Initiating private-collective innovation: The fragility of knowledge sharing*

Simon Gächter[a]
University of Nottingham
CESifo and IZA

Georg von Krogh[b]
Stefan Haefliger[c]
ETH Zurich

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Incentives to innovate are a central element of innovation theory. In the private-investment model, innovators privately fund innovation and then use intellectual property protection mechanisms to appropriate returns from these investments. In the collective-action model, public subsidy funds public goods innovations, characterized by non-rivalry and non-exclusivity in using these innovations. Recently, these models have been compounded in the private-collective innovation model where innovators privately fund public goods innovations. Private-collective innovation is illustrated in the case of open source software development. This paper contributes to the work on this model by investigating incentives that motivate innovators to share their knowledge in an initial situation, before there is a community to support the innovation process. We use game theory to predict knowledge-sharing behavior in private-collective innovation, and test these predictions in a laboratory setting. The results show that knowledge sharing is a coordination game with multiple equilibria, reflecting the fragility of knowledge sharing between innovators with conflicting interests. The experimental results demonstrate important asymmetries in the fragility of knowledge sharing and, in some situations, more knowledge sharing than theoretically predicted. A behavioral analysis suggests that knowledge sharing in private-collective innovation is not only affected by material incentives, but also by social preferences such as fairness. The results offer general insights into the relationship between incentives and knowledge sharing and contribute to a better understanding of the initiation of private-collective innovation.

Keywords: innovation, private-collective innovation model, knowledge sharing, open source software, experimental economics.

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[a] University of Nottingham, School of Economics, Sir Clive Granger Building, University Park, Nottingham NG7 2RD, United Kingdom. E-mail: simon.gaechter@nottingham.ac.uk.
[b] ETH Zurich, Department of Management, Technology, and Economics MTEC, Kreuzplatz 5, 8032 Zurich, Switzerland. E-mail: gvkrogh@ethz.ch.
[c] ETH Zurich, Department of Management, Technology, and Economics MTEC, Kreuzplatz 5, 8032 Zurich, Switzerland. E-mail: shaefliger@ethz.ch Phone: +41 44 632 8776
Corresponding author.

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1. Introduction

Explaining why and under what conditions innovation happens is a major task for innovation scholars. Software like Linux, Apache, or Firefox, brought the open source software (OSS) movement from obscurity into the public domain and in the process generated much debate among academics and practitioners. OSS is to a large part created by software developers who voluntarily and freely share their knowledge, in what von Hippel and von Krogh (2003) have termed the "private-collective innovation model."[1] This model does not require innovations to be published or released under an open source license, but the innovator forfeits any means of appropriating exclusive returns from selling the innovation. Innovators following the private-collective model of innovation only retain partial ownership of the intellectual property they create, giving up their right to sell and control the use of the innovation after publication or release (see Boldrin and Levine, 2001, and Bessen and Maskin, 2009, for a critical discussion of intellectual property and patents). This model prompted a number of empirical studies on the motivation of OSS developers (e.g. Lakhani and Wolf, 2005; Hertel et al. 2003). On the one hand, research found that participation in a community of software developers could explain contributions to OSS. The community rewards developers who innovate and behave consistently with the community's social norms, by providing new software, discussion platforms to exchange ideas, assistance in improving software, employment opportunities, or public recognition of their effort. These rewards offset the developers' contribution costs (Hertel et al. 2003; Roberts et al. 2006). On the other hand, these studies also revealed a puzzle: what motivates the *initiation* of private-collective innovation before a community has been established and such social norms have emerged? None of the previous studies could shed light on this question because they focused on contributions to running software development projects. Yet, the answer to this question is crucial. This paper aims to contribute to a better understanding why the first innovator shares knowledge. If we can specify conditions under which the innovation processes emerge, we then may assess the general utility of private-collective innovation beyond established OSS communities.

The essence of private-collective innovation can be illustrated in a simple dyadic relationship: one innovator (firm, entrepreneur, leader, OSS developer) shares knowledge with (at least) one other innovator. In general, this knowledge can be tacit or explicit (Nonaka, 1994), but explicit knowledge (e.g. articles, comments, ideas, engineering plans, design drawings, formulas, algorithms, procedures, software, etc.) can more easily be shared and become non-exclusive and non-rival (Arrow, 1984). During the initiation of private-collective innovation, with no access to public funding, employment contracts or social norms, any innovator can choose to share his or her explicit knowledge as a public

[1] Not all OSS is available as a public good. However, if the software is not available as a public good and is, say, created and used by a single developer, that developer follows the private, rather than the private-collective model of innovation. By definition, private-collective innovation entails the publication or release of innovation (von Hippel and von Krogh, 2006). For a definition of open source turn to: http://www.opensource.org/licenses

good (using, for example, an open source license), or keep it private and use secrecy or intellectual property rights to appropriate private (exclusive) returns from the innovation for example by licensing it to a third party. Under many circumstances, the innovator's incentive to conceal rather than to share knowledge is strong. For example, if an innovator has an idea for a new product that shows great market potential if licensed as a commercial product (rather than using an open source license), the incentive to defect from private-collective innovation can be strong. Several scholars have argued that knowledge sharing is often hampered by such massive conflicts of interest (e.g. Huber, 1982; Michailova and Husted, 2003; Cabrera and Cabrera, 2002; Osterloh and Frey, 2000), and will be fragile at the initiation of private-collective innovation. Authors have suggested that a cost-benefit analysis could shed more light on how different interests and incentives influence innovators' propensity to share knowledge (Foss and Mahnke, 2003: 78–79). In short, two questions stand out in the initiation of private-collective innovation: first, how fragile is knowledge sharing?; and second, what cost and benefit incentives are sufficient to induce sharing rather than concealing knowledge in the initiation of private-collective innovation?

Conducting research on the motivation for initiating private-collective innovation is challenging. Once innovators have shared knowledge and set innovation in motion, they can be identified by the field researcher. However, since the decision to share knowledge is private, it is difficult if not impossible to study knowledge sharing in the field, and especially difficult to identify innovators who decided not to share their knowledge and their reasons for doing so (see Nonnecke and Preece, 2000). To circumvent these difficulties, we model the incentive structure behind knowledge sharing and make use of an experimental method to understand the behavioral consequences of these incentives. The paper contributes to the literature on private-collective innovation by questioning what incentives motivate innovators to share their knowledge in an *initial situation*, before a community and social norms are available to sustain private-collective innovation.

In section two of this paper, we review existing research, and discuss the role of incentives in private-collective innovation. We develop a game theoretic model of knowledge sharing at the initiation of private-collective innovation. We show that knowledge sharing is a coordination game with multiple equilibria. Since there are many outcomes of knowledge sharing, we develop an experimental research design to identify behavioral strategies, given different incentives. The third section explains our research design and methods, and the fourth section presents the results. We find there are important asymmetries in knowledge sharing and, in some situations, much more knowledge sharing than theoretically predicted. A behavioral analysis suggests that knowledge sharing is affected not only by material incentives, but also by social preferences, such as fairness. In Section 5 we discuss our findings and conclude.

2. Incentives for knowledge sharing in private-collective innovation

Three models have specified incentives that give rise to innovation in society and economy: the private-investment model (Demsetz, 1967; Arrow, 1984), where the innovation remains a private good for the innovator who retains the rights to consume it, sell it, or provide access to it for third parties for a fee; the collective-action model, which relies on collective or public subsidy for public goods innovations (e.g. Olson, 1965; Stephan, 1996; Dasgupta and David, 1994) and where innovators relinquish control of knowledge or other assets they have developed and make them a public good (Hargrave and Van de Ven, 2006; Garud et al., 2002); and the private-collective innovation model (Von Hippel and von Krogh, 2003), where innovators fund public good innovations voluntarily and privately. OSS is often discussed as an exemplar of the latter model. In thousands of OSS projects in existence today, ranging from the operating system GNU Linux to the Firefox browser, individuals, research teams, universities, firms, and governments give their money, limited time, and talent to create software free for all to inspect, download, use, modify, and freely redistribute to others in a modified or unmodified form. The term "open source software" refers to copyright licenses, such as the GNU General Public License (GPL), that simultaneously guarantee access to the source code to users of the software and keep the innovation available as a public good once it has been shared with users (see discussion of this point in Lerner and Tirole, 2002; O'Mahony, 2003; Osterloh and Rota, 2007). Although open source licenses vary in restrictiveness[2] and in their tolerance for integration with proprietary software, the GNU General Public License is the most commonly used. To date it has been used by 124,000 out of 170,000 projects listed on sourceforge.com, and it forms the backdrop of this paper.

The private-collective model proposes that the efforts and participation of innovators in a community create incentives to innovate. A number of empirical studies have provided evidence for this proposition. Research has uncovered community-related incentives. These include: the application and testing of the software by many users and developers (Raymond, 1998; Lakhani and Wolf, 2005; Shah, 2006); the adaptation of OSS to solve specific technical problems on several developers' computers (Franke and von Hippel, 2003); the learning that takes place when users share knowledge and jointly write OSS (Kuk, 2006); the individual software developers' creation of software modules that can be combined into a whole software product by the work of many (Baldwin and Clark, 2006); the reputation that individuals achieve among peer developers in the community (Roberts et al., 2006); the developers' obligation to help fellow software users solve problems installing programs on their computers (Lakhani and von Hippel, 2003); and the developers' identification with a specific

[2]Differences in restrictiveness apply to the use of OSS in conjunction with proprietary software. The GNU General Public License mandates a so-called "copyleft" provision stating that all other software derived from or used together with software licensed under the GPL adheres to the same license terms. Other OSS licenses, such as the BSD License, are less restrictive or, in other words, allow copies and derivatives to be used in proprietary software as long as the authors are acknowledged (see e.g. URL: http://www.openbsd.org/policy.html).

community (Hertel et al., 2003). In their review of research on OSS, Bergquist and Ljungberg (2001) suggested that a cornerstone of OSS developer communities is the way they evolve strong social norms of reciprocity that enable them to operate as "gift economies." When software developers receive "gifts," in terms of advice, acknowledgment, or software from others they feel an "obligation" to reciprocate by giving new or improved software, advice, and tips.[3]

The private-collective model of incentives to innovate presupposes an active community of innovators, and until now has not explicitly covered the initiation of innovation (von Hippel and von Krogh, 2003; 2006). It has always been understood as "routine collective action" (Useem, 1998), where innovators build on already existing technology to create new and useful products. However, incentives during initiation differ substantially from incentives once the community is established and working routinely. According to Elster (1986), the initiation of collective contributions to a public good requires a higher incentive level than that required to sustain them.

Consider four examples of research on OSS development that highlight the evolving nature of incentives as communities grow and prevail. First, an initial gift (Bergquist and Ljungberg, 2001) must be exchanged before a social norm of reciprocity can be established in the community. OSS developers may only feel gratitude and an obligation to return a gift if they have first received useful software, appreciation, or advice. Second, when a developer releases a first working version of OSS to the public, other developers who find the software product useful will join the development effort and build a community (Raymond, 1998; Lerner and Tirole, 2002). The role of working software (a public good) in generating development activity has been confirmed by statistics on new developers joining the Freenet open source peer-to-peer project (von Krogh et al. 2003). Third, Baldwin and Clark (2006) showed that the modularity of software architecture is positively related to the options available to OSS developers in terms of exchanging valuable work. The value of these options, and hence the incentive to contribute, hinges on a modular structure of existing software architecture already created by many developers. Fourth, Shah (2006) found that long-term OSS developers take on mundane tasks in a community, such as giving advice to newcomers or maintaining mailing lists. This work reaches beyond the developers' immediate, individual goals of satisfying their technical needs. Thus the motivation for contributing to the community changes over time in an OSS project.

The evidence that incentives change as communities emerge and grow suggests that we cannot infer characteristics of initial knowledge-sharing situations from our observations of established private-collective innovation; nor can we make assumptions about levels of incentive in such situations. Therefore, in order to capture the initiation of private-collective innovation before the establishment of a community and the emergence of social norms, we introduce two rather weak assumptions from von Hippel and von Krogh (2003; 2006). These allow us to model the basic

[3]Lately, studies have also found private-collective innovation incentives in other fields than software, including product development and cultural goods (e.g. de Vries et al., 2006; Jeppesen and Fredriksen, 2006).

structure of knowledge sharing (sequentiality and asymmetry in conflicts of interest) and can be illustrated by a sequential two-person game that models an initial knowledge-sharing situation:

1. Knowledge sharing enhances value for the party that receives the knowledge.
2. Mutual knowledge sharing makes knowledge public and precludes the exclusivity of received knowledge for one's own private financial benefit. By implication, a necessary (but not sufficient) condition for exclusive appropriation is unilateral knowledge sharing.

Assumption 1 states that knowledge sharing is value enhancing (net of adoption costs of the new knowledge) for the innovator receiving the knowledge. This is an innocuous assumption, because in case it does not hold, knowledge sharing is not really of economic interest. Value enhancement occurs if one party shares his or her knowledge, and is further enhanced if there is *mutual* knowledge sharing (von Hippel and von Krogh, 2003). Assumption 1 does not state whether or not the act of sharing knowledge is costly for the innovator. We will discuss this later. Note also that knowledge is distinct from other resources, such as land or money. Sharing it does not necessarily diminish the rewards it will bring for the innovator who first held it. For example, in OSS, the software developer who shares his source code with another developer will still have a copy that can be used to solve technical problems on his own machine. By "innovators" we mean both individuals and firms. Recent research provides evidence that firms often reveal knowledge freely and extensively, including software code released under an open source license and developed in-house (e.g. Henkel, 2006; Stuermer et al., 2009).

Assumption 2 says that mutual knowledge sharing rules out the exclusive appropriation of received knowledge for one's own private financial benefit (von Hippel and von Krogh, 2003). This is because mutual knowledge sharing makes knowledge a public good and, by definition, the returns on a public good cannot be exclusive (Arrow, 1984)[4]. Appropriation refers to the capacity of the knowledge holder to receive a return equal to the value created by the knowledge, for example, by keeping it secret or by protecting it through intellectual property rights (Arrow, 1984; Teece, 1986; Grant, 1996). An individual who combines her own concealed knowledge with knowledge received from others may receive a higher return than the returns from knowledge sharing. Sharing knowledge entails opportunity costs of giving up exclusivity that must be added to the possible out-of-pocket costs of sharing.

Assumption 2 is important because it allows us to model conflicts of interest as a possible consequence of unilateral knowledge sharing. This asymmetry captures the real-life differences between innovators' prior knowledge and their opportunities. For example, a programmer may face a technical problem. She combines her software with a technical solution provided by others, and in

[4]An example would be publishing a software (and source code) on the internet, with everybody being allowed to use the software for free. In this case a private market is not viable any longer and hence exclusivity is ruled out. Assumption 2 does not preclude products, services, and business models that build on the public knowledge by combining it with complementary assets and skills, thus partial, or non-exclusive, appropriation.

doing so learns to solve the problem more efficiently. If, thanks to this combined knowledge, the programmer can create software that allows her to sell a software product on the market, she might choose to release a binary version of the software only and license the software to third parties in return for a fee. However, if the software is protected by an OSS license, the programmer's ability to sell the software is limited by others' rights to do the same or give the software away for free, in other words, exclusive appropriation becomes impossible.[5] As we mentioned earlier, most open source licenses guarantee the rights of current and future users to freely download, inspect, modify, and release modified and unmodified versions of the source code (not the binary version) to third parties. Open source licenses thus lower the opportunity costs of sharing, suggesting a model structure that allows us to observe the sensitivity of mutual sharing to varying levels of conflicts of interest.

Knowledge is accumulative; it enables learning and can provide complementary benefits to either of the innovators involved. In the absence of the sort of hierarchy, incentive structure, employment contracts and other contextual factors found in firms, innovators act according to social preferences, such as fairness, efficiency-seeking, and reciprocity. To uncover what motivates the initiation of private-collective innovation, we now turn to some basic incentives for knowledge sharing.

2.1. *The knowledge-sharing game*

The generic properties of the conflicts of interest in knowledge sharing that follow from our two assumptions can be illustrated in a sequential dyadic relationship. An example of sequential knowledge sharing is an individual's decision to contribute software to an existing open source project and add his or her own solution to what has already been published.

Figure 1 illustrates our "knowledge sharing games." For simplicity, we call the two innovators leader (L) and follower (F). Both innovators have the choice of sharing (*s*) or concealing (*c*) knowledge. In the knowledge-sharing game in Figure 1, L moves first and decides whether to share or conceal his knowledge. F is informed of L's choice and decides whether to share or conceal his or her knowledge. Note that the model allows F to decide whether or not to share knowledge, even if L has decided to conceal.[6] After F's choice, the game ends and payoffs are realized: b_i (i = L,F) denotes a base payoff where v_i is the value enhancement through sharing knowledge, a_i is the exclusivity payoff, and k denotes the expenses for sharing explicit knowledge. These payoffs are derived from the assumptions and explained in detail below.

[5] Other business models derived from the use of publicly available software, e.g. in combination with proprietary software, can still create conflicts of interest for the receiver. Henkel (2006) showed that mutual revelation can be compatible with private benefits in the example of embedded Linux. Further private benefits can include intrinsic motivation (Osterloh and Frey, 2000; Ryan and Deci, 2000).

[6] In our example, this would correspond to adding a solution to an existing project even if the project leader has not (yet) contributed code. The famous example is Linus Torvalds' discussion of a new operating system before publishing code (Moon and Sproull, 2000; Moody, 2001). Fora or mailing lists may provide a social context independent of the initial sharing of code.

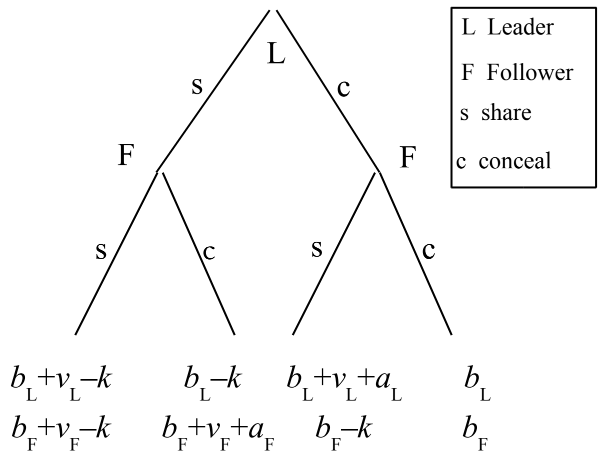


Figure 1. *The knowledge-sharing game.*

Before analyzing the incentive structure and inherent conflicts of interest in the knowledge-sharing game, payoffs must be specified. Each actor receives some basic net benefit $b_i \geq 0$, i = L, F, even if he or she only retains knowledge. An example would be programmers who produce software that is useful to them without receiving any knowledge from another programmer. According to Assumption 1, net value is enhanced for the knowledge recipient. In Figure 1, this is reflected in payoffs $v_i > 0$, i = L, F, to player i if player $j \neq i$ shares his or her knowledge. For instance, if L shares his or her knowledge, then, irrespective of F's choice, F receives payoff v_F in addition to his or her basic payoff b_F. If F shares his or her knowledge, then L's base payoff b_L is augmented by payoff v_L. If player j conceals, then v_i=0, i = L, F.

Assumption 2 says that knowledge (a public good created by mutual sharing) cannot be turned into an exclusive benefit. Therefore, a necessary (but not sufficient) condition of turning received knowledge (in combination with one's own knowledge) into an exclusive benefit is that knowledge sharing is unilateral. Only the innovator who can combine his or her own knowledge with knowledge obtained, and does not share his or her own knowledge, can possibly enjoy the benefits from exclusive appropriation, denoted by $a_i \geq 0$, i = L, F. Therefore, if L shares and F conceals, F can exclusively appropriate a_F. Likewise, L only appropriates a_L, if he conceals and F shares his or her knowledge. Notice that the payoff connected to exclusivity can be zero (which is why asymmetric sharing is only a necessary, not a sufficient, condition). This is the case, for instance, if exclusive appropriation of shared software is prevented by an Open Source license (see O'Mahony, 2003, for a discussion of various protective measures for OSS). Exclusivity is the crucial variable in the subsequent experiment, as will become clear in the game-theoretic analysis. Intuitively, exclusivity constitutes the opportunity costs of sharing knowledge, because benefits from exclusive appropriation are foregone if knowledge is shared.

One might argue that, in real life, sharing explicit knowledge in innovation is costly (for example shipping documents or traveling to meet people). The cost of knowledge sharing is modeled with the variable k.[7] These costs are "out-of-pocket expenses," distinct from the opportunity costs that are created by exclusivity (private returns from the exclusive appropriation of knowledge). If knowledge sharing is costless, $k = 0$. OSS development is characterized by this condition. Von Hippel and von Krogh (2003) and Kogut and Metiu (2001) argue that the internet makes the sharing of knowledge between programmers a near costless activity. This is in contrast to the high out-of-pocket expenses needed to share or replicate many other technologies across sites, such as manufacturing processes, physical product prototypes, or chemical compounds (Kogut and Zander, 1992, and Teece, 1977, discuss many costs involved, such as local adaptation of the technology to the manufacturing site simply to make it run).

2.2. Theoretical predictions

We are now ready for a game-theoretic analysis of the conflicts of interest inherent in this knowledge-sharing game. First, we assume that players are rational and purely self-interested. Second, we predict the outcomes considering fairness as a social preference, building on the model by Fehr and Schmidt (1999). Fairness considerations play an important role in bilateral exchanges and apply to a broad range of economic situations (Fehr and Gächter, 2000).

Observe the implications of positive out-of-pocket costs $k > 0$. In case $v_i > k > 0$, the sequential knowledge-sharing game is a sequential prisoner's dilemma game, where the only equilibrium is mutual concealment. This holds irrespective of the exclusivity a_i.[8] Therefore, in the present model, knowledge sharing by self-interested innovators is not possible if $k > 0$ (of course, mutual concealment is inefficient). Since both players want to conceal in the sequential prisoner's dilemma, there is no genuine conflict of interest either. Therefore we confine our attention to the consequences of opportunity costs in sequential knowledge sharing if $k = 0$ for both players.[9] The following proposition summarizes the knowledge-sharing game:

Proposition 1: Knowledge sharing based on rationality and self-interest:

(i) *Mutual concealment is always an equilibrium outcome.*

[7] We assume that (i) k is the same for both players because market prices for shipping costs or access to the internet are the same for everyone, and (ii) $k < v_i$, i = L,F (the costs of knowledge sharing are smaller than the value created).

[8] If the leader and the follower decide simultaneously and $k > 0$, the knowledge-sharing game becomes a prisoner's dilemma.

[9] If sharing knowledge is actually beneficial for the sharer, i.e., if the sharer would be paid for the act of sharing, $k < 0$. The implications are that, if abs(k) > a_F, F will always share whether L conceals or shares. In this case the result is that mutual sharing is an equilibrium if abs(k) > a_L.

(ii) *A necessary condition for mutual sharing as an equilibrium outcome is that $a_F = 0$. A necessary and sufficient condition for sharing in all subgames is that exclusivity payoffs are zero for both players ($a_L = a_F = 0$).*

(iii) *In all constellations of exclusivity payoffs $(a_L \geq 0)x(a_F \geq 0)$, there always exist equilibria with unilateral knowledge sharing (in addition to mutual concealment).*

The first basic message of the proposition is that the knowledge-sharing game has multiple equilibria. Appendix A contains the complete list of these. Proposition 1(i) makes it clear that in addition to possible unilateral and mutual knowledge-sharing equilibrium outcomes, mutual concealment is always an equilibrium. The intuition for this result is that, under $k = 0$, F will, in both subgames where she has to make a decision, either be indifferent to sharing and concealment (in the subgame after L chooses *c*, or in the subgame after L chooses *s* and $a_F = 0$) or be better off by concealing (in the subgame after *s* and if $a_F > 0$). Thus, concealment is *always* a best response for F. It then follows that it is best for L to choose *c* as well, since he is indifferent to sharing and concealment in this case.

Proposition 1(ii) says that mutual sharing will only occur as an equilibrium outcome if F cannot gain exclusivity payoffs. Since F is indifferent to both sharing and concealment in this case, F may resolve her indifference by sharing. Given that F shares, L may also share, provided $a_L = 0$. In this case L is equally indifferent to sharing and concealment (L's payoff is b_L+v_L anyway). As soon as $a_F > 0$, F will conceal, if L shares and mutual sharing can no longer be an equilibrium. Thus, $a_F = 0$ is a necessary condition for mutual sharing; $a_L = a_F = 0$ is necessary and sufficient.

The rationale for proposition 1(iii) is that in cases of indifference to both sharing and concealment, both choices are a best response. That is, when matched with the other innovator's best response of sharing, concealment can be a best response, and vice versa.

Proposition 1 shows that genuine conflicts of interest, where one innovator wants to conceal and the other share, can only arise if there are positive opportunity costs to sharing knowledge for one innovator alone. There is no conflict of interest in the mutual knowledge-sharing (-concealment) equilibria, because it is in both innovators' interest to share (conceal) their knowledge.

A particularly interesting situation is the one where neither innovator has opportunity costs of sharing (i.e., $a_F = a_L = 0$). As von Hippel and von Krogh (2003) argue, this situation is characteristic of many open source licensed projects. The analysis shows that the resulting open source knowledge-sharing game is no prisoner's dilemma, but a game with multiple equilibria with different efficiency consequences. Mutual knowledge sharing can occur simply because innovators are indifferent to both sharing and concealment and are prepared to resolve their indifference by sharing. It is exactly this indifference that allows for mutual sharing among self-interested innovators.[10] However, by the same token, mutual concealment is also an equilibrium, albeit an inefficient one.

Proposition 1 is crucial for understanding the fragility of knowledge sharing in the initiation of private-collective innovation, because it highlights the structure of the conflicts of interest inherent in knowledge sharing. The dual findings that (i) mutual concealment is always an equilibrium outcome, and (ii) that only equilibria with unilateral knowledge sharing or mutual concealment exist as soon as $a_F > 0$, gives a theoretical meaning to the "fragility of knowledge sharing." In sections 3 and 4 of this paper, we complement this theoretical result with evidence of the behavior that causes fragile knowledge sharing. Since knowledge sharing is a game with multiple equilibria, it is an open question which equilibrium innovators will play. This is an inherently empirical question that we attend to in the remainder of the paper.[11]

Proposition 1 summarizes a benchmark game-theoretic analysis under the simplifying assumption that innovators are rational and selfish (i.e., they only maximize their own payoffs). However, the research on open source communities we discussed earlier (e.g., Bergquist and Ljungberg, 2001), and research in psychology and experimental economics, has repeatedly revealed that rather than being selfish, many people are equipped with "social preferences." In addition to pecuniary payoffs, people also care about equity, efficiency, and reciprocity (Camerer, 2003, chapter 2). Since knowledge sharing has various payoff and efficiency consequences, social preferences might also matter in the context of private-collective innovation.

One simple model of social preferences is the inequity aversion model of Fehr and Schmidt (1999). According to this model, players' utilities increase in their own material payoff but decrease if there is inequality in bilateral payoff comparisons. For instance, an inequality-averse F will always conceal if L has concealed because sharing only increases L's payoff but not F's and therefore would put F at a payoff disadvantage (Fig 1). Players in the Fehr-Schmidt model might also dislike advantageous inequality, that is, situations in which they earn more than their co-player. For instance, after L has shared, F might consider sharing if he is sufficiently averse to advantageous inequality, that is, if his dislike of the payoff advantage *vis-á-vis* L ($v + a_F$) outweighs the material gain compared to concealment (the material payoff gain from concealment compared to sharing is a_F).

To see this more formally, consider the Fehr-Schmidt utility function of F: $U_F = \pi_F - \alpha_F \max[\pi_L - \pi_F, 0] - \beta_F \max[\pi_F - \pi_L, 0]$ where π_i, $i = F, L$ indicates the material payoffs as they were relevant in the experiment; $\alpha_F \geq 0$ measures F's aversion to disadvantageous inequity ($\pi_L - \pi_F > 0$) and β_F measures aversion against advantageous inequity ($\pi_F - \pi_L > 0$) ($\alpha_F \geq \beta_{F.} \geq 0$;

[10] An example would be a programmer who develops software for himself. Sharing it does not diminish the utility of the software for him, but may be beneficial for another programmer. So given that he is not worse off by sharing, and somebody is potentially better off, he might easily be prepared to share his software with others.
[11] See, e.g., Camerer et al. (1997), Weber et al. (2001) and Camerer (2003, Chap. 7) for discussions of the difficulties of coordination.

$\beta_F < 1$). Plugging the relevant payoffs in the utility function shows immediately that an inequity-averse follower will never share if L has concealed.

F might share, however, if L has shared. F's utility from sharing, given that L has shared, is $U_F(s \mid s) = b + v$. The utility from concealing is $U_F(c \mid s) = b + v + a_F - \beta_F(b + v + a_F - b)$, that is, F enjoys the material benefit of $b + v + a_F$ and suffers a disutility of $\beta_F(v + a_F)$ from earning $(v + a_F)$ more than L. F will share if and only if $U_F(s \mid s) > U_F(c \mid s)$ which is the case if $\beta_F > a_F/(v + a_F)$. In our experiment $v = 20$ (see next section). Therefore, our different levels of the exclusivity payoff require the following minimal $\beta_F^*(a_F)$ to induce F to share: $\beta_F^*(0) > 0; \beta_F^*(10) > 1/3; \beta_F^*(20) > 1/2$ and $\beta_F^*(30) > 3/5$. Thus, the higher the benefits from exclusivity the higher has F's aversion against advantageous inequality to be to induce him to share despite giving up exclusivity.
What can we say about L's behavior? If L expects F to share, it will be best for L to share, as L's payoff for sharing will be $b + v$ rather than b if he conceals. If L expects F to conceal, it will be best for L to conceal as well. We summarize the role of inequity aversion in knowledge sharing in our second proposition:

Proposition 2: knowledge sharing under inequity aversion

(i) *If followers are even slightly inequity averse they will always conceal if the leader has concealed. If the leader shares the follower will also share, if he or she is sufficiently inequity averse. The degree of inequity aversion needed to induce a follower to share increases in the follower's exclusivity payoff a_F.*

(ii) *The leader will always share if he expects the follower to share and conceal if the follower conceals.*

Which parameters for β_F are plausible? Based on results from student participants Fehr and Schmidt (1999: 844) assume that 30 percent of people have $\beta = 0$; another 30 percent have $\beta = 0.25$ and 40 percent have $\beta = 0.6$.[12] If we assume that our student participants have similar β-values as those reported by Fehr and Schmidt, and know about the distribution of these values, then we can make the following prediction about mutual sharing (remember that L will always share if he expects F to share): If L shares, 70 percent of Fs (with a $\beta > 0$) will share if $a_F = 0$ (the remaining 30 percent are indifferent toward the outcome), and 40 percent will share if $a_F > 0$.

Apart from inequality aversion, other kinds of social preferences might impact the fragility of knowledge sharing, namely efficiency-seeking and reciprocity. If followers (perhaps in addition to inequality aversion) think concealment is unkind and that leaders who conceal are greedy ("They

[12] These values should only be seen as a rough approximation, rather than as exact point estimates. See Bellemare, Kroeger, and van Soest (2008) for econometric estimates based on a representative sample.

conceal because they want to appropriate my shared knowledge"), reciprocity predicts that, in this subgame, followers who want to "punish" greedy leaders will conceal.[13]

Efficiency concerns (e.g., Charness and Rabin, 2002; Engelmann and Strobel, 2004) make different predictions if L has concealed knowledge. If F is concerned with efficiency, he might share knowledge because his own payoff is not affected; but L's payoff is increased and efficiency is enhanced.

3. Research design and methods

The generic incentive *structures* in the initiation of private-collective innovation follow from the two basic assumptions we discussed in section 1. As we saw in section 2, it is difficult, if not impossible, to examine possible defection by innovators in field studies of private-collective innovation. Therefore, we will test the behavioral consequences of the model in a laboratory decision scenario that has the same incentive structure as the theoretical model we described earlier. Paying the experimental subjects according to the payoffs of the model ensures that the subjects face the monetary equivalent of the incentives that are assumed in the model (see Smith, 1982, for a comprehensive methodological discussion of this "induced value" technique). In this way, one can observe real economic decisions by human decision makers who face real stakes in a situation that has the same form as the model of knowledge sharing discussed above.

Since (i) the only crucial variables are the exclusivity payoffs, and (ii) none of the theoretical results requires $b_L \neq b_F$ and/or $v_L \neq v_F$, we simplify the analysis to focus on variations in a by assuming $b_L = b_F = b$, and $v_L = v_F = v$. We also assume that $k = 0$, i.e., out-of-pocket costs are absent. In the experiments, we implemented the extensive form game of Figure 1. We chose the following parameters: $b = 10$ and $v = 20$. We did not change these parameters during the experiment since, theoretically, they are of minor interest. The exclusivity payoffs vary between four levels: $a_i \in \{0, 10, 20, 30\}$, i = L, F. The rationale for four levels of a_i is as follows. Note that for $a_i = 0$ or 10, the social optimum (i.e., the sum of payoffs) is always achieved in mutual sharing. If $a_i = 20$, both mutual and asymmetric knowledge sharing are socially optimal. If $a_i = 30$, the social optimum is that only one player shares knowledge and the other conceals. We included this payoff in the design as well, since there is evidence from experiments that efficiency-seeking is often an important behavioral motive. It is particularly interesting to examine how combinations of a_L and a_F influence the likelihood of knowledge sharing, and therefore we vary these payoffs systematically, by playing all 16 possible payoff combinations a_Fxa_L ($\{0, 10, 20, 30\}$x$\{0, 10, 20, 30\}$).

[13] Choosing c in case L chooses c, is a "punishment" for L, if L expected F to choose s instead, since L's payoff is smaller under c than under s. Reciprocity theories (Rabin, 1993; Dufwenberg and Kirchsteiger, 2004; Falk and Fischbacher, 2006) make similar predictions to inequality aversion in this game and so we do not consider them separately here.

Each participant in the experiments played 16 games—each resulting from a_Fxa_L—once. Subjects were randomly allocated to their roles as leaders or followers. After they had read the instructions (see Appendix B), they made their decisions in each of the 16 games without feedback. We programmed and conducted the experiments in z-Tree (Fischbacher, 2007). For simplicity, subjects saw only the sum of payoffs ($b + v$) or b alone on their screens. Moreover, we told subjects that the only payoffs that would change in each of the 16 games were payoffs for the follower (called y on the screens) that resulted from the share-conceal combination (L chooses s, F chooses c) and the payoff for the leader (called x on the screens) in the conceal-share combination (L chooses c, F chooses s). We did not inform subjects beforehand about the values of x and y. They were told that only these two payoffs would change from period to period. However, subjects did know that there would be 16 periods. The order of x-y combinations was randomly determined but the same for all subjects.[14]

We avoided possibly value-laden content labels for the choices, following common practice in experimental economics. The players were not referred to as "leaders" or "followers," but as "decision maker 1 and 2." Choices were framed neutrally and did not refer to knowledge sharing. Choices were termed *left* or *right* (in the game in Figure 1, left corresponds to share and right to conceal).[15] Leaders simply decided whether to choose the left or right option. For followers, we applied the strategy method (Selten, 1967). That is, followers had to make a left-right decision whether the leader chose left or right. Neither leaders nor followers received any feedback. The rationale for the strategy method is twofold: first, it allows the observation of F's behavioral reactions to both possible leader choices. This would not be possible if F were restricted to making a decision after he or she has seen a specific leader choice.[16] Second, asking for contingent choices has the added advantage that feedback does not have to be given in each round. This makes decisions between individuals independent, which is advantageous in the statistical analysis of the data. In particular, since with the strategy method without feedback decisions are independent between subjects, we can use the observed sharing frequencies to calculate the expected probability that a randomly matched leader-follower pair

[14] One might object that, despite the lack of feedback, some "virtual learning" (Weber, 2003) might affect all players similarly because they all played the games in the same order. To test whether this procedure had an impact on our results, we ran further experiments (with 51 subjects) where we randomized the sequence of games for each individual (i.e., each individual played the 16 games in a different sequence). For each of the 16 games we apply tests of proportion to test the null hypothesis that the frequency of leaders' sharing decisions in the experiments, where everyone played the 16 games in a same order, is the same as in the control experiment, where people play the games in different orders. We applied the same test to the followers' sharing decisions after the leader had shared and concealed. In all, we performed 48 tests. We could not reject the null hypothesis (at $p<0.05$) of equal proportions of sharing decisions in 45 out of 48 tests. We concluded that our results (reported below) are robust to the sequence of play.

[15] The research methodology behind this design choice is to look at the basic incentive structure behind knowledge sharing. Future research should address the role of context for the fragility of knowledge sharing.

[16] There is evidence that in simple coordination games like ours the strategy method does not lead to systematically different responses than ordinary game playing. See Brandts and Charness (2000) for a systematic analysis. They study coordination games with and without the strategy method. In the experiments without the strategy method, subjects are simply confronted with the choice of a first mover and then make their decision. Under the strategy method, subjects make decisions for all possible moves of another player. The behavioral results do not differ between the methods.

(not just the actual matched pair) plays a certain strategy combination, and—of particular interest—the probability of mutual sharing. This would not be feasible without the strategy method and independence of decisions.

To determine payoffs, leaders and followers were matched randomly in each period. However, we did not provide feedback on the 16 games until the end, when subjects received the earnings from each of the 16 games in cash. In each of the games, payoffs were determined according to the decisions of a randomly matched leader-follower pair. During the experiment, payoffs were denoted by points. Finally, we exchanged the accumulated sum of points into Swiss Francs at an exchange rate of one point = 0.04 Swiss Francs.

We conducted the experiments at the Universities of St. Gallen and Zurich in Switzerland, with 228 undergraduates from various fields as experimental subjects. They provided a total of 3616 share-conceal decisions. The experiments lasted 30 minutes and subjects earned on average 15 Swiss Francs (approximately US$ 12.3). Across all games, leaders and followers earned very similar amounts.

4. Experimental results

Our analysis of the results from the experiments on knowledge sharing in the initiation of private-collective innovation is largely descriptive. Appendix D contains an econometric analysis that corroborates our results statistically.

4.1 *Sharing decisions*

Since the only parameters in the experiments are combinations of a_Fxa_L, we will present most results as a function of these parameters.[17]

Result 1: (i) *Contingent on the leader sharing, followers share in about 73 percent if* $a_F = 0$. *If* $a_F > 0$ *the probability that the follower shares drops dramatically* (*to less than 30 percent*) *and decreases further in* a_F. *This holds for all levels of the leader's exclusivity payoff* a_L.

(ii) *When the leader conceals, we find that the probability of followers sharing is on average 45.3 percent across all* a_Fxa_L*-combinations*.

Figures 2a and 2b provide the main support for Result 1. For each of the 16 a_Fxa_L-games, the figures show the frequencies at which F shared in the sub-game after L shared (Figure 2a) and concealed (Figure 2b). A comparison of these figures shows that L's decision strongly affects F's sharing behavior.

[17] Appendix C documents the frequency of L's sharing choices for all 16 games, as well as F's choices after L shared and concealed. Since we have information from the full strategy set of our knowledge sharing game, we also document the expected frequencies at which the various strategies are played.

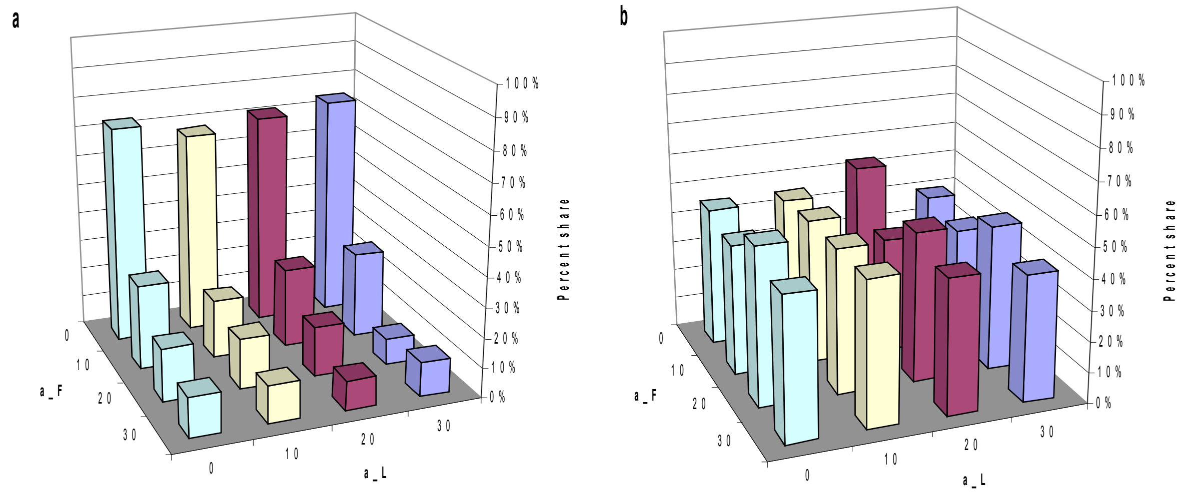


Figure 2. *Percentage of followers who share if* (a) *the leader shares and* (b) *if the leader conceals*

Figure 2a illustrates the contingent probability at which Fs are prepared to share knowledge, in case L shares. Recall that under our assumptions of rationality and selfishness, there should not be any knowledge sharing in the event of a positive exclusivity payoff a_F. If $a_F = 0$, rational and self-interested followers are indifferent to both sharing and concealment. This implies that behavior is undetermined in this case. To the extent that Fs are inequality averse or care for efficiency, F might be willing to share (Proposition 2). For all levels of a_L this was the case for between 67 to 74 percent of followers.

The followers' willingness to share dropped dramatically for $a_F > 0$. This holds for all levels of a_L. If $a_F = 10$, the likelihood that F will share was between 20 and 29 percent. If $a_F = 30$ it dropped even further to between 10 to 14 percent.

Figure 2b illustrates the contingent probability at which Fs are prepared to share knowledge in case L conceals. The results show that Fs chose to share in between 37.5 and 53.6 percent of cases. The average over all a_Fxa_L-combinations was 45.3 percent (which is not significantly different from 50 percent, the expected outcome of indifference between sharing and concealing; t-test with individual average sharing rates as observations).

Recall that Proposition 1 predicts that F does not share in case $a_F > 0$, and is indifferent in case $a_F = 0$, whereas Proposition 2 (in combination with plausible parameters) predicts 70 percent sharing if $a_F = 0$ and 40 percent sharing if $a_F > 0$. Thus, the evidence of F sharing after L has shared appears to be consistent with Proposition 2. However, the fact Fs share in almost 50 percent of the cases in which L conceals is inconsistent with inequality aversion but consistent with efficiency considerations.

The next result concerns the probability that the leaders share knowledge in the initiation of private-collective innovation.

Result 2: *The probability that leaders share is affected negatively by both their own and their followers' exclusivity payoffs.*

Figure 3 is the main support for Result 2, which shows the percentage of cases in which L shared in each of the 16 a_Fxa_L-games.

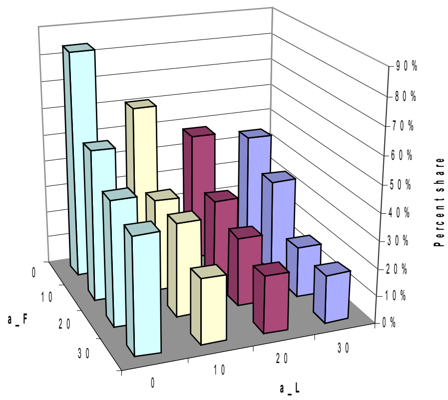


Figure 3. *Percentage of leaders who share*

As Figure 3 shows, the likelihood that L shares knowledge decreases in both a_F and a_L. In case both exclusivity payoffs are zero, Ls share in 84.2 percent of the cases. The probability that Ls share is lowest if $a_F = a_L = 30$ (it equals 17.5 percent). Thus, in the inception of private-collective innovation, Ls take into account not only their own exclusivity payoff a_L, but also their followers' (a_F).

4.2 *The fragility of knowledge sharing*

As we have seen, innovators' opportunity costs of knowledge sharing strongly affect the likelihood that mutual knowledge sharing will occur in the initiation of private-collective innovation. We close our empirical analysis by examining the fragility of mutual knowledge sharing, using the possibilities inherent in collecting data with the help of the strategy method with no feedback between rounds. The design of the strategy method (i) provides many independent observations and (ii) allows the observation of strategies, not just realizations of decisions in the game. The likelihood of a certain outcome can be estimated (see Appendix C).

Fragility is operationalized as the change in the expected probability of mutual knowledge sharing, when the opportunity costs of sharing change. Note that the fragility of mutual knowledge sharing is a composite of L's and F's sharing behavior. It is therefore an empirical question whether L's or F's behavior is more important for the fragility of mutual knowledge sharing. The result is as follows:

Result 3: *Knowledge sharing is substantially more fragile in a_F than in a_L.*

Formally, we define $\pi_{ss}(a_L,a_F)$ as the probability of mutual sharing of two randomly matched innovators, dependent on the exclusivity payoffs a_L and a_F. Figure 4 depicts the empirical observation of $\pi_{ss}(a_L,a_F)$, which is the expected frequency of mutual knowledge sharing as a function of all 16 (a_Fxa_L)-games. For a given game, the expected frequency results from the probability that L shares multiplied by the probability that F shares.

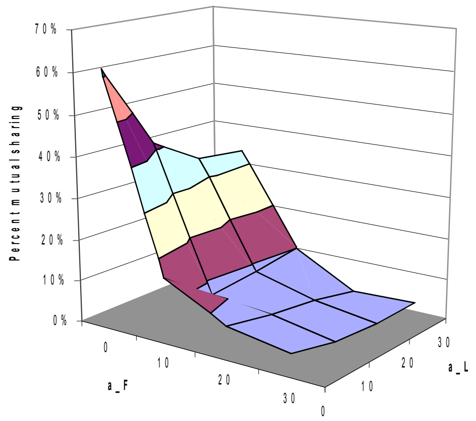


Figure 4. *The fragility of knowledge sharing—percentage of mutual sharing*

We define the marginal change of the probability π_{ss} in the exclusivity payoffs (i.e., $\Delta\pi_{ss}(a_L,a_F)/\Delta a_i$, i=L,F), as the fragility of mutual knowledge sharing induced by i's exclusivity payoff a_i, i = L,F. Figure 4 shows that $\pi_{ss}(a_L,a_F)$ is convex in a_i, i = L,F, and more fragile in a_F than in a_L. Of particular interest is $\Delta\pi_{ss}(0,0)/\Delta a_i$, i=L,F, i.e., the marginal change in the probability of mutual sharing once an exclusivity payoff becomes positive. The expected probability of mutual sharing drops dramatically, once $a_F > 0$. Compare in particular $a_F = 0$ and $a_F = 10$, when $a_L = 0$, which reveals a marginal drop in mutual sharing of 45.9 percentage points. The drop is much smaller in a_L than in a_F, namely 19.99 percentage points (compare $a_L = 0$ and $a_L = 10$ when $a_F = 0$). Importantly, in the initiation of private-collective innovation, mutual knowledge sharing is substantially more fragile in F's than L's benefits from exclusivity. In other words, F's opportunity costs of sharing represented by exclusive returns threaten mutual knowledge sharing more than L's.

5. Discussion and conclusion

We investigated the relationship between incentives and knowledge sharing when initiating private-collective innovation. The first part of the study showed that incentives in knowledge sharing give rise to a knowledge-sharing game, a coordination game with multiple equilibria (rather than a public goods game, although mutual knowledge sharing makes knowledge a public good between innovators). Some of these equilibria entail mutual sharing. However, the analysis also revealed that knowledge sharing is fragile: as soon as innovators face opportunity costs of sharing, mutual sharing ceases to be an equilibrium of the knowledge-sharing game. In contrast, mutual concealment is always an equilibrium in the knowledge-sharing game, albeit an inefficient one. The theoretical analysis also revealed that many equilibria entail unilateral knowledge sharing, where one innovator shares his or her knowledge while the other conceals. These equilibria describe genuine conflicts of interest in knowledge sharing, and situations that would prevent private-collective innovation. In the second part of the study, we implemented the model in a controlled laboratory experiment with monetary incentives that took the same form as the incentive structure for knowledge sharing in the initiation of private-collective innovation. The experimental results demonstrated important asymmetries in the fragility of knowledge sharing and, in some situations, much more knowledge sharing than predicted by purely selfish behavior. Taking into account that some people care about fairness, mutual sharing outcomes can correspond to equilibrium strategies even when there is a conflict of interests between innovators.

A few limitations apply to this study. Initial decisions might be affected by repeated interactions with the same individuals. However, the goal of our study was to understand the basic incentive structure of the constituent game that underlies any repeated interaction. For this reason we studied a one-shot game that is not confounded with repeated interactions. Future works should study repeated knowledge sharing games as well as non-repeated games with the possibility of multiple followers. Our model did not include fundamental psychological dispositions explicitly. Context-specific attitudes or processes might influence knowledge-sharing behavior, such as open source ideology, altruism, or OSS development routines. The initiation of private-collective innovation could be facilitated or restrained by cultural factors specific to the context of software development, academia, biotechnology, and so on. However, from a game theoretical point of view one might argue that these factors would be incorporated into the payoffs of the knowledge sharing game (from a game-theoretical view payoffs in games are utilities anyway). To the extent that these added psychological factors do not change the *structure* of payoffs, our analysis would not change. Moreover, our conventional experimental economics approach of inducing material incentives (Smith 1982) allowed us to observe to what extent social preferences matter on top of material incentives.

This work presents four implications for theory and research. First, to our knowledge, our study is the first to investigate the role of incentives to share knowledge in the laboratory. We provide evidence that economic incentives matter greatly in initial knowledge-sharing decisions. From an economic viewpoint, sharing or concealing knowledge affects costs and benefits for innovators. These results confirm the argument of many authors that it is important to conduct cost-benefit analyses of knowledge-sharing situations (Foss and Mahnke, 2003; see also Takeishi, 2002; Szulanski, 2000). Our study also demonstrates the benefits of an experimental setup for studying knowledge sharing in various situations, in particular where decisions are difficult or impossible to observe in field studies. Building on the results from this study and the findings of other game theoretical work on knowledge sharing (Harhoff et al., 2003; von Hippel, 1987), future research needs to identify the empirical parameters, such as a variety of cost-benefit types, that enable private-collective innovation in various fields. They may include benefits from unilateral sharing such as reputation or signaling.

Second, since many people not only care for their own costs and benefits but also entertain social preferences, knowledge sharing is likely to be affected by inequality aversion, reciprocity, and efficiency considerations. We found that when the leader initiated sharing, the extent of knowledge sharing amongst the participants in the laboratory experiment exceeded the predictions from Proposition 1, and provided empirical evidence for a conjecture in the literature that social preferences impact on knowledge sharing (di Norcia, 2002; Wasko and Faraj, 2000; Faraj and Sproull, 2000; Orlikwoski, 1992; Kim and Mauborgne, 1998; Kogut and Zander, 1996; Bergquist and Ljungberg 2001). Interestingly, there is also more sharing in situations where inequality aversion and reciprocity predict little sharing, namely when the leader decides to conceal. A concern for efficiency can explain followers' sharing in these situations.

Future studies should distinguish between the various forms of social preferences that impact on knowledge-sharing decisions in the laboratory. This work should also attempt to investigate the transition from a "pure" sharing decision by the leader and the immediate follower, to those situations where interactions between leaders and followers recur, and/or other innovators enter the game. The results from this work will shed more light on the transition from the initiation to the maintenance of private-collective innovation.

Third, our study is important for understanding if and how private-collective innovation can diffuse in OSS and beyond. Recall that the incentive structure in the initiation of private-collective innovation makes knowledge sharing highly fragile. Fragility is likely in any field where an innovator contemplates sharing knowledge as a public good. By showing that the probability of knowledge sharing drops as a consequence of the opportunity costs of sharing, we operationalized and demonstrated the fragility of knowledge sharing. We found that mutual knowledge sharing is susceptible to relatively low incentives for not sharing. This result is important for the initiation of private-collective innovation: if opportunity costs to knowledge sharing are low, innovators are more likely to make their work freely available. In the case of OSS, the findings suggest that opportunities to sell innovations in the software market should influence the decision to publish software under an open source license. However, OSS licenses provide an elegant solution to the problem of the fragility of knowledge sharing in the initiation of private-collective innovation. Such licenses restrict the opportunities to release binary versions of the published code and (unlawfully) license it for a fee to a third party, thus limiting followers' opportunity costs. If innovators share through an OSS license, they know that followers cannot enjoy exclusive financial benefit from selling the software. In fact, innovators may hope that followers use the software and feed back improvements (Raymond, 1998; Lakhani and von Hippel, 2003). Future work should investigate the initiation of private-collective innovation with different license forms. Although across OSS projects in general the most common license is the GNU GPL, as we point out in footnote 2, there are various forms of licenses providing innovators with different weak or strong limitations to appropriate exclusive returns from innovation (for an overview of licenses, see Lerner and Tirole, 2005). Research should investigate the extent to which these licenses create effective incentives for initiating private-collective innovation, too.

One should expect private-collective innovation to flourish only in settings where some forms of license limit followers' opportunity costs ($a_F = 0$), and not in others. In the absence of such licenses, one should expect private or collective action models of innovation to dominate. An important emerging area for private-collective innovation incentives is research tools for life sciences and biotechnology—for example, tools for human genome research or genetic engineering of plants. In recent years there has been a dramatic expansion in the patenting of these types of tool by biotechnology firms, and authors warn that unless open source-style licenses are applied to such tools, progress could be halted (Hope, 2008: Jefferson, 2006; Broothaerts et al. 2005). In order to advance their research, universities are often forced to license expensive tools from firms. However the funding for these licenses are in many cases limited or entirely absent. Although universities often contributed to the development of these tools in the first place, researchers are often not allowed to transfer the innovation to public sector institutions or use them to develop products, for example agricultural products for developing countries. Thus, firms are repeatedly accused of blocking innovation rather than using patents to share knowledge on which others can build. Feldmann (2004) discusses how open source-style licenses in biotechnology have the potential to bring innovations in this area into the public domain, and create downstream, non-economic rewards by tapping unused innovation resources (e.g. smaller research labs or individual researchers) that traditional patenting cannot reach. Work exploring open source-style licenses in biotechnology should investigate innovators' incentives to conceal or share knowledge on research tools. An issue here is the extent to which licenses applied to research tools can prevent follower-innovators from capturing and commercially exploiting them. To what extent do open source-style licenses apply to this area, where innovation is costly, takes longer, patenting is already widespread, and where the opportunity costs (incentives to defect) may be immense from the outset? A thorough investigation of these issues will help researchers understand to what extent the widespread initiation of private-collective innovation can be expected in this area.

The initiation of private-collective innovation may also be of interest to policy scholars. Recently, many countries have adopted a policy of using OSS in governmental agencies and publicly funded institutions. Researchers have investigated the consequences of these policies for public expenditure, firm, and industry competitiveness, etc. (Ghosh, 2005; Casadesus-Masanell and Ghemawat, 2006). Policy research on OSS can be complemented with future work on the initiation of private-collective innovation. An interesting situation would occur if at least one follower-innovator for a software product were a government agency committed to OSS policy. This could potentially lower the opportunity costs of knowledge sharing, implying that innovators would be more likely to make their work freely available in the public domain. Thus, a policy could impact not only on the diffusion but also on the initiation of OSS projects. Our study cannot reach a conclusion about the effects of an OSS policy, but this is an important area for future research.

Fourth, since knowledge sharing plays a crucial role in innovation, the relationship between incentives and knowledge sharing offers fertile ground for the study of the role of incentives beyond the firm-market dichotomy. The firm is usually defined in terms of asset ownership, contracting and incentives (Holmstrom and Milgrom, 1994; Foss, 1996). But there is a continuum of external sourcing methods and hybrids between firms and markets (Leonard-Barton, 1995), which vary in terms of ownership and contracting (OSS communities are one of them). As Holmstrom and Milgrom (1994) comment, little is known about the interdependencies among the defining characteristics of firms. The role of private-collective innovation in software reinforces the need to study non-traditional forms of economic organization (e.g. Hargrave and Van de Ven, 2006). Knowledge sharing and incentives could function as signposts for innovation scholars into organizations that blend the characteristics of firms and markets.

We close with a methodological comment about the use of laboratory experimental methods to study issues in management and organization theory. We argue that studying the causal consequences of incentives in knowledge sharing requires the full observation of all costs and benefits, as well as actual decisions to share or conceal. Since these requirements are impossible to fulfill in the field, our paper was based on a laboratory study where the theoretical model of knowledge sharing was implemented. Experimental results, such as those from our study, complement field investigations. In particular, the tight results from the laboratory can help guide field research, which has the advantage of being more realistic but also the drawback that causal inferences are often unfeasible. Our paper joins recent studies[18] that use laboratory methods to study specific phenomena relevant to management and organization theory that are hard to investigate in the field.

[18] Recent examples comprise the formation of corporate cultures (Weber and Camerer, 2003), bargaining (Zwick and Chen, 1999), deception in organizational decision making (Brandts and Charness, 2003), leadership (Weber et al., 2001), incentives in mergers (Montmarquette et al., 2004) and policies to foster innovation (Meloso et al., 2008).

References

Arrow, K.J. 1984. Information and economic behavior, in *Collected papers of Kenneth Arrow,* Volume 4. Cambridge, MA: Belknap Press.

Baldwin C.Y., K.B. Clark. 2006. The Architecture of Participation: Does Code Architecture Mitigate Free Riding in the Open Source Development Model? *Management Science*. **52** 1116-1127.

Bellemare, C., S. Kroeger, A. van Soest. 2008. Measuring inequity aversion in a heterogeneous population using experimental decisions and subjective probabilities. *Econometrica* 76(4), 815-839.

Bergquist M., J. Ljungberg. 2001. The power of gifts: organizing social relationships in open source communities. Information Systems Journal. 11 305-320.

Bessen, J., E. Maskin. 2009. Sequential innovation, patents, and imitation. *RAND Journal of Economics* 40(4), 611 – 635.

Boldrin, M., D. Levine. 2001. The case against intellectual property. *American Economic Review* **92** 209-212.

Brandts, J., G. Charness. 2000. Hot vs. cold: Sequential responses and preference stability in experimental games. *Experimental Economics* **2** 227-238.

Brandts, J., G. Charness. 2003. Truth or Consequences: An Experiment. *Management Science* **49** 116-130.

Broothaerts W., Mitchell H.J., Weir B., Kaines S., Smith L.M.A., Yang W., Mayer J.E., Roa-Rodriguez C., Jefferson R.A. 2005. Gene transfer to plants by diverse species of bacteria. *Nature* **433** 629-633.

Cabrera, A., E.F. Cabrera. 2002. Knowledge-sharing dilemmas. *Organization Studies* **23** 687-710.

Camerer, C. 2003. *Behavioral game theory.* Princeton: Princeton University Press.

Camerer, C., M. Knez, and R. Weber. 1997. Coordination in organizations: A game-theoretic perspective. Zur Shapira, (ed). *Organizational Decision Making* Cambridge Series on Judgment and Decision Making, Cambridge, U.K.

Charness, G., M. Rabin. 2002. Understanding social preferences with simple tests. *Quarterly Journal of Economics* **117** 817-869.

Casadesus-Masanell, R., P. Ghemawat. 2006. Dynamic mixed duopoly: A model motivated by Linux vs. Windows. *Management Science.* **52** 1072-1084.

Dasgupta, P. and P. A. David. 1994. Toward a New Economics of Science. *Policy Research* **23** 487-521.

de Vries, R.E., van den Hooff B., de Ridder J.A. 2006. Explaining knowledge sharing - The role of team communication styles, job satisfaction, and performance beliefs. *Communication Research*. **33** 115-135

Demsetz, H. 1967. Towards a theory of property rights. *American Economic Review.* **57** 347-359.

di Norcia, V. 2002. The knowledge economy and moral community. *Journal of Business Ethics* **38** 167-177.

Dufwenberg, M., G. Kirchsteiger. 2004. A theory of sequential reciprocity. *Games and Economic Behavior* **47** 268-298.

Elster, J. 1986. *An introduction to Karl Marx.* Cambridge: Cambridge University Press.

Engelmann, D., M. Strobel. 2004. Inequality Aversion, Efficiency, and Maximin Preferences in Simple Distribution Experiments. *American Economic Review* **94** 857-869.

Falk, A., U. Fischbacher. 2006. A theory of reciprocity. *Games and Economic Behavior.* **54** 293-315.

Faraj, S., L. Sproull. 2000. Coordinating expertise in software development teams. *Management Science*. **46** 1554-1568.

Fehr, E., S Gächter. 2000. Fairness and retaliation: The economics of reciprocity. *Journal of Economic Perspectives* **14** 159-181.

Fehr, E., K. Schmidt. 1999. A theory of fairness, competition, and cooperation. *Quarterly Journal of Economics* **114** 817-868.

Feldman, R.C. 2004. The Open Source Biotechnology Movement: Is it Patent Misuse?. *Minnesota Journal of Law, Science & Technology* 6 117-167.

Fischbacher, U. 2007. z-Tree, Toolbox for readymade economic experiments. *Experimental Economics* 10(2), 171-178.

Foss, N.J. 1996. Knowledge-based approaches to the theory of the firm: Some critical comments. *Organization Science* **7** 470-476.

Foss, N.J., V. Mahnke. 2003. Knowledge management: What can organizational economics contribute? M. Easterby-Smith and M. Lyles (eds). *Handbook of Organizational Learning and Knowledge Management* (pp. 78-104). Oxford: Blackwell.

Franke, N. and E. von Hippel. 2003. Satisfying heterogeneous user needs via innovation toolkits: The case of Apache security software. *Research Policy.* **32** 1199-1216.

Garud, R., Jain, S., Kumaraswamy, A. 2002. Institutional entrepreneurship in the sponsorship of common technological standards: the case of Sun Microsystems and Java. *Academy of Management Journal* **45** 196-214.

Ghosh, R.A. 2005. Free/Libre/Open Source Software: Policy Support. Report. University of Maastricht.

Grant, R.M. 1996. Toward a Knowledge-Based Theory of the Firm. *Strategic Management Journal* **17** SI 109-122.

Hargrave, T.J., Van de Ven, A.H. 2006. A collective action model of institutional innovation. *Academy of Management Review* **31** 864-888.

Harhoff, D., Henkel, J., von Hippel, E. 2003. Profiting from voluntary infomation spillovers: How users benefit by freely revealing their innovations. *Research Policy* **32** 1753-69.

Henkel, J. 2006. Selective revealing in open innovation processes: The case of embedded Linux. *Research Policy* **35** 953-969.

Hertel, G., Niedner, S, and S. Herrmann. 2003. Motivation of Software Developers in open source Projects: An Internet-based Survey of Contributors to the Linux Kernel. *Research Policy* **32** 1159-1177.

Holmstrom B., P. Milgrom. 1994. The firm as an incentive system. *American Economic Review* **84** 972-991.

Hope, J. 2008. *Biobazaar: the open source revolution and biotechnology*. Harvard University Press: Camridge MA.

Huber, G. 1982. Organizational information systems: Determinants of their performance and behavior. *Management Science* **28** 138-155.

Jefferson, R.A. 2006. Science as Social Enterprise: The CAMBIA BiOS Initiative. *Innovations* **1** 13-44.

Jeppesen, L.B., L. Frederiksen. 2006. Why do Users Contribute to Firm-hosted User Communities? The case of computer-controlled music instruments. *Organization Science* **17** 45-63.

Kim, W.C., R. Mauborgne. 1998. Procedural justice, strategic decision making, and the knowledge economy. *Strategic Management Journal* **19** 323-338.

Kogut, B., A. Metiu. 2001. Open-source software development and distributed innovation. *Oxford Review of Economic Policy* **17** 248-264.

Kogut, B., U. Zander. 1996. What firms do? Coordination, identity, and learning. *Organization Science* **7** 502-518.

Kuk, G. 2006. Strategic Interaction and Knowledge Sharing in the KDE Developer Mailing List. *Management Science*. **52** 1031-1042.

Lakhani, K.R., R.G. Wolf. 2005. Why hackers do what they do: Understanding Motivation and effort in Free/Open Source software projects. In: Feller, J. Fitzgerald, B., Hissam S., K.R. Lakhani (eds.). *Perspectives on Free and Open Source software*. MIT Press.

Lakhani, K.R., E. von Hippel. 2003. How open source software works: „Free" user-to-user assistance. *Research Policy*. **32** 923-43.

Lerner, J., J. Tirole. 2002. Some simple economics of open source. *Journal of Industrial Economics*. **52** 197-234.

Lerner, J. and J. Tirole. 2005. The Scope of Open Source Licensing. *Journal of Law, Economics, and Organization*. 21(1):20-56.

Leonard-Barton, D. 1995. *Wellsprings of knowledge*. Harvard Business School Press.

Michailova, S., K. Husted. 2003. Knowledge-sharing hostility in Russian firm. *California Management Review* **45** 59-77.

Meloso, D., J. Copic, P. Bossaerts. 2008. Promoting intellectual discovery: patents vs. markets. *Science* 323, 1335-1339.

Montmarquette, C., J.L. Rullière, M.C. Villeval, R. Zeiliger. 2004. Redesigning Teams and Incentives in a Merger: An Experiment with Managers and Students. *Management Science.* **50** 1379-1389.

Moody, G. 2001. *Rebel Code: Linux and the Open Source Revolution*, London,UK: Penguin.

Moon, J.Y., L. Sproull. 2000. Essence of distributed work: The case of the Linux kernel. *First Monday*. **5**(11).

Nonaka, I. 1994. A dynamic theory of organizational knowledge creation. *Organization Science* **5** 14-37.

Nonnecke, B. and Preece, J. 2000. *Lurker demographics: Counting the silent*, The Hague, ACM. Proceedings of CHI 2000.

O'Mahony, S. 2003. Guarding the commons: How community managed software projects protect their work. *Research Policy*. **32** 1179-1198.

O'Mahony, S., Ferraro F. 2007. The emergence of governance in an Open Source community. *Academy of Management Journal*. **50**(5) 1079-1106.

Olson, M. 1965. *The Logic of Collective Action*. Cambridge, MA: Harvard University Press.

Orlikowski, W.J. 1992. *Learning from notes: Organizational issues in groupware implementation*. MIT Sloan Working Paper #3428-92. URL: http://ccs.mit.edu/papers/CCSWP134.html

Osterloh, M, B.S. Frey. 2000. Motivation, Knowledge Transfer, and Organizational Forms, *Organization Science* **11** 538-550.

Osterloh, M., S.G. Rota. 2007. Open Source Software Development - Just Another Case of Collective Invention?, *Research Policy* **36**(2) 157-171.

Rabin, M. 1993. Incorporating fairness into game theory and economics. *American Economic Review* **83** 1281-1302.

Raymond, E.S. 1998. Homesteading the Noosphere. *First Monday*. **3**(10).

Roberts, J., Hann, I.-H. and S. Slaughter. 2006. Understanding the Motivations, Participation and Performance of Open Source Software Developers: A Longitudinal Study of the Apache Projects. *Management Science*. **52** 984-999.

Ryan, R.M., Deci, E.L., 2000. Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *American Psychologist.* **55** 68-78

Selten, R. 1967. Die Strategiemethode zur Erforschung des eingeschränkt rationalen Verhaltens im Rahmen eines Oligopolexperimentes. Sauermann, H. (ed). *Beiträge zur experimentellen Wirtschaftsforschung* (pp. 136-168). Tübingen: J.C.B. Mohr (Paul Siebeck).

Shah, S.K. 2006. Motivation, Governance and the Viability of Hybrid Forms in Open Source Software Development. *Management Science*. **52** 1000-1014.

Smith, V. 1982. Microeconomic systems as experimental science. *American Economic Review* **72** 923-955.

Stephan, P. 1996. The Economics of Science. *Journal of Economic Literature* **34** 1199-1235.

Stuermer, M.; Spaeth, S. & von Krogh, G. 2009. Extending private-collective innovation: a case study *R & D Management* **39**, 170-191.

Szulanski, G. 2000. The process of knowledge transfer: A diachronic analysis of stickiness. *Organzational Behavior and Human Decision Processes* **82** 9-27.

Takeishi, A. 2002. Knowledge partitioning in the interfirm division of labor: The case of automotive product development. *Organization Science* **13** 321-338.

Teece, D.J. 1977. Technology transfer by multinational firms: The resource cost of transferring technological know-how. *The Economic Journal* **87** 242-261.

Teece, D.J. 1986. *The Multinational Corporation and the Resource Cost of International Technology Transfer.* Cambridge: Ballinger.

Useem, B. 1998. Breakdown theories of collective action. *Annual Review of Sociology* **24** 215-238.

von Hippel, E., G. von Krogh. 2003. The Private-Collective Innovation Model in Open Source Software Development: Issues for organization science. *Organization Science* **14** 209-223.

von Hippel, E., G. von Krogh. 2006. Free revealing and the private-collective model of innovation incentives. *R&D Management* **36** 295-306.

von Hippel, E. 1987. Cooperation Between Rivals: Informal Know-How Trading. *Research Policy* **16** 291-302.

von Krogh, G., S. Spaeth, K.R. Lakhani. 2003. Community, joining, and specialization in open source software innovation: A case study. *Research Policy.* **32** 1217-1241.

Wasko, M.M., S. Faraj 2000. "It is what one does": why people participate and help others in electronic communities of practice. *Journal of Strategic Information Systems* **9** 155-173.

Weber, R. 2003. Learning with no feedback in a competitive guessing game. *Games and Economic Behavior* **44** 134-144.

Weber, R., C. Camerer. 2003. Cultural Conflict and Merger Failure: An Experimental Approach. *Management Science* **49** 400-415.

Weber, R., Y. Rottenstreich, C. Camerer , M. Knez. 2001. The illusion of leadership: Misattribution of cause in coordination games. *Organization Science* **12** 582-598.

Zwick, R. X.P. Chen. 1999. What Price Fairness? A Bargaining Study. *Management Science* **45** 804-823.

Appendix A: Equilibria of the sequential knowledge-sharing game.

The extensive form game of Figure 1 has the following unique normal form representation, where the leader (L) is the row player and the follower (F) the column player. F has to make decisions at two information sets, and has four strategies at her disposal, which we denote as *ss*, *sc*, *cs*, and *cc*. The Nash equilibria of the extensive form game can be found in its strategic form representation. We assume that players are rational and purely self-interested.

	ss	*sc*	*cs*	*cc*
s	b_L+v_L-k, b_F+v_F-k	b_L+v_L-k, b_F+v_F-k	b_L-k, $b_F+v_F+a_F$	b_L-k, $b_F+v_F+a_F$
c	$b_L+v_L+a_L$, b_F-k	b_L, b_F	$b_L+v_L+a_L$, b_F-k	b_L, b_F

Table A1. *Strategic form representation of the knowledge sharing game*

Result A1 (Nash equilibria of the sequential knowledge sharing game if sharing is costly):
If $v_i > k > 0$, *then the only Nash equilibrium is the strategy profile* (*c*, *cc*), *i.e., L conceals, and F conceals in both subgames. This holds irrespective of* a_i, *i*=L,F.

Result A2 (Nash equilibria of the sequential knowledge sharing game if sharing is costless):
If $k = 0$, *the equilibrium strategies depend on* a_i, *i*=L,F. *We get the following pure strategy Nash equilibrium profiles (**bold** strategy profiles are subgame perfect)*:

- *If* $a_L=0$, $a_F=0$: ***(s, ss)***, ***(s, sc)***; ***(s, cc)***; ***(c, ss)***; ***(c, cs)***; ***(c, cc)***.
- *If* $a_L>0$, $a_F=0$: ***(s, sc)***; ***(s, cc)***; ***(c, ss)***; ***(c, cs)***; ***(c, cc)***.
- *If* $a_L=0$, $a_F>0$: ***(s, cc)***; (*c*, *ss*); ***(c, cs); (c, cc)***.
- *If* $a_L>0$, $a_F>0$: ***(s, cc)***; (*c*, *ss*); ***(c, cs); (c, cc)***.

Both results follow from the payoffs specified in the strategic form representation.

There is also a host of *mixed strategy equilibria*. They have the following form. In all mixed strategy equilibria, L plays a pure strategy of either concealing or sharing with probability 1. In other words, in all mixed strategy equilibria it is only F who mix. Their mixing probabilities are as follows:

- If $a_L=0$ and $a_F>0$, then F mixes *s* and *c* in both subgames with probability 0.5. L conceals.
- If $a_L=10$ and $a_F>0$, there are two equilibria, in both of which L conceals: (i) in the subgame after L has chosen *c*, F plays *c* with probability 0.6 and *s* with probability 0.4. In the subgame after *s* F plays *c* with probability 0.4 and *s* with probability 0.6. (ii) In the subgame after L has chosen *c*, F plays *c* with probability 0.33 and *s* with probability 0.67. In the subgame after *s* F plays *c* with probability 0 and *s* with probability 1.
- If $a_L=20$ and $a_F>0$, there are two equilibria, in both of which L conceals: (i) in the subgame after L has chosen *c*, F plays *c* with probability 0.67 and *s* with probability 0.33. In the subgame after *s* F plays *c*

with probability 0.33 and *s* with probability 0.67. (ii) In the subgame after L has chosen *c*, F plays *c* with probability 0.5 and *s* with probability 0.5. In the subgame after *s*, F plays *c* with probability 0 and *s* with probability 1.

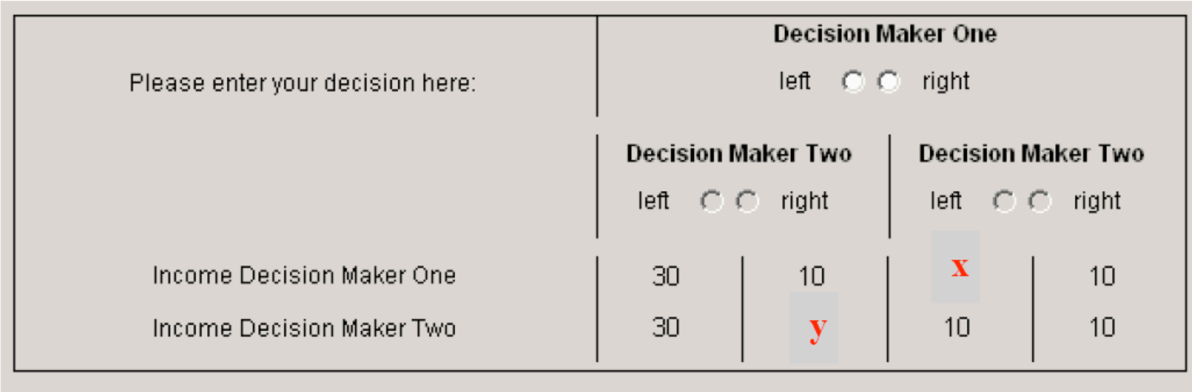
- If a_L=30 and a_F>0, there are two equilibria, in both of which L conceals: (i) in the subgame after L has chosen *c*, F plays *c* with probability 0.7143 and *s* with probability 0.2857. In the subgame after *s*, F plays *c* with probability 0.2857 and *s* with probability 0.7143. (ii) In the subgame after L has chosen *c*, F plays *c* with probability 0.6 and *s* with probability 0.4. In the subgame after *s*, F plays *c* with probability 0 and *s* with probability 1.
- If a_L=0 and a_F=0, there are two equilibria, in both of which F mixes between *s* and *c* with probability 0.5. In one equilibrium L shares and in the other L conceals with probability 1.
- If a_L>0 and a_F=0, there are four equilibria, which have the same structure as the equilibria described above for a_F>0. In two equilibria, L shares with probability 0 and in two equilibria L shares with probability 1. The mixing probability of F corresponds to those for a_L=10, a_L=20 and a_L=30.

Appendix B: Experimental Instructions

This experiment is about economic decision processes. Please read the following instructions carefully. You are not allowed to talk during the experiment. If you have any questions, please refer directly to the instructor.
The points incurred as income during the experiment are converted to Swiss francs and paid out cash. In the experiment, your income is calculated in points.
One point = 4 Rappen**.**

Description of the decision situation

- The decision situation in this experiment involves two decision makers.
- The first decision maker decides first: he/she can choose either “left” or “right.”
- The second decision maker also faces the choice between left and right. He/she has to choose before he/she knows how the first decision maker has decided. This means that the second decision maker has to choose between left and right, both where the first decision maker chose left and where he/she chose right.
- The relevant decision situation is displayed schematically here, as you will see it later on the screen:



How decisions are made

The incomes for both decision makers derive from the combination of both decisions. If, for example, the first decision maker chooses left and the second also chooses left, both receive an income of 30 points. If both choose right, they receive an income of 10 points each.

The income for the first decision maker is shown in the first row. The second row indicates the income for the second decision maker.

Altogether, you have to decide for **16 situations**. The incomes generated by the decision combinations vary across the situations:

(1) if the first decision maker chooses left and the second chooses right;

(2) if the first decision maker chooses right and the second subsequently chooses left.

In the display above, the incomes from these situations are marked with x and y. Only the incomes x and y vary from period to period across the situations. During each period, the current values of x and y will be labeled in red on the screen. All other incomes remain **unchanged** across the 16 periods.

How do you make decisions?

- You will be assigned the role of first or second decision maker **at random**. Your role assignment will be communicated on the screen.
- Through all 16 periods you will be either the first or the second decision maker.
- During **every one** of the 16 periods of the experiments you will be rematched to another **randomly chosen** counterpart.
- If you are the **first decision maker** you have to decide in every period whether you choose left or right.
- If you are the **second decision maker** you have to decide in every period whether you choose left or right for **both** possible decisions (left or right) taken by the first decision maker.
- The income from all decision situations will be aggregated and converted to Swiss francs.
- During the 16 periods you will not know how your counterparts decided. You will be informed about your income at the end of the experiment.
- Your income derives in every period from the combination of decisions, given your decision and your counterpart's decision.

- Before the start of the experiment, you will have to answer two control questions on the screen.

Appendix C

In this appendix we document the frequency of individual decisions for each of the 16 games. We also analyze the strategies and equilibria that subjects actually played.

	s_L	s_F after s_L	s_F after c_L
a_L=0, a_F=0	0.84211	0.73214	0.45536
a_L=10, a_F=0	0.61404	0.67857	0.45536
a_L=20, a_F=0	0.48246	0.71429	0.53571
a_L=30, a_F=0	0.44737	0.74107	0.40179
a_L=0, a_F=10	0.55263	0.28571	0.42857
a_L=10, a_F=10	0.34211	0.19643	0.47321
a_L=20, a_F=10	0.30702	0.26786	0.37500
a_L=30, a_F=10	0.35088	0.28571	0.37500
a_L=0, a_F=20	0.45614	0.17857	0.51786
a_L=10, a_F=20	0.34211	0.16964	0.47321
a_L=20, a_F=20	0.25439	0.16964	0.49107
a_L=30, a_F=20	0.18421	0.08929	0.47321
a_L=0, a_F=30	0.42105	0.13393	0.46429
a_L=10, a_F=30	0.23684	0.12500	0.47321
a_L=20, a_F=30	0.21053	0.09821	0.43750
a_L=30, a_F=30	0.17544	0.11607	0.41071

Table C1. *Frequency of chosen actions*

In section 2 we explained that a theoretical property of the sequential knowledge-sharing game is the multiplicity of equilibria in the absence of out-of-pocket costs of knowledge sharing. The next step is to investigate which of the equilibria are behaviorally relevant. We describe them in Table C2, which summarizes the distribution of choices over the strategy space as a function of the opportunity costs of sharing.

The leader (L) has two strategies, share (*s*) and conceal (*c*). The follower (F), however, has four strategies (see Figure 1): he/she can (i) share if L shares or conceals (denoted *ss*), (ii) conceal if L shares and share if L conceals (denoted *cs*), (iii) share if L shares and conceal if L conceals (denoted *sc*), and (iv) conceal irrespective of L's choice (denoted *cc*). Therefore, the strategy space of the whole game is (*s*, *c*)x(*ss*, *sc*, *cs*, *cc*). Since we have applied the strategy method in our design, we can observe the behavior in the complete strategy space of the 16 games.

Table C2 shows the strategies and—given the subjects' actual choices—lists the expected distribution of strategy combinations for the relevant cases of (a_Fxa_L)-combinations (each row sums to 100 percent). Under the assumption that L and F are randomly and independently matched, the expected distribution is determined by multiplying the observed frequency of *s*- or *c*-choices by L and the frequency of F's respective strategy. For instance, in the game with (a_L=0, a_F=0), L decided for *s* in 84.21 percent of the cases, and F chose the strategy *ss* in 38.39 percent. This makes an expected frequency of observing the (*s*, *ss*)-strategy combination of 38.39x84.21=32.33 percent. Equilibrium strategies are shaded, and bold letters indicate subgame perfect strategy combinations.

	Outcome is ...							
	mutual concealment		unilateral knowledge sharing				mutual sharing	
	(*c*, *sc*)	(*c*, *cc*)	(*s*, *cs*)	(*s*, *cc*)	(*c*, *ss*)	(*c*, *cs*)	(*s*, *ss*)	(*s*, *sc*)
a_L=0, a_F=0	5.50	**3.10**	6.01	**16.54**	**6.06**	**1.13**	**32.33**	**29.32**
a_L>0, a_F=0	15.31	**10.69**	3.53	**11.33**	**19.21**	**3.32**	20.37	**16.24**
a_L=0, a_F>0	5.45	**22.28**	17.87	**20.28**	4.98	**19.63**	4.54	4.97
a_L>0, a_F>0	6.98	**33.88**	9.86	12.35	5.38	**27.04**	1.96	2.54

Table C2. *Expected frequency of strategy combinations given subjects' choices*

Strategy profiles (*c*, *sc*) and (*c*, *cc*) induce a *mutual concealment* outcome ((*c*, *sc*) is a non-equilibrium profile, however). When no player has opportunity costs of sharing knowledge, then the expected frequency of mutual concealment is 8.6 percent. When both players have positive exclusivity payoffs, the expected frequency of mutual concealment jumps up to 40.86 percent.

The four strategy profiles—(*s*, *cs*), (*s*, *cc*), (*c*, *ss*), (*c*, *cs*)—induce *unilateral knowledge sharing*, which allows at least one party to benefit if exclusivity is possible. For instance, if (a_L>0, a_F>0), then we expect unilateral knowledge sharing in 54.63 percent of cases. Particularly interesting is the strategy combination (*c*, *cs*), which induces unilateral sharing that results in an unequal payoff benefiting L. In our data, the expected frequency at which F is prepared to resolve indifference in favor of L, if L conceals, is 27.04 percent.

Finally, the strategy profiles (*s*, *ss*) and (*s*, *sc*) induce a mutual sharing outcome (compare Figure 1). In case no player has a positive exclusivity payoff, that is if a_L=0 and a_F=0, we observe that the expected frequency of strategy combinations leading to mutual sharing (as an equilibrium) is 61.65 percent. This percentage drops dramatically once at least one player has positive opportunity costs of sharing knowledge. If L alone has positive opportunity costs (a_L>0, a_F=0), the expected frequency of strategies that induce mutual sharing outcomes is 36.61 percent (16.24 percent are consistent with equilibrium play). If only F has positive opportunity costs (a_L=0, a_F>0), mutual sharing does not occur in equilibrium. However, we observe mutual sharing in 9.51 percent of all strategy combinations. In case both have positive exclusivity benefits (a_L>0, a_F>0), the likelihood of strategies supporting mutual sharing drops to 4.5 percent.

In summary, mutual sharing occurs particularly when it is an equilibrium of the knowledge-sharing game. Yet, for the reasons discussed in section 2.4, we observe mutual knowledge sharing even if it is not an equilibrium.

Appendix D: An econometric analysis of sharing decisions

An econometric analysis provides further support for Results 1 and 2. Table D1 provides econometric evidence for the impact of the exclusivity benefits a_F and a_L on (a) F's knowledge sharing decision after L decided to share; (b) F's knowledge-sharing decision after L concealed, and (c) L's knowledge-sharing decision. As the share-conceal decision is binary, we ran a logit regression with the binary variable (1=share, 0=conceal) as the dependent variable. The independent variables are dummies for the respective levels of a_F and a_L; the omitted benchmarks are $a_F = 0$ and $a_L = 0$. To account for the fact that a subject's decisions might be correlated across games, we calculate robust standard errors with clustering of decisions at subject level (between subjects decisions are independent by design).[19] Since coefficients of logit estimations are hard to interpret, we report the marginal effects in Table D1, which shows how an increase in a_i, i = L,F, influences the probability of sharing.[20]

	(a) Followers' share or conceal decision after leader has shared	(b) Followers' share or conceal decision after leader has concealed	(c) Leaders' share or conceal decision
Dummy $a_L = 10$	-0.0450 (0.0221)*	0.0044 (0.0225)	-0.1701 (0.0263)**
Dummy $a_L = 20$	-0.0218 (0.0219)	-0.0067 (0.0206)	-0.2524 (0.0300)**
Dummy $a_L = 30$	-0.0286 (0.0189)	-0.0596 (0.0216)**	-0.2833 (0.0363)**
Dummy $a_F = 10$	-0.4572 (0.0365)**	-0.0508 (0.0240)*	-0.1914 (0.0311)*
Dummy $a_F = 20$	-0.5685 (0.0353)**	0.0286 (0.0187)	-0.2832 (0.0367)**
Dummy $a_F = 30$	-0.6039 (0.0365)**	-0.0132 (0.0267)	-0.3453 (0.0390)**
Observations	1824	1824	1824
Wald $\chi^2(6)$	183.5**	17.75**	149.73**
Pseudo R^2	0.2113	0.0043	0.0916

Robust standard errors in parentheses; * significant at 5%; ** significant at 1%

Table D1. *Marginal effects of logit estimation of the sharing decision.*

Column (a) reports the results of how F change their knowledge-sharing decision, relative to the benchmark game where $a_L = a_F = 0$. Holding L's exclusivity payoffs constant, we find that the drop in F's knowledge-sharing rates is quite dramatic and highly significant. Relative to the benchmark, the likelihood F will share drops by more than 45 percent, if his/her exclusivity payoff changes from 0 to 10. The likelihood of sharing drops by more than 60 percent, once $a_F = 30$. L's exclusivity payoff does not matter: a χ^2-test cannot reject the null hypothesis that the three dummies are jointly not different from zero (p=0.194). In other words, in their knowledge-sharing decision F do not take L's exclusivity payoff into account when deciding whether to share knowledge or not.

Column (b) shows F's knowledge-sharing decision, after L has concealed. The estimated changes in probability of sharing are small (although in two cases significant) and we do not find a systematic pattern.

Column (c) documents L's sharing rate, relative to the benchmark. L is significantly less likely to share if his/her own exclusivity payoff a_L is high, but also if F's exclusivity payoff a_F is high.

[19] A random effects panel model yields very similar results.

[20] Specifically, we calculate the marginal effects when all dummies are zero. The marginal effect measures dy/dx for a discrete change of a dummy variable from 0 to 1.