did not consider here the possibility to send fake signals that do not contain any useful knowledge and that only aim at misleading competitors. It is the role of the referee of a scientific journal or of the patent examiner to warrant the quality of the signal and hence to prevent misleading signal from emerging. Yet, if referees do not do a thorough work many scientific articles and patents will not contain valuable knowledge[23]. A framework that would take this feature into account would permit to underline more strategic behaviours.

It would also be interesting to specify a dynamic model that would last several periods and to consider more than two agents in order to make the assumption of open knowledge

[23] We learn in the French newspaper *les échos* that regarding patents in biotechnologies: "some patent offices tend more easily to accept a patent rather than to refuse it, all the more that in the former case they do not have to justify their decision. It is also the case that the examiner is remunerated only if the patent is accepted" (M. Ciprut, *Brevet : une réforme du système international en 2003* ?, "Les échos", 13.01.2003, translation is mine).

disclosure more realistic. Yet, such dynamic models with heterogeneous agents may be hard to resolve analytically. One could therefore use numerical simulations in order to investigate how such models behave (Muller and Pénin, 2004).

To conclude, it must be emphasised that the link between adverse selection and open knowledge disclosure can be extended to many situations. It is not only limited to situations for which firms attempt to set up R&D collaborations. For instance, our model may work in the following cases: As a government decides to distribute grants to encourage innovation within particular industries, as private investors decide to finance industrial projects, as graduate students choose their future employer, as a firm wants to take-over spin-offs or to enter new markets. In all these situations the principal must select between different contractors, each of them yielding different returns depending on their competences, which are usually unknown to the principal (at least partly). It follows that in all these situations the most competent firms may be induced to reveal widely some of their knowledge in order to reduce the problems caused by incomplete information and, for instance, to be granted public contracts or subsidies, to hire promising young graduate students, to gather capital on financial markets or to dissuade potential competitors from entering a given market.

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Appendix 1: Proof of Proposition 1

Given firm *E* beliefs, we have a separating PBE only if the competent firm plays *S* and the less competent firm does not, the two following conditions must hold: (1) the competent firm plays *S* given firm *E* beliefs and given that the less competent firm does not and; (2) the less competent firm does not play *S* given firm *E* beliefs and given that the competent firm does. Assuming that $\frac{1}{2}\pi_E^1+\frac{1}{2}\pi_E^2\geq\pi_E$ the first condition implies that:

$$\pi_1^E(S_1)\geq\frac{1}{2}\pi_1^E+\frac{1}{2}\pi_1^{E,2}$$

$$\Leftrightarrow \quad \delta_1 k_1^E-\alpha\delta_2\left(k_2+\beta_2 k_1^S\right)-c_1^E\geq\frac{1}{2}\left(\delta_1 k_1^E-\alpha\delta_2 k_2-c_1^E\right)+\frac{1}{2}\left(\delta_1 k_1-\alpha\delta_2 k_2^E\right)$$

$$\Leftrightarrow \quad k_1^S\leq\frac{\delta_1\left(k_1^E-k_1\right)+\alpha\delta_2\left(k_2^E-k_2\right)-c_1^E}{2\alpha\delta_2\beta_2} \qquad \textit{(condition 1)}$$

Still assuming that $\frac{1}{2}\pi_E^1+\frac{1}{2}\pi_E^2\geq\pi_E$, the second requirement implies that:

$$\pi_2^{E,1}(S_1)>\frac{1}{2}\pi_2^E(S_1,S_2)+\frac{1}{2}\pi_2^{E,1}(S_1,S_2)$$

$$\Leftrightarrow \quad \delta_2\left(k_2+\beta_2 k_1^S\right)-\alpha\delta_1 k_1^E>\frac{1}{2}\left[\delta_2\left(k_2^E+\beta_2 k_1^S\right)-\alpha\delta_1\left(k_1+\beta_1 k_2^S\right)-c_2^E\right]+\frac{1}{2}\left[\delta_2\left(k_2+\beta_2 k_1^S\right)-\alpha\delta_1\left(k_1^E+\beta_1 k_2^S\right)\right]$$

$$\Leftrightarrow \quad k_2^S>\frac{\delta_2\left(k_2^E-k_2\right)+\alpha\delta_1\left(k_1^E-k_1\right)-c_2^E}{2\alpha\delta_1\beta_1} \qquad \textit{(condition 2)}$$

Furthermore, in the case where $\frac{1}{2}\pi_E^1+\frac{1}{2}\pi_E^2<\pi_E$, i.e. in the case where firm *E* refuses cooperation with both firms *A* and *B* whether the latter both signal their knowledge or whether none of them signal it, conditions 1 becomes:

$$\pi_1^E(S_1)\geq\pi_1$$

$$\Leftrightarrow \quad k_1^S\leq\frac{\delta_1\left(k_1^E-k_1\right)-c_1^E}{\alpha\delta_2\beta_2} \qquad \textit{(condition 1')}$$

and condition 2 becomes:

$$\pi_2^{E,1}(S_1) > \pi_2(S_1, S_2)$$

$$\Leftrightarrow \quad k_2^S > \frac{\left(k_1^E - k_1\right)}{\beta_1} \qquad \textit{(condition 2')}$$

Appendix 2: Proof of proposition 2

A situation for which only the less competent firm discloses her knowledge cannot be a PBE because if firm *E* expects that only the firm of the less competent type discloses, she will decide to cooperate with the firm who does not disclose her knowledge. Hence, as long as to disclose knowledge is assumed to be costly, firm *E* beliefs will always induce the firm of the less competent type to deviate and not to play *S*, i.e. firm *E*'s beliefs will not be confirmed by firms *A* and *B* decisions.

Appendix 3: Proof of proposition 3

Assume first that firm *E*, given that both firms *A* and *B* disclose their knowledge, chooses to collaborate with a probability of one half with each firm. This condition implies that expected profit under collaboration is higher than the expected profit without collaboration:

$$\frac{1}{2}\pi_E^1 + \frac{1}{2}\pi_E^2 \geq \pi_E \qquad \textit{(condition 4)}$$

Given this condition, we have a pooling PBE only and only if, knowing firm *E* strategy, firms *A* and *B* decide to disclose their knowledge whatever their type, i.e. if the two conditions below hold:

$$\pi_1^{E,2}(S_2) \leq \frac{1}{2}\pi_1^E(S_1,S_2) + \frac{1}{2}\pi_1^{E,2}(S_1,S_2)$$

$$\Leftrightarrow \quad k_1^S \leq \frac{\delta_1\left(k_1^E - k_1\right) + \alpha\delta_2\left(k_2^E - k_2\right) - c_1^E}{2\alpha\delta_2\beta_2} \qquad \textit{(condition 1)}$$

$$\pi_2^{E,1}(S_1) \leq \frac{1}{2}\pi_2^E(S_1,S_2) + \frac{1}{2}\pi_2^{E,1}(S_1,S_2)$$

$$\Leftrightarrow \quad k_2^S \leq \frac{\delta_2\left(k_2^E - k_2\right) + \alpha\delta_1\left(k_1^E - k_1\right) - c_2^E}{2\alpha\delta_1\beta_1} \qquad \textit{(condition 3)}$$

Condition *4* ensures that firm *E*, given her beliefs, chooses to cooperate if both firms *A* and *B* disclose their knowledge. Conditions *1* and *3* ensure that, given firm *E* strategy, firms *A* and *B* play *S* whatever their type. Therefore, under these three conditions we have a pooling PBE in which both firms choose to openly disclose knowledge.

Furthermore, in the case where $\frac{1}{2}\pi_E^1 + \frac{1}{2}\pi_E^2 < \pi_E$, we can also have a PBE in which firms, whether competent or not, disclose their knowledge. Assume that:

$$\frac{1}{2}\pi_E^1 + \frac{1}{2}\pi_E^2 < \pi_E \qquad \textit{(condition 5)}$$

Given this condition and given firm *E*'s beliefs, firms *A* and *B* decide to disclose their knowledge whatever their type only if the two conditions below hold:

$$\pi_1(S_1,S_2) \geq \pi_1^{E,2}(S_2)$$

$$\Leftrightarrow \quad k_1^S \leq \frac{\left(k_2^E - k_2\right)}{\beta_2} \qquad \textit{(condition 6)}$$

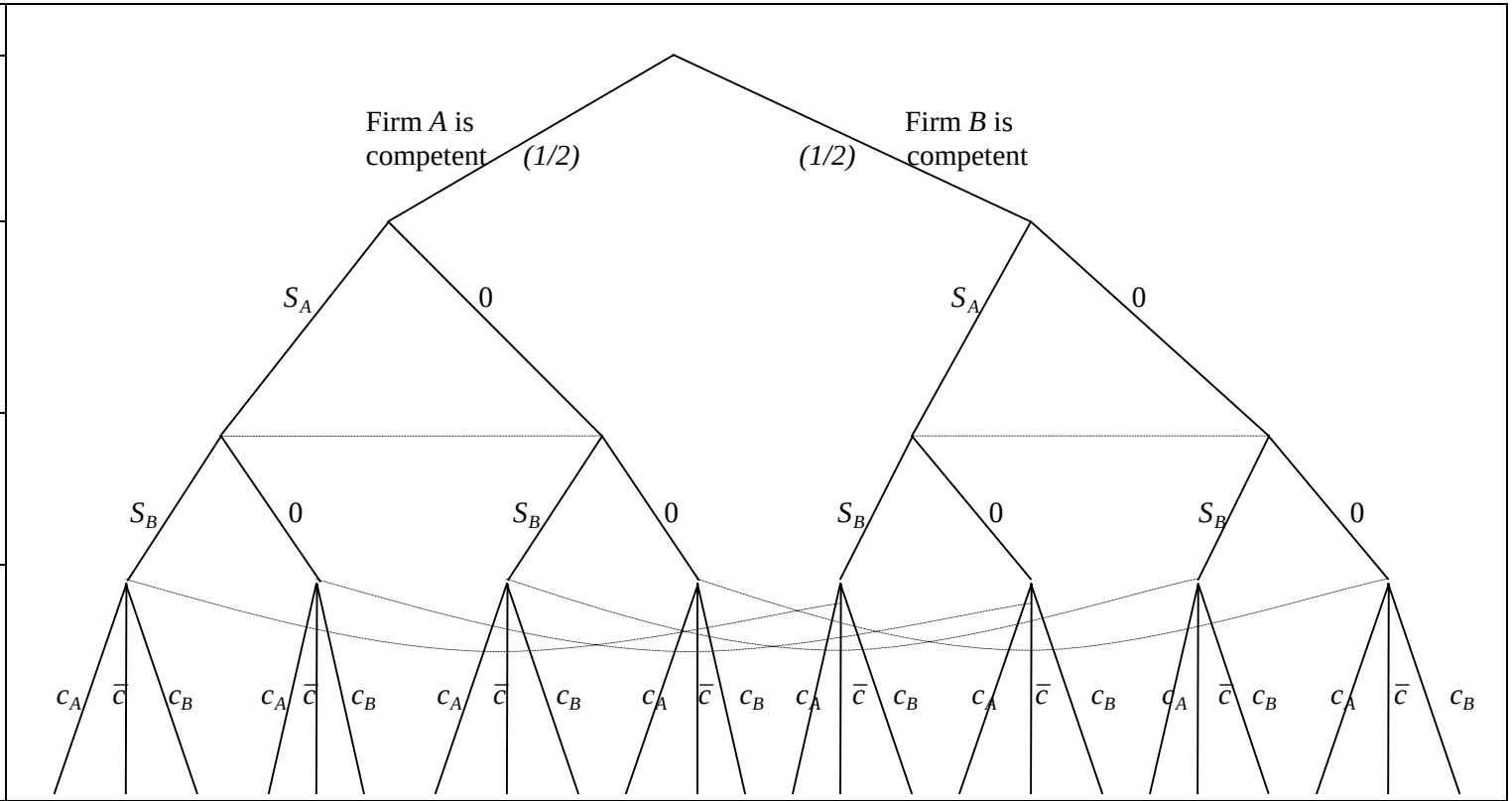
$$\pi_2(S_1,S_2) \geq \pi_2^{E,1}(S_1)$$

$$\Leftrightarrow \quad k_2^S \leq \frac{\left(k_1^E - k_1\right)}{\beta_1} \qquad \textit{(condition 7)}$$

Condition *5* ensures that firm *E*, given her beliefs, chooses to refuse cooperation with both firms *A* and *B* even though they both disclose their knowledge. Conditions *6* and *7* ensure that, given firm *E* strategy, firms *A* and *B* play *S* whatever their type.

Appendix 4: Decision tree of the signalling game

Stage	Player	Decision
1	Nature	Determines the type of firms *A* and *B*
2	Firm *A*	Chooses to openly disclose knowledge or not
	Firm *B*	Chooses to openly disclose knowledge or not
3	Firm *E*	Chooses whether or not to cooperate with a given firm



Payoffs firm *A*	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*	*m*	*n*	*o*	*p*	*q*	*r*	*s*	*t*	*u*	*v*	*w*	*x*
Payoffs firm *B*	*o*	*n*	*m*	*u*	*t*	*s*	*r*	*q*	*p*	*x*	*w*	*v*	*c*	*b*	*a*	*i*	*h*	*g*	*f*	*e*	*d*	*l*	*k*	*j*
Payoffs firm *E*	π_E^1	π_E	π_E^2	π_E^1	π_E	π_E^2	π_E^1	π_E	π_E^2	π_E^1	π_E	π_E^2	π_E^2	π_E	π_E^1	π_E^2	π_E	π_E^1	π_E^2	π_E	π_E^1	π_E^2	π_E	π_E^1

Legend: $a=\pi_1^E(s_1,s_2)$; $b=\pi_1(s_1,s_2)$; $c=\pi_1^{E,2}(s_1,s_2)$; $d=\pi_1^E(s_1)$; $e=\pi_1(s_1)$; $f=\pi_1^{E,2}(s_1)$; $g=\pi_1^E(s_2)$; $h=\pi_1(s_2)$; $i=\pi_1^{E,2}(s_2)$; $j=\pi_1^E$; $k=\pi_1$; $l=\pi_1^{E,2}$; $m=\pi_2^E(s_1,s_2)$; $n=\pi_2(s_1,s_2)$; $o=\pi_2^{E,1}(s_1,s_2)$; $p=\pi_2^E(s_2)$; $q=\pi_2(s_2)$; $r=\pi_2^{E,1}(s_2)$; $s=\pi_2^E(s_1)$; $t=\pi_2(s_1)$; $u=\pi_2^{E,1}(s_1)$; $v=\pi_2^E$; $w=\pi_2$; $x=\pi_2^{E,1}$.

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