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DRUID Working Paper No. 06-25

The Jukebox Mode of Innovation –
a Model of Commercial Open Source Development

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October 2006

Abstract:
In this paper, I describe and analyze the phenomenon of informal development collaboration between firms in the field of embedded Linux, a type of open source software. To explain the observed phenomenon of voluntary revealing, I develop a duopoly model of quality competition. The central assumptions are that firms require two complementary technologies as inputs, and differ with respect to the relative importance they attach to these technologies. The main results are, first, that a regime with compulsory revealing can lead not only to higher profits, but also to higher product qualities than a proprietary regime. Second, when the decision to reveal is endogenized equilibria arise with voluntary revealing by both players.

Key words: Innovation; development collaboration; open source software; embedded Linyx

Jel codes: L11; L15; L86

1 Introduction

There is a long-standing debate on what the ideal incentive system for innovation would be. The recent surge of open source software (OSS) has added new aspects to this debate. Open source licenses do not allow royalties to be charged, and every user of the software is entitled to obtain, to modify and to redistribute the source code (Open Source Initiative 2003). Hence, options for both appropriation and protection of open-source-related innovations are restricted, and one would correspondingly expect reduced incentives to innovate. Nonetheless, commercial firms undertake many and in some cases large contributions to such software (e.g., Moody 2001).

A particularly interesting case of commercial OSS development is that of "embedded Linux". The term denotes variants of the operating system Linux that are used in "embedded devices" such as VCRs and machine controls. Embedded Linux is unusual in that most established motives for commercial firms to contribute to OSS do not apply. Still, empirical evidence presented in Section 2 shows that firms developing embedded Linux do disclose considerable amounts of their code (Henkel 2005). They do so mainly in order to elicit informal development support from other firms—in particular their competitors—and indeed receive such support. In this context it is important to note that, even though embedded Linux comes under an OSS license, firms do have considerable latitude with respect to revealing their code or keeping it secret.

To explain this informal collaboration I propose a mechanism hitherto not described in the literature. It rests upon complementarity between technologies and heterogeneity between firms' technology needs. It is dubbed the "jukebox mode of innovation"—an analogy to heterogeneous tastes of music-lovers who feed a jukebox. I develop a duopoly model of quality competition in which the above characteristics interact to enable collaboration. The central assumptions of the model are deduced from empirical findings and supported by quotes from expert interviews (Henkel 2003).

I find that when revealing is compulsory, an equilibrium with each firm specializing in the development of one technology exists for most parameter values considered. In this equilibrium, each firm adopts its competitor's developments. Central results then are the following. First, for medium to high levels of heterogeneity and low to medium intensity of competition not only firm profits, but also *product qualities* are higher under the open regime than under the proprietary regime. While larger profits are not too surprising due to cost savings under the open regime, superior product qualities *are* surprising (cf., on

spillovers in cost-reducing R&D, Spence 1984): Given the positive externality that firm A's investment in product quality has on its competitor, one would have expected a lower marginal return to quality improvements than under the proprietary regime, and hence a lower equilibrium quality. The second main result is that, when the choice between revealing and secrecy is endogenized the advantages of informal collaboration are not lost in a prisoner's dilemma. This is the case, e.g., in the model devised by Eaton & Eswaran (1997), who obtain technology sharing as an equilibrium only in a repeated game. Here, in contrast, equilibria with both firms opting to reveal exist in a one-shot game.

The "jukebox mode of innovation" present in embedded Linux is highly relevant for the embedded systems industry. This industry is huge—of 6.2 billion processors manufactured in 2002 more than 98% went into embedded systems (Ganssle & Barr 2003). Of these, a considerable share is running embedded Linux since, according to a survey by VDC (2004), it is one of the three most widely used operating systems in this field. Hence, studying the development mode of embedded Linux not only reveals a new mechanism of informal collaboration, but also helps to better understand a large and fast-growing industry. Furthermore, the model is applicable to other instances of OSS development where firms' technology needs are heterogeneous, technologies are complementary, and competition is not too strong. Examples are most middleware software packages, in particular the Apache webserver software (Franke & von Hippel 2003). Since revealing in my model is voluntary, not forced by the OSS license, the model should also be applicable to non-OSS software, as will be discussed in Section 6.

The mechanism I analyze is related to, but different from other instances of voluntary revealing of innovations. Allen (1983), in his study of 19th century iron production in England, describes situations of "collective invention" in which firms revealed details on improvements of their furnaces (see also Cowan & Jonard (2003) and Nuvolari (2004)). In Allen's words, collective invention "differs from R&D since the firms did not allocate resources to invention—the new technical knowledge was a by-product of normal business operation" (Allen 1983, p. 2). Thus, the firms were users of their innovations; furthermore, they had largely homogeneous technology needs. This is also true for those instances of OSS development that have been likened to collective invention by Meyer (2003), Nuvolari (2001), and Osterloh & Rota (2004). In contrast, I analyze a situation where firms do allocate resources to R&D, where they benefit from their innovations by selling them, and where heterogeneity of technology needs plays a central role.

Under certain conditions, free revealing might be favored by sequentiality of the innovation process. Bessen & Maskin (2000) present a duopoly model in which firms' innovative

steps are sequential and complementary to each other, and show that the availability of patent protection can be an impediment to innovation. The situation they analyze is somewhat similar to the one observed in the field of embedded Linux, but differs in important points. Heterogeneity of technology needs does not play a role in their model, and innovative steps are sequential rather than simultaneous. Furthermore, the decision to reveal is not endogenized. Harhoff, Henkel & von Hippel (2003) model a mix of user innovation—voluntarily made public—and subsequent, complementary manufacturer innovation. These authors do consider complementarity between technologies and heterogeneity in technology needs. Still, their results do not explain the phenomena under study in this paper since, in their model, complementary innovation is performed by a supplier, not by a competitor.

Fershtman & Kamien (1992) analyze under what conditions firms requiring two complementary technologies for their products would be willing to engage in cross-licensing instead of developing both technologies in-house. The situation they look at is thus quite similar to that under study in this paper. However, when collaboration in the form of cross-licensing arises in their model it is *contract-based*, while informal collaboration *without* contractual obligation is precisely what this paper focuses on. Beyond that, also heterogeneity of needs does not play a role in their model.

Complementarity is the driving force also behind the concept of "absorptive capacity" introduced by Cohen & Levinthal (1990). The term refers to knowledge and skills that enable a firm to benefit from incoming knowledge spillovers, and for its build-up typically requires internal R&D. Wiethaus (2005) shows that firms might choose *identical* broad R&D approaches when spillovers are large, since the latter can best be exploited with an absorptive capacity based on the same R&D approach. His results apply to embedded Linux insofar as choosing Linux over alternative operating systems enables a firm to benefit from incoming spill-overs from other firms working on this software. However, Wiethaus' model does not address how firms behave *given* heterogeneity of technology needs *within* embedded Linux. In contrast to Wiethaus (2005), Kamien & Zang (2000) and Gerlach, Rønde & Stahl (2005) argue that larger spillovers will make competing firms pursue firm-*specific* approaches, since then outgoing knowledge flows do not benefit the competitor. Also these models provide only limited insights into the phenomena observed in the field of embedded Linux. Here, technological heterogeneity is *given* by the diversity of applications of embedded Linux (as opposed to emerging endogenously from the model), while *outgoing spillovers* are endogenous.

The remainder of the paper is organized as follows. In Section 2, I present empirical

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evidence on the informal development collaboration observed in embedded Linux. The model set-up is defined in Section 3. Section 4 presents the results from the model analysis. Section 5 links these results to empirical observations and discusses model assumptions. Conclusions are drawn in Section 6.

2   Informal collaboration in Embedded Linux

This paper is motivated by a qualitative empirical study (Henkel 2003) and a large-scale survey (Henkel 2005) of embedded Linux. This term denotes variants of the Linux operating system that are in one way or another adapted to embedded devices. Correspondingly, "developing embedded Linux" refers to the development of various modules or extensions that make Linux suitable for embedded systems. Examples are the *RTAI* real-time module ("Real-Time Application Interface"), the toolkit *busybox*, the "shrunk" C library *uclibc*, and architecture-specific code for processors used in embedded devices. While all variants of Linux largely share the same code base, modules such as those mentioned above differentiate embedded from standard Linux.

Unlike general-purpose devices such as PCs, embedded devices are built for a specific purpose. Examples are mobile phones, VCRs, machine controls and power plants. Market analysis as well as everyday experience show that embedded devices are becoming ever more widespread (Balacco & Lanfear 2002). Their fields of application are extremely heterogeneous, which entails a large diversity of hardware and software. Embedded software may have to fulfill particular requirements with respect to stability, real-time capability, and low memory needs. This heterogeneity has led to high industry fragmentation in the field of embedded operating systems. Adaptation of existing operating systems to individual needs is common, and even in-house development by device manufacturers is still rather widespread.

Such in-house development has, in recent years, become less attractive due to increasing complexity of embedded devices (Webb 2002). This is one of the reasons why, as an alternative to licensing a proprietary embedded operating system, embedding Linux has emerged as an attractive option. Linux is a fully-fledged, stable, and well maintained operating system. Due to its modularity (cf. Baldwin & Clark 2003) and its being open source software, it is well suited for adaptation to individual needs and is by now widely used in embedded systems (Lombardo 2001, Balacco & Lanfear 2002, Webb 2003, VDC 2004). Its development is driven by specialized software firms (e.g., FSMLabs, Lynux-

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Works, MontaVista, and TimeSys in the US and Denx Software, Emlix, Mind and Sysgo in Europe), board vendors (e.g., Hitachi, Intel, and Motorola), and device manufacturers (e.g., Philips, Sharp, and Siemens) (Henkel 2003).

The commitment of commercial firms to embedded Linux may seem surprising, given that Linux is licensed under the General Public License (GPL). This license requires that all further developments based on the respective software be themselves licensed under the GPL (Free Software Foundation 1991). This implies that by the time a device running embedded Linux comes onto the market, the source code of the specific version of embedded Linux it contains must be made available to all buyers. If a device is sold to the mass market this implies that the code is all but publicly available—and competitors can freely use it. Yet, considerable latitude with respect to revealing code does exist. A firm can choose to be extremely "open" by making its code available to the public right after development. Alternatively (and in accordance with the GPL), it can give the code only to (possibly few) paying customers, and only when the device comes to market. Such delay affords considerable protection given the fast pace of the embedded systems market and the fact that lead time is generally considered a quite effective means of protection (e.g., Sattler 2003). Furthermore, it is accepted (if disputed) practice to make drivers (specific software modules that link the operating system to hardware components) available only as loadable binary modules, not as source code (Marti 2002).

The above means of protection are indeed widely used, but *selectively*: very often, firms forgo available protection and voluntarily reveal their code (Henkel 2005). Among the motives to do so, those related to external development support rank highly. The statement *". . . because other developers make bugfixes and reveal them"* received agreement from 69.7% of respondents, disagreement from 11.5% ($N = 134$).[2] For the statement, *". . . because others develop the code further and reveal their developments in turn"* 67.9% of responses were positive, 14.2% negative. For dedicated software firms, also motives related to marketing are important. However, most other motives suggested in the literature on commercial OSS development do not apply.[3]

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[2]Survey participants were offered twelve motives of why their firm contributes code to public OSS projects, and were asked to indicate their level of agreement on a 5-point scale ranging from "strongly disagree" to "strongly agree".

[3]Garnering development support from hobby programmers (Baake & Wichmann 2003, Dahlander & Magnusson 2005) can be ruled out as a motive since embedded Linux is nearly exclusively developed by firms. Standard setting, IBM's explicit goal in its support of Linux as a server operating system (Moody 2001, p. 292), is not an issue for most firms engaging in embedded Linux, which basically require a reliable operating system for their devices. Also the motive to increase demand for a complement to the software can largely be ruled out: Embedded Linux code is a built-in part of their devices for hardware firms, and

As argued above, there is high *heterogeneity* between firms' technology needs in the field of embedded Linux. For informal development collaboration, this has two implications. First, heterogeneity limits the negative competitive effects of free revealing, as illustrated by Quote (1) below.[4] Since the software is to some degree specific to the respective device, it is of lower value to competitors who can in most cases not use it without modification (Quote 2). Second, heterogeneity prevents a waiting game since it is unlikely that someone else will reveal the exact piece of software that a firm requires at a certain point in time (Quote 3).[5] Despite heterogeneous technology needs, once a specific development has been made public other firms might find it useful as a basis for further developments (Quotes 4, 5). In particular, since it adds to the overall quality of embedded Linux, a revealed improvement to one technology may make it worthwhile for some other agent to develop another technology further (Quote 5). Hence, there is *complementarity* between the various technologies that make up embedded Linux. For example, improving the networking capabilities makes more sense the better the real-time features of the operating system. These two aspects—heterogeneity in technology needs and complementarity between individual technologies—are at the center of the model developed in the following section.

(1) *"When you look at it closely you find that many [firms] pursue somewhat different goals. In RTAI [Real-Time Application Interface] they are no real competitors, even though that can happen now and then."* (Software vendor, EU)

(2) *"The embedded market is so extremely fragmented that no solution fits all needs. That is, the demand for specific adaptations is enormous."* (Device manufacturer, EU)

(3) *"We're very much customer-driven. If the customer needs something and it's not available in the open source, we'll just do it. And we're not going to wait for somebody else to do it. I think everybody else sees that about the same way."* (Software vendor, US)

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the core product for dedicated software firms. While signaling technical prowess (Lerner & Tirole 2002) is, to some degree, a motive for software firms to reveal code, it falls short of explaining contributions by hardware manufacturers. Finally, firms that develop OSS as *users* (Franke & von Hippel 2003, von Hippel 2001) will typically be more willing to reveal it than firms *selling* their code (Henkel & von Hippel 2005). However, firms active in embedded Linux belong to the second category.

[4]Quotes are taken from 30 interviews conducted by the author in 2002 and 2003 (Henkel 2003).

[5]Heterogeneity of needs also plays a central role in the models of OSS development devised by Bessen (2001) and Johnson (2001). However, heterogeneity works in a different way in these approaches than in the present one.

(4) *"There are some people out there who do work in an area that we take advantage of, and take advantage of our work."* (Software vendor, US)

(5) *"Usually [the further development of embedded Linux] is not considered to be a joint effort in the case of the embedded Linux vendors [. . .], it is more of a leveraging of other works to fit a market niche, so they are done somewhat isolated yet leveraged."* (Software vendor, US)

The situation described is similar to that of a bar where several patrons feed the jukebox. In this metaphor, the overall operating system, made up of modules from various contributors, corresponds to a whole night of music at the bar, made up of individual pieces of music. Each person feeding the jukebox wishes to hear a particular song that is unlikely to be chosen by someone else. Still, all others also benefit from the music. Thus, the public goods problem is overcome by heterogeneity in taste. Due to this analogy, the innovation mechanism explored in this paper is dubbed the "jukebox mode of innovation".

3 Model set-up

I develop a duopoly game in which firms A and B compete in the quality of their products. Each firm offers one product, each of which requires two technologies (T1 and T2) as input. One can think of these technologies as modules that each firm adds on top of the common and publicly available code base of embedded Linux. This common code base does not appear in the model. The firms' technology levels in technologies T1 and T2 are denoted by q_{Xi}, where $X \in \{A, B\}$, $i \in \{1, 2\}$. In order to attain technology level q_{Ai} firm A can bear the corresponding development cost to attain the "development level" $d_{Ai} = q_{Ai}$. Alternatively, if B has developed *and revealed* d_{Bi}, A can adopt B's development at no cost, yielding $q_{Ai} = q_{Bi} = d_{Bi}$ and $d_{Ai} = 0$ (see below for the game's timing structure). I assume that a technology can only either be completely adopted or be completely developed in-house.[6]

The profit functions are $\Pi_A(q_{A1}, q_{A2}, q_{B1}, q_{B2})$ and $\Pi_B(q_{A1}, q_{A2}, q_{B1}, q_{B2})$.[7] They are

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[6]This assumption is justified for developments that have to be done "in one go". That is, they can not be broken up in sub-modules or in consecutive steps that each lead to a useable piece of software.

[7]More precisely, Π_X also depends on the development levels d_{X1} and d_{X2}. Hence, in order to account correctly for development cost the profit functions should carry as additional arguments two dummy variables indicating if technology i is developed in-house or adopted from the competitor. However, in order to avoid overly burdensome notation I do not make these dependencies explicit. Instead, I will point out when the cost part of the profit function is modified due to spill-overs from the competitor.

parameterized by three parameters a, b, and c, modeling homogeneity of technology needs (a), complementarity between technologies T1 and T2 (b), and the intensity of competition (c). These parameters will explicitly appear in the concrete functional form of Π_X to be defined below (see equations (1) to (3)). I make the following assumptions:

(1) Symmetry: $\Pi_A = \Pi_B$ when $q_{A1} = q_{B2}$, $q_{A2} = q_{B1}$. That is, T1 plays the same role for firm A as T2 does for firm B, and T2 for firm A corresponds to T1 for firm B.

(2) The profit function can be split into a revenue function R and a cost function K which is separable: $\Pi_A(q_{A1}, q_{A2}, q_{B1}, q_{B2}) = R_A(q_{A1}, q_{A2}, q_{B1}, q_{B2}) - K_{A1}(q_{A1}) - K_{A2}(q_{A2})$ (if A develops both T1 and T2 in-house).

(3) Concavity: $\partial^2 \Pi_A / \partial q_{Ai}^2 < 0$ for $i = 1, 2$.

(4) The mixed partial derivatives vanish: $\partial^2 \Pi_A / \partial q_{Ai} \partial q_{Bj} \equiv 0$ for $i, j = 1, 2$ (note that one derivative is with respect to A's technology level q_{Ai}, the other one with respect to B's technology level q_{Bj}).

(5) Revenues increase in the respective firm's technology levels: $\partial R_X / \partial q_{Xi} > 0$. Revenues vanish when technology levels are zero: $R_A(0, 0, q_{B1}, q_{B2}) = 0$.

(6) $a \in [0, 1]$ measures the degree of *homogeneity in technology needs*. Homogeneous technology needs are modeled by $a = 1$. If $a < 1$, then technology T1 is more important for A than T2, and vice versa for B. For Π_A: for $q_{A1} = q_{A2} \wedge q_{B1} = q_{B2}$, $\partial \Pi_A / \partial q_{A1} = \partial \Pi_A / \partial q_{A2}$ if $a = 1$, and $\partial \Pi_A / \partial q_{A1} > \partial \Pi_A / \partial q_{A2}$ if $a < 1$. Furthermore, if $a = 0$ then $\partial \Pi_A / \partial q_{A2} = 0$ and $R_A(0, q_{A2}, q_{B1}, q_{B2}) = 0$.

(7) $b \geq 0$ models the degree of *complementarity* between T1 and T2. For $b = 0$, there is no complementarity ($\partial^2 \Pi_A / \partial q_{A1} \partial q_{A2} \equiv 0$), while $\partial^2 \Pi_A / \partial q_{A1} \partial q_{A2} > 0$ for $b > 0$.

(8) $c \geq 0$ parameterizes the *intensity of competition*. For $c = 0$, competitive pressure vanishes ($\partial \Pi_A / \partial q_{B1} \equiv \partial \Pi_A / \partial q_{B2} \equiv 0$), while $\partial \Pi_A / \partial q_{Bi} < 0$ ($i = 1, 2$) for $c > 0$.

Assumptions 1 through 4 are made to simplify the analysis. Assumption 5 is obvious. Assumptions 6 through 8 define how the central characteristics of the model are implemented in the profit functions.

As to the game's timing structure, I analyze a three-stage and a four-stage simultaneous-move game. In the three-stage game, firms decide about entering the market, then choose

the technologies they will develop (none, 1, 2, or both), and finally determine the development levels for the chosen technologies. I compare a "proprietary" regime where all developments are kept secret to an "open" regime where revealing is compulsory. The latter can be interpreted as an idealized type of OSS development where no latitude exists with respect to keeping innovations secret. In the four-stage game, revealing is endogenized. After the market-entry decisions, in the newly introduced stage two, firms have to commit either to revealing their developments or to keeping them secret. This timing is motivated by the observation that firms tend to have long-term strategies with respect to revealing their code, which are based on a firm's relationship to the open source community, on its culture, and on its employees and their attitudes. All of these characteristics can not easily be changed in the short term. A similar timing structure underlies the model by Baake & Wichmann (2003).

The restriction to only two possible actions—full revealing and complete secrecy—is a simplification made for purposes of the analysis. In reality, firms might reveal some of their developments and hold back others. All actions are observable, such that there is full information. The equilibrium concept employed is subgame perfection (Selten 1965).

The model formulation laid out above will be used to derive general results in Section 4.1. In 4.2, I will employ a concrete functional form for the profit functions in order to pursue the analysis in more detail. In this functional form, the firms' product qualities as functions of their technology levels are defined as

$$Q_A = q_{A1} + aq_{A2} + bq_{A1}q_{A2} , \qquad Q_B = aq_{B1} + q_{B2} + bq_{B1}q_{B2} . \tag{1}$$

Development costs borne by firm X for technology i are given by[8]

$$K_{Xi} = d_{Xi}^2 . \tag{2}$$

The quadratic form of the cost function models capacity restrictions. An additional linear term would make sense, but is omitted in order to keep the analysis tractable. Its absence implies that developing each technology to at least some small level is always preferable to doing without it. This assumption does not restrict the model's generality too much.

Competition takes place in product qualities Q_A, Q_B. Buyers' utility as well as price

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[8]The fact that the cost term does not carry a coefficient does not constitute a restriction of generality, since by re-scaling technology levels and profits a coefficient β in the cost term can be scaled to $\tilde{\beta} = 1$.

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setting are not made explicit in order to keep the model tractable. Profits are defined as

$$\Pi_A = Q_A - cQ_B - K_A \, , \qquad \Pi_B = Q_B - cQ_A - K_B \, . \qquad (3)$$

Before I proceed with the model, it may be important to comment on the two parameters a and c. It is plausible that firms with very similar technology needs (high a) will often also have similar market offerings, and hence face stronger competition (high c) for lack of differentiation. In the real world, a and c will thus be positively correlated. However, this does not mean that they can not vary independently. For example, in a growing market where firms face capacity restrictions, competition can be weak despite identical technologies and market offerings. In contrast, firms using different technologies can compete strongly with each other, in particular when buyers have to decide not only between sellers but also between technologies. It is thus justified to treat a and c as independent parameters.

4 Results

4.1 General profit functions

For a general profit function the game can not be solved completely. This is simply due to the fact that, e.g., high fixed cost of market entry may lead to "no entry" by both players being the only equilibrium of the overall game. However, assuming that market entry has taken place, the following central results can be proved.

Proposition 1 *Assume that assumptions (1) to (8) hold, that $b > 0$ (complementarity), and that $a < 1$ (heterogeneous technology needs). Then the following holds.*
(i) There exists an intensity of competition $\bar{c} > 0$ such that for all $c \in [0, \bar{c}[$ equilibrium technology levels and product qualities are higher under the open regime with each firm developing only its respective more important technology than under the proprietary regime with each firm developing both technologies.[9]

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[9]In Propositions 1 to 3, I have to *assume* that, in the open regime, each firm chooses to develop its respective more important technology. While it is extremely plausible that the players behave this way, in can not be proved to be an equilibrium action without further assumptions. If, e.g., the cost function K_{A1} contains a very large fixed component then it will make sense for A to deviate from the action "develop T1" to "develop no technology" (and still adopt T2 from B). Even if this means strongly

(ii) Without complementarity (b = 0), equilibrium technology levels of the respective more important technology (T1 for A, T2 for B) are, for c > 0, always lower under the open then under the proprietary regime.

The intuition behind this result (proved in Appendix A.1) is the following. Due to heterogeneity, B develops T2 to a higher level than A does. Under the open regime, A benefits from this increased technology level and, due to complementarity between technologies T1 and T2, invests itself more into developing T1. This increased investment will not take place when technologies are not complementary, as is underlined by part (ii) of the proposition. The negative incentive effect resulting, under the open regime, from spill-overs to the competitor is limited due to low intensity of competition.

Higher technology levels lead to higher revenues, but also to higher cost. On the other hand, cost saving are realized under the open regime since parallel developments are avoided. The following proposition (proved in Appendix A.2) shows that, under suitable circumstances, the net effect on profits is positive.

Proposition 2 *Under the assumptions made in Proposition 1, there exists an intensity of competition $\tilde{c} > 0$, $\tilde{c} \leq \bar{c}$, such that for all $c \in [0, \tilde{c}[$ equilibrium profits are higher under the open regime than under the proprietary regime.*

This proposition suggests a welfare comparison of the two regimes. However, without further assumptions one can not prove the (apparent) superiority of the open regime (for $c < \tilde{c}$): while firm profits are higher and product qualities superior, firms might sell their improved goods at such increased prices that higher deadweight-loss on the consumer side vitiates the above gains. Still, welfare superiority of the open regime is highly plausible.

In any case, considering only the firm side the open regime's equilibrium is clearly Pareto superior. However, when the decision to reveal is endogenized in a four-stage game, the reduced game in which firms choose between open and proprietary behavior might exhibit the structure of a prisoner's dilemma. The following proposition, proved in Appendix A.3, shows that, under suitable conditions, this is not the case: revealing by both firms can obtain endogenously.

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reduced revenues (since T2 is relatively less important for A), it may mean increased profits. However, it will be shown in Section 4.2 that, for the specific profit function, each firm focusing on its more important technology is a subgame equilibrium for *all* parameter values.

Proposition 3 *Under the assumptions made in Proposition 1, there exists a degree of homogeneity $\hat{a} > 0$ and an intensity of competition $\hat{c} > 0$, $\hat{c} \leq \bar{c}$, such that for all $a \in [0, \hat{a}[$ and all $c \in [0, \hat{c}[$ a symmetric subgame equilibrium exists in stage 2 of the four-stage game (after both haven chosen to enter the market) in which both firms choose "revealing".*

4.2 Specific profit function

In order to illustrate the general results from the preceding section, I will in the following employ the specific profit function introduced in equations (1) to (3). Since retaining the parameter b (measuring the strength of complementarity) explicitly renders the equations rather complex, I set $b = 1$ and will discuss a variation of b qualitatively in Section 5. Setting $b = 1$ does not restrict applicability of the propositions derived above since only the property $b > 0$ was used.

Proprietary regime

Proposition 4 *Under the proprietary regime, there is a unique symmetric equilibrium in which both firms enter the market if*

$$c \leq c_b(a) := 3\frac{1 + a + a^2}{8 + 11a + 8a^2} \ . \tag{4}$$

See Figure 1. In this equilibrium, firms choose the development levels

$$d_{A1} = d_{B2} = (2 + a)/3 \ , \qquad d_{A2} = d_{B1} = (1 + 2a)/3 \ , \tag{5}$$

and earn the profits

$$\Pi_X^{prop} = \frac{1 + a + a^2}{3} \ \textit{(monop.)}, \ \ \Pi_X^{prop} = \frac{1 + a + a^2}{3} - c\frac{8 + 11a + 8a^2}{9} \ \textit{(duop.)} \ . \tag{6}$$

For $c > c_b(a)$, there are two equilibria with only one of the firms entering the market.[10] Development levels are the same as in the duopoly case.

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[10]These are equilibria in pure strategies. Equilibria where in the first stage mixed strategies are played exist, but are unstable. They are not explored further.
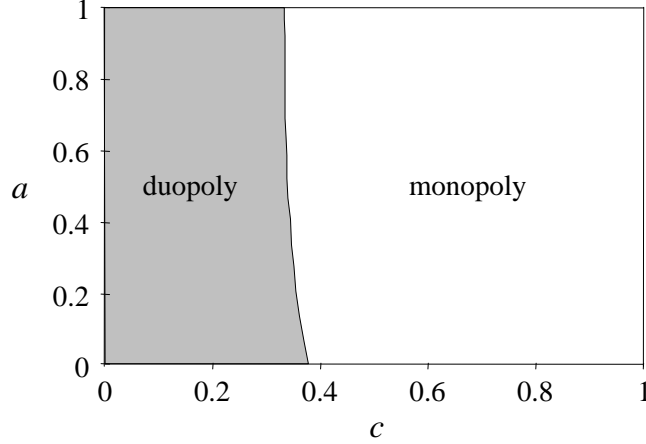
Figure 1: Proprietary regime: Areas of different equilibria (duopoly, monopoly) in parameter space (a, c). Border curve described by $c_b(a)$.

Open regime

Under the open regime, the stage-two decisions on what technology to develop are no longer trivial: no development, development of the respective more important technology, and development of both technologies are all potentially sensible options.[11] The calculation of development levels in the final-stage subgame equilibria is presented in Appendix A.4. The resulting payoffs allow to reduce the stage-two subgame, assuming market entry by both firms, to a matrix game as shown in Table 3 in the Appendix. Concerning the equilibria of this subgame, the following proposition holds (proof: see Appendix A.5):

Proposition 5 *When, under the open regime, both firms have entered the market, then the second-stage subgame has the following equilibria:*
(i) Development of only the respective more important technology by each firm is a subgame equilibrium for all parameter values.
(ii) Development of both technologies by one firm and free riding by the other firm (asymmetric equilibrium) is a subgame equilibrium in a segment of the parameter space as shown in Figure 2 and defined by equations (23) and (24) in the Appendix.

The above solution of the second-stage subgame allows the reduction of the entire game to a 2×2 matrix game. For this reduction, an assumption is required on which subgame

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[11]For simplicity, I exclude the case that a firm chooses to develop only the one technology which is less important for its product quality. While an equilibrium with A developing technology 2 and B developing technology 1 does arise for low heterogeneity of technology needs, it is plausible that firms can coordinate in such a way that each develops only the respective more important technology.

13
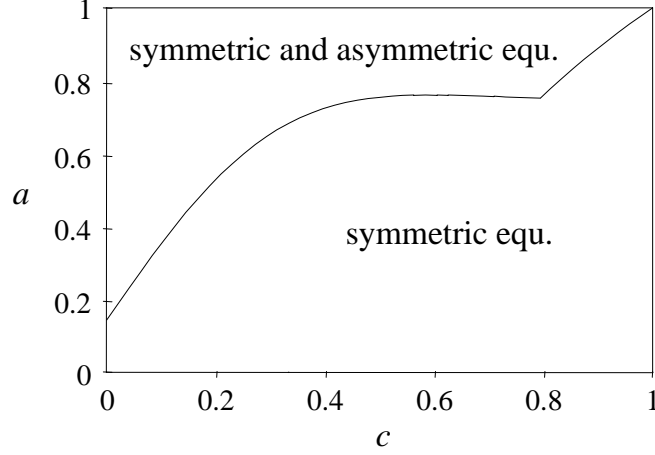
Figure 2: Open regime: Types of second-stage subgame equilibria in (a, c)-parameter space after market entry by both firms.

equilibrium obtains when the second-stage subgame has multiple equilibria. Since the central question of this paper is under which conditions symmetric equilibria with informal division of labor exist, I focus on the symmetric equilibria. Under this assumption, payoffs for firm A in the second-stage subgame equilibrium as a function of market entry decisions are given by (7) (symmetrically for firm B), which leads to Proposition 6.

$$
\Pi_A^{open} =
\begin{cases}
\dfrac{1 + a + a^2}{3} & \text{if } B \text{ does not enter} \\[4mm]
\dfrac{(1 - ac)(1 + a - c - c^2)}{(1 + c)^2} & \text{if } B \text{ enters}
\end{cases}
\tag{7}
$$

**Proposition 6** *(i) Under the open regime, a symmetric duopoly equilibrium exists if*

$$
a \geq c^2 + c - 1 \ . \tag{8}
$$

In this equilibrium, each firm develops only the respective more important technology and adopts the other technology from its competitor (see Figure 3).
(ii) For $a < c^2 + c - 1$, no duopoly equilibrium exists.

Hence, in a large part of the parameter space an equilibrium with informal division of labor between the firms exists. In contrast, a monopoly equilibrium arises when competition is strong, which is intuitive. In addition, high heterogeneity in technology needs (low a) favors such equilibria, since under high heterogeneity gains from adopting the
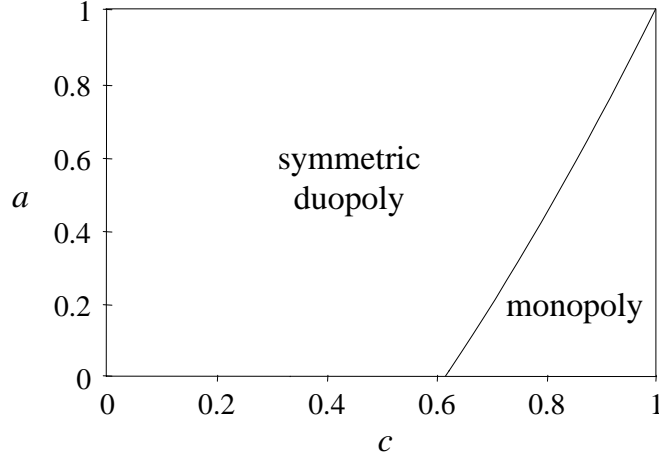
Figure 3: Open regime: Areas of different equilibria (duopoly, monopoly) in parameter space (a, c). Border curve described by equation (8).

competitor's developments are lower.

Comparison of proprietary and open regimes

The following proposition, proved in Appendix A.6, corresponds to Propositions 1 and 2 for the general case.

Proposition 7 *(i) A duopoly exists under the proprietary regime only for low intensity of competition (area X in Figure 4a), while under the open regime it exists in most parts of the parameter space (areas X, Y).*
(ii) Duopoly profits under the open regime are higher than under the proprietary regime (applies to area X).
(iii) For strong heterogeneity in technology needs and/or low intensity of competition, equilibrium product qualities are higher under the open regime than under the proprietary regime (see Figure 4b).

Endogenous choice between revealing and secrecy

In order to solve the four-stage game by backward induction, each final-stage subgame equilibrium needs to be determined. Tables 4 and 5 in Appendix A.7 show the actions and payoffs, respectively, in the final-stage subgame when only firm A has chosen to reveal. The final-stage subgames with both firms or no firm revealing have already been solved above. The case that A only develops the less important technology 2 is, as before, excluded. In Appendix A.7, the best responses for both players in the third-stage

15
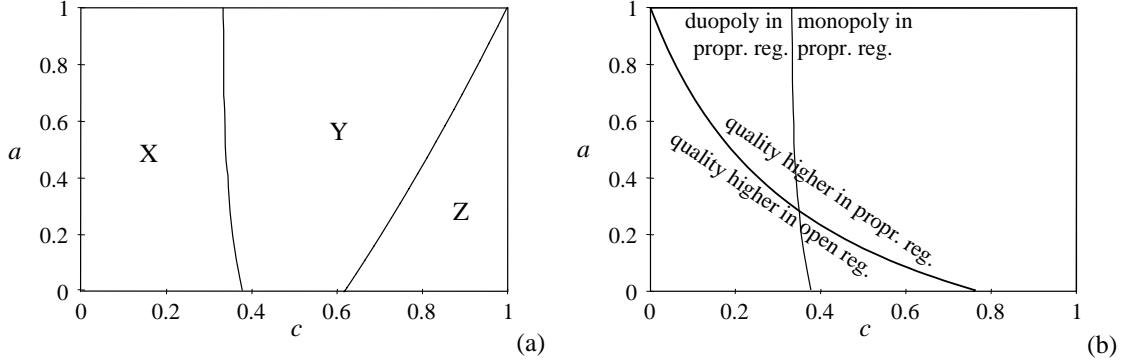
Figure 4: Comparison of equilibria under proprietary and open regime. (a): Market structure. Proprietary regime: duopoly in X, monopoly in Y, Z. Open regime: Duopoly in X, Y, monopoly in Z. (b): Product qualities. Border curve given by $a_q(c)$, equation (27).

subgame are determined. Comparing the payoffs with those under the open regime and the proprietary regime allows one to solve the second stage (choice between revealing and secrecy) and then the entire game. The results are summarized in the following Proposition, which is illustrated by Figure 5 and proved in Appendix A.7. The border curves $a_4(c)$ and $a_5(c)$ of the shaded areas are described by equations (29) and (30).

Proposition 8 *When the choice between revealing and secrecy is endogenous, an equilibrium in which both firms enter the market, choose revealing, and develop only their respectively more important technology exists under the following conditions:*
(i) For low levels of competition and low to medium homogeneity in technology needs (shaded area bottom left in (a, c) parameter space, Figure 5).
(ii) For strong competition and high homogeneity in technology needs (shaded area top right in Figure 5).
In case (i), but not in case (ii), also a duopoly equilibrium with secrecy by both firms exists.

To illustrate Proposition 8, Table 1 shows as a numerical example the various third-stage subgame equilibria for the parameter values $(a, c) = (0.2, 0.2)$. Columns one/two and five/six represent equilibria of the entire game, with quality and profits being considerably higher in the "revealing" than in the "secrecy" equilibrium. Columns three/four show the outcome in case a firm deviates in stage two from one of the equilibria. When B unilaterally deviates from "revealing" to "secrecy", A can no longer adopt T2 from B and thus develops it in-house. However, since for A T2 is less important than for B, A

16
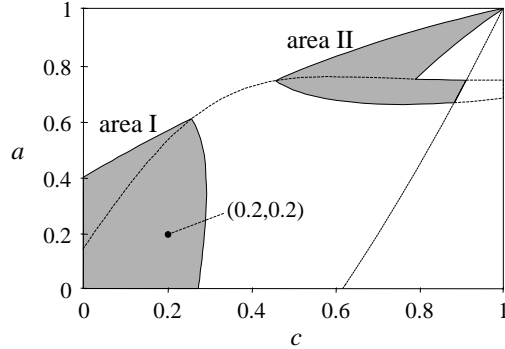
Figure 5: Endogenous revealing: Existence of equilibria with both firms choosing to reveal (shaded areas).

chooses a development level of 0.4, far below what A can adopt from B when both reveal (0.8). Due to complementarity between T1 and T2, A's reduced level of T2 also reduces its marginal benefit of investing in T1, such that d_{A1} goes down as well, from 0.8 to 0.6. Since B adopts this development, the same argument implies that also B's incentives to invest in T2 are reduced. However, this negative *technology effect* is counteracted by the positive *competition effect*: by keeping d_{B2} secret, B avoids the negative competitive effect from A's improved quality. In the example, the two effects happen to cancel each other out, such that d_{B1} remains at the level of 0.8. Still, also B's quality is reduced because of the decrease in d_{A1}. Despite the fact that A's quality is reduced far more and competition from A is thus strongly reduced, profits for B decrease from 0.64 to 0.576.

The last two columns show the subgame equilibrium when both firms have opted for secrecy. Development levels, quality, and profits are lower than when both reveal, while costs are higher. Still, it constitutes an equilibrium since a unilateral deviation to "revealing" would lower the respective firm's payoff even further, from 0.18 to 0.12.

A closer inspection of subgame equilibria in area II of parameter space (Figure 5) reveals that they strongly differ from those in area I. Their existence is not so much driven by complementarity between A's and B's developments but by the fact that, under strong competition, the cost of developing both technologies is too high (a duopoly with secrecy by both firms would lead to negative profits, see Figure 1). Despite the fact that these equilibria are unexpected and even surprising, the following discussion focuses on area I since it corresponds to the empirical setting at hand. Furthermore, monopoly profits in area II are so much larger than duopoly profits that in real situations, a monopoly

	Revealing by both		Revealing only by A		Secrecy by both	
	A	B	A	B	A	B
d_{X1}	0.8	$0^\dagger$	0.6	$0^\dagger$	0.73	0.47
d_{X2}	$0^\dagger$	0.8	0.4	0.8	0.47	0.73
Q_X	1.6	1.6	0.92	1.4	1.17	1.17
K_{X1}	0.64	0.64	0.52	0.64	0.76	0.76
Π_{X1}	0.64	0.64	0.12	0.576	0.18	0.18

Table 1: Numerical example: Third-stage subgame equilibria for different actions in stage two for $(a, c) = (0.2, 0.2)$. † indicates that the respective technology development is adopted from the competitor.

outcome seems far more likely.

5   Discussion

The model results correspond to observations made in the embedded Linux industry. To start with, the prevalence of duopoly equilibria under the open regime (Propositions 6 and 7(i)) finds its empirical analogy in the fact that market entry into the embedded Linux industry, and into open-source-based industries in general, is easier than entry under a proprietary regime (cf. Gruber & Henkel 2005). A start-up in the field of embedded Linux can build upon the publicly available code (in the model: the developments of the other firm) and just needs developments on top in order to differentiate its market offering. In contrast, a proprietary regime has a stronger tendency towards monopoly. The necessity to develop not only differentiating product features, but also the basic product, makes market participation more costly. A quote from an expert interview illustrates this:

> *"We can use the free software to focus our engineering effort on what we sell. [...] I would say that the biggest difficulty that a company like WindRiver and QNX [vendors of proprietary embedded operating systems] has is that they have to do that enormous amount of maintenance on many things that are not specific to their product, but generic. [...] Our big investment is on areas where we believe we have a competitive advantage on."* (Software vendor, US)

Propositions 2 and 7(ii)—higher duopoly profits under the open than under the proprietary regime—may or may not be surprising. It is plausible since, under the open regime, each firm has to bear the development cost of only one technology, not both. Yet, the availability of one's developments for the competitor should reduce innovation incentives, potentially to such a degree that profits, despite cost savings on development, are lower than under the proprietary regime. This is not the case, though—the incentive-reducing effect of free-riding is overcompensated by efficiency gains resulting from the avoidance of parallel developments and higher returns to quality due to complementarity.

Propositions 1 and 7(iii) contain the first central result: The open regime can yield product qualities superior to those that obtain under the proprietary regime. The condition for this result is that technology needs are sufficiently heterogeneous (a small) and/or the intensity c of competition is low. The result is driven by specialization and complementarity between technologies. Since, under the open regime, A can adopt B's technology level d_{B2}, which is superior to what A would have developed under the proprietary regime, A's marginal gain from investment in technology 1 is higher under the open regime (provided competition is not too strong). The result holds in the area below the downward-sloping curve shown in Figure 4b.

The above findings help to understand the fast technological development that embedded Linux has experienced. The following quote from an expert interview concerning proprietary embedded operating systems illustrates the findings from the model:

> "In the next version [of the operating system] several new features were needed and there was only one supplier—the vendor of the operating system. But when they get to their limits, they have a problem. This can't happen to you with Linux, because no matter which new technology comes up you can be sure that within three to six months the first reference implementations are available—that is, much earlier than a proprietary vendor can supply them." (Software vendor, EU)

Also the second central result, concerning endogenous revealing, corresponds to empirical observations. As pointed out in Section 2, firms engaged in embedded Linux development do have a choice between revealing and protecting their developments, despite the fact that Linux is OSS. Still, large amounts of code are *voluntarily* made public, as the survey has shown (Henkel 2005).

Several modeling assumptions merit discussion. To start with, the coefficient b of the complementarity term in the firms' quality functions was set to 1. It is hard to say if this

value is "big" or "small" compared to real complementarity effects in embedded Linux. However, Propositions 1 to 3 have shown that the central results of the paper are valid whenever $b > 0$. Hence, with small values of b ($b < 1$) the areas of parameter space where the results hold will shrink, but not vanish.

More fundamental are the assumptions made on market structure. First, market entry has been excluded. This is justified by the observation made in the qualitative study of embedded Linux that competitive positions are protected more by complementary assets, in particular hardware and scarce personnel, than by secrecy. This finding is consistent with various studies on the appropriability of rents from innovation, which rank lead time and complementary assets as more effective mechanisms than secrecy (and as much more effective than legal protection mechanisms) (Levin, Klevorick, Nelson & Winter 1987, Harabi 1995, Cohen, Nelson & Walsh 2000, Arundel 2001). Hence, even though the software is freely available, entrants can not easily replicate the incumbents' market position.

As market entry, also merging was excluded. Arguments for merging are economies of scale and of scope, the latter resulting from knowledge spillovers between different research projects (as shown, e.g., by Henderson & Cockburn (1996) for the pharmaceutical industry). However, under the open regime in my model, these advantages are realized by an open exchange—merging is not required. Reducing competition remains as a motive for merging, but is not too compelling given low intensity of competition. Furthermore, in the real world the number N of firms is larger than two, and competition-related benefits from merging decrease in N. Hence, the historically grown fragmented market structure in the field of embedded Linux is preserved by the open regime, and the model assumption is justified by the model itself.

The number of firms was set to two. One might conjecture that endogenous revealing becomes less plausible when more firms (N) are in the market, since unilateral deviation from "revealing" might then be less harmful to the respective player. However, while the effect that such deviation would have on each other firm decreases in N, the negative repercussions on the deviating firm add up over all other firms. Hence, the phenomenon of endogenous revealing is not likely to vanish for larger numbers of firms.

Finally, the possibility of licensing was not considered. In the particular case of embedded Linux, this is correct since (per-unit) royalties are excluded by the applicable open source license. More generally, the assumption is justified when the developments under consideration are not big enough to make licensing worthwhile. Furthermore, de-

vice manufacturers that develop embedded Linux to run on their hardware are not in the business of licensing software (see von Hippel (1988, pp. 45-46) on the difficulties involved in changing functional roles in the context of innovation).

6 Conclusions

The debate about the benefits and drawbacks of intellectual property rights (IPRs) goes back many decades and even centuries (Machlup & Penrose 1950, Arrow 1962). IPRs are intended to increase appropriability of innovation rents and thus incentives to innovate (e.g., Gallini & Scotchmer 2002). However, their impact on the diffusion of innovations and on second-generation innovators is ambiguous. While they can facilitate markets for technology (Arora, Fosfuri & Gambardella 2001), they can also restrict adoption and further development of innovations. In addition, fragmentation of IPRs required for a new product can lead to a "tragedy of the anticommons" with inefficiently low adoption of innovations (Heller 1998). Given the high importance of spill-overs for overall economic development (Romer 1990, Grossman & Helpman 1991), weaker IPRs may indeed fuel innovation (Mazzoleni & Nelson 1998, Lessig 2001, Boldrin & Levine 2002). This is true in particular for industries where innovation is strongly sequential, such as semiconductors and software (Levin 1982, Farrell 1995, Bessen & Maskin 2000).

The present paper adds to this debate by exploring circumstances under which free revealing of innovations is preferable to secrecy. It was found that if competition is not too strong, technologies are complementary, and heterogeneity of technology needs is medium or high, an open regime yields higher product qualities as well as higher profits than a proprietary regime. Also, even though a precise proof would require additional assumptions, overall welfare is likely to be higher. Under the same conditions, when the decision to reveal is endogenous, revealing by both players is an equilibrium. One might have expected a prisoner's dilemma where bilateral revealing is beneficial for both players but secrecy is individually rational. Such a situation is indeed prevalent in large parts of the parameter space. However, for low intensity of competition and middle to high values of technical heterogeneity, a coordination game arises: not only secrecy, but also revealing by both players is an equilibrium. In the latter case, product qualities as well as profits are higher. Thus, under certain conditions not protection, but free revealing of an innovation is the best way to appropriate rents from it.

It is plausible that firms in the embedded Linux industry are "used" to revealing due

to the open source culture. Despite a certain latitude to keep developments secret, they are aligned on the revealing equilibrium of the coordination game. Similar conditions as in embedded Linux with respect to heterogeneous technology needs and complementarity between technologies exist also in other industries, especially in other segments of the software market. Examples are middleware and webserver software. The reason why nonetheless in many instances informal, open collaboration does not exist might be that the relevant actors are trapped in a proprietary equilibrium and lack a mechanism to achieve coordination on revealing.

The innovation process that could be identified was dubbed the "jukebox mode of innovation" since it is made up from complementary and heterogeneous contributions, just like the choices of music made at a jukebox. The model was developed to capture the essence of this innovation process. It should contribute to the understanding of innovation processes driven by voluntary spillovers.

A Appendix

A.1 Proof of Proposition 1

(i) Under the open regime, since $q_{B1} \equiv q_{A1}$ because of adoption of T1 by B, the symmetric Nash equilibrium is characterized by $q_{A1} = q_{A2} = q_{B1} = q_{B2} =: q^{open}$ and

$$\frac{\partial \Pi_A}{\partial q_{A1}} + \frac{\partial \Pi_A}{\partial q_{B1}} = 0 \quad . \tag{9}$$

Note that due to assumption 2 (additive separability of Π_A) the above partial derivatives do not depend on T2 being developed in-house or adopted from B (as is the case here). Under the proprietary regime, the symmetric Nash equilibrium is characterized by $q_{A1} = q_{B2} = q_{A1}^{prop}$, $q_{A2} = q_{B1} = q_{A2}^{prop}$, and

$$\frac{\partial \Pi_A}{\partial q_{A1}} = 0 , \tag{10}$$

$$\frac{\partial \Pi_A}{\partial q_{A2}} = 0 . \tag{11}$$

Due to concavity of Π_A, these equations define curves $\bar{q}_{A1}(q_{A2})$ (10) and $\bar{q}_{A2}(q_{A1})$ (11) the intersection of which yields the sought-for equilibrium. Implicit differentiation allows to calculate the slopes, where assumption *(4)* (vanishing mixed partial derivatives) is used:

$$\frac{d\bar{q}_{A1}}{dq_{A2}} = -\frac{\partial^2 \Pi_A}{\partial q_{A1} \partial q_{A2}} \left(\frac{\partial^2 \Pi_A}{\partial q_{A1}^2} \right)^{-1} > 0 \tag{12}$$

$$\frac{d\bar{q}_{A2}}{dq_{A1}} = -\frac{\partial^2 \Pi_A}{\partial q_{A1} \partial q_{A2}} \left(\frac{\partial^2 \Pi_A}{\partial q_{A2}^2} \right)^{-1} > 0 \tag{13}$$

The positive signs follow from assumptions 3 and 7 (concavity and complementarity).

If the intensity c of competition is zero, the partial derivative w.r.t. q_{B1} vanishes in equation (9), and equation (10)—defining the curve $\bar{q}_{A1}$—is fulfilled at the "open" Nash equilibrium. That is, the curve $\bar{q}_{A1}(q_{A2})$ runs through the equilibrium point (q^{open}, q^{open}).

If technology needs are heterogeneous $(a < 1)$, then by definition of heterogeneity, $\partial \Pi_A / \partial q_{A2} < \partial \Pi_A / \partial q_{A1} = 0$ at (q^{open}, q^{open}). Due to concavity of Π_A, this implies that equation (11) (defining the curve $\bar{q}_{A2}$) is, for $q_{A1} = q^{open}$, fulfilled for some $q_{A2} < q^{open}$. That is, the curve $\bar{q}_{A2}(q_{A1})$ runs "below" the open equilibrium point.

Taking the above two paragraphs together and considering that both $\bar{q}_{A1}$ and $\bar{q}_{A2}$ have a positive slope we find that they must intersect at some point $(q_{A1}^{prop}, q_{A2}^{prop})$ with $q_{A1}^{prop} < q^{open}$ and $q_{A2}^{prop} < q^{open}$. This point may be a corner solution. For reasons of continuity, these inequalities also hold for all c in some suitably chosen interval $[0, \bar{c}[$ with $\bar{c} > 0$.

(ii) If $b = 0$, then the curves $\bar{q}_{A1}$ and $\bar{q}_{A2}$ have zero slope (see (12) and (13)). That is, in a (q_{A1}, q_{A2}) coordinate system, $\bar{q}_{A1}$ is a vertical straight line and $\bar{q}_{A2}$ a horizontal straight line. Hence, in the absence of competition ($c = 0$), the q_{A1} coordinate of the open and the proprietary equilibrium are identical since $\bar{q}_{A1}(q_{A2})$ runs through both points. If $c > 0$, then $\partial \Pi_A / \partial q_{B1} < 0$ in (9) and thus $\partial \Pi_A / \partial q_{A1} > 0$, which implies $q^{open} < \bar{q}_{A1}(q^{open}) \equiv \bar{q}_{A1}(q_{A2}^{prop}) \equiv q_{A1}^{prop}$. $\qquad\Box$

A.2 Proof of Proposition 2

Starting with A's profit in the open regime's equilibrium, the following chain of inequalities holds for $c = 0$:

$$R_A(q^{open}, q^{open}, q^{open}, q^{open}) - K_{A1}(q^{open}) \tag{14}$$
$$> \quad R_A(q_{A1}^{prop}, q^{open}, q_{A1}^{prop}, q^{open}) - K_{A1}(q_{A1}^{prop}) \tag{15}$$
$$> \quad R_A(q_{A1}^{prop}, q_{A2}^{prop}, q_{A1}^{prop}, q^{open}) - K_{A1}(q_{A1}^{prop}) \tag{16}$$
$$= \quad R_A(q_{A1}^{prop}, q_{A2}^{prop}, q_{A2}^{prop}, q_{A1}^{prop}) - K_{A1}(q_{A1}^{prop}) \tag{17}$$
$$\geq \quad R_A(q_{A1}^{prop}, q_{A2}^{prop}, q_{A2}^{prop}, q_{A1}^{prop}) - K_{A1}(q_{A1}^{prop}) - K_{A2}(q_{A2}^{prop}) \tag{18}$$

Inequality (15) holds since it implies A's deviating from its equilibrium action q^{open} to q_{A1}^{prop}. The following inequality (16) holds since revenues increase in the firm's own technology levels and $q_{A2}^{prop} < q^{open}$ for $c < \bar{c}$. Equality (17) holds since, for $c = 0$, B's technology levels do not influence A's profits. Inequality (18) is obvious. The last line shows A's profit in the proprietary equilibrium. This proves that, for $c = 0$, equilibrium profits are larger in the open than in the proprietary equilibrium. For reasons of continuity, this statement is also true for all c in some suitable chosen interval $[0, \tilde{c}[$ with $\tilde{c} > 0$. $\qquad\Box$

A.3 Proof of Proposition 3

It needs to be shown that, under suitable parameter values, unilateral deviating in stage 2 of the four-stage game from "open" to "proprietary" is not profitable. That is, if A

chooses "proprietary" while B chooses "open" in stage 2 ("semi-open regime", sor), then A's payoff in the ensuing subgame equilibrium of stages 3 and 4 is lower than its payoff in the subgame equilibrium that follows a choice of "open" by both players.

Given the above, A has three options in stage 3: develop both T1 and T2, develop T1 and adopt T2 from B, or adopt both T1 and T2 from B. B, on the other hand, can not adopt any technology from A and will hence choose to develop both technologies (possibly with $q_{Bi} = 0$ if costs are too high).

The first option, to develop both T1 and T2 inhouse and adopt nothing from B, yields in the final stage a situation identical to that in the proprietary regime. The resulting profit for A has been shown in Proposition 2 to be lower than that in the open regime if c is sufficiently low.

To discuss the second option, I first show that $q_{B2}^{sor} < q^{open}$ if $c = 0$, $a < 1$, and $b > 0$. This is true because at $c = 0$ the semi-open regime for B is identical to the proprietary regime (no incoming knowledge spill-overs, while outgoing spillovers are irrelevant for B's profits), and $q_{B2}^{prop} < q^{open}$ has been shown in Proposition 1(i). Then, starting with A's profits in the open regime's equilibrium the following chain of inequalities holds for $c = 0$:

$$R_A(q^{open}, q^{open}, q^{open}, q^{open}) - K_{A1}(q^{open}) \tag{19}$$
$$> \quad R_A(q_{A1}^{sor}, q^{open}, q^{open}, q^{open}) - K_{A1}(q_{A1}^{sor}) \tag{20}$$
$$= \quad R_A(q_{A1}^{sor}, q^{open}, q_{B1}^{sor}, q_{B2}^{sor}) - K_{A1}(q_{A1}^{sor}) \tag{21}$$
$$> \quad R_A(q_{A1}^{sor}, q_{B2}^{sor}, q_{B1}^{sor}, q_{B2}^{sor}) - K_{A1}(q_{A1}^{sor}) \tag{22}$$

Inequality (20) holds since it implies A's deviating from its subgame equilibrium action q^{open} to q_{A1}^{sor}. Equality (21) holds since, for $c = 0$, B's technology levels do not influence A's profits. The following inequality (22) holds since revenues increase in the firm's own technology levels and $q_{B2}^{sor} < q^{open}$ for $c = 0$. The last line shows A's profit in the "semi-open" subgame equilibrium. This proves the proposition (given option 2) for $c = 0$. For reasons of continuity, this statement is also true for all c in some suitable chosen interval $[0, \hat{c}[$ with $\hat{c} > 0$.

Finally, the third option (to adopt both technologies from B) can be shown to yield lower profits than the open equilibrium when heterogeneity is high enough. Consider that, if $c = 0$ and $a = 0$, B will only develop T2 in the semi-open regime. Then, since $\partial \Pi_A / \partial q_{A2} = 0$ if $a = 0$ (see Assumption 6), spill-overs from B regarding T2 are irrelevant

for A. Hence, in order to realize positive profits, A has to develop T1 in-house. For reasons of continuity, in-house development of T1 is more attractive than full free-riding also for sufficiently small positive values of homogeneity a ($a < \hat{a}$). In turn, as shown in the preceding paragraph, a semi-open regime with in-house development of T1 and adoption of T2 from B is inferior to an open regime for sufficiently small values of c. $\square$

A.4 Third-Stage Subgame Equilibria under the Open Regime

Given decisions on market entry and choice of technology, Nash equilibria for development levels are calculated in the standard manner. One can show that the matrix of second order derivatives of the profit functions is negatively definite, which means that the first order conditions do indeed identify maxima of the profit functions. Since the latter are quadratic functions of the variable, maxima are unique. The resulting actions d_{Ai} of firm A in each subgame equilibrium are given in Table 2. The corresponding actions of firm B obtain from symmetry considerations. Cases where a firm chooses $d_{Xi} = 0$ and adopts d_{Yi} from its competitor (i.e., $q_{Xi} = d_{Yi}$ are indicated by † resp. ‡ in Table 2). It should be noted that, when A develops both technologies and B none, the expression for d_{A2} becomes negative for $a < (3c - 1)/(2 - c + c^2)$ (see equation 23 and Figure 6a). In this case the given expressions are to be replaced by $d_{A2} = 0$ and $d_{A1} = (1 - ac)/2$.

From the subgame equilibrium actions given in Table 2 payoffs can be calculated. They are given, for firm A, in Table 3.

A.5 Second-Stage Subgame Equilibria under the Open Regime

Given the payoffs obtained by solving the game's third and final stage (see Table 3), the second-stage subgame's equilibria can be determined. The case that only one firm has entered the market in stage one is identical to the monopoly case under the proprietary regime, with equilibrium development levels given by (5) and payoffs by (6). In the following, market entry by both firms is assumed and best responses by firm A to all possible actions by firm B are determined. Details of the proofs are omitted in order to simplify the presentation. They are available from the author upon request.

A's best response to no development by B: If A develops only T1, it receives the payoff $(1-ac)^2/4 \geq 0$. This implies that development of T1 is always superior to no development (the limiting case $a = c = 1$ is not analyzed further). Development of T1 is superior to

development of T1 and T2 if (see Figure 6a)

$$a < a_1(c) := \frac{3c - 1}{2 - c + c^2} \, .$$ (23)

A's best response to development of T2 by B: It can be shown that development of T1 is, for all parameter values, superior to both no development and development of T1 and T2.

A's best response to development of T1 and T2 by B: It can be shown that development of T1 is always superior to development of T1 and T2. In addition, one can prove that development of T1 is superior to no development if and only if (see Figure 6b)

$$a < a_2(c) := \frac{-306 + 72c - 1432c^2 - 416c^3 + 214c^4 - 96c^5 + 68c^6 + 8c^7 + 4\sqrt{V}}{2\left(63 - 324c + 190c^2 - 310c^3 - 249c^4 + 124c^5 + 4c^6 + 6c^7\right)} \, ,$$ (24)

where

$$V \;=\; +6561 + 4374c + 2997c^2 + 29\,970c^3 + 47\,043c^4 + 26\,064c^5 - 15\,137c^6$$

Actions by firm A in third-stage subgame equil.	Actions by A in stage two					
	no development		T1		T1, T2	
	d_{A1}	d_{A2}	d_{A1}	d_{A2}	d_{A1}	d_{A2}
no devel.	0	0	$\frac{1-ac}{2}$	0	$\frac{2+a-c(1+3a-c)}{3+2c-c^2}$	$\frac{1+2a-c(3+a-ac)}{3+2c-c^2}$
T2	0	$0^\dagger$	$\frac{1-ac}{1+c}$	$0^\dagger$	$\frac{2+a-c(2a+1)}{3+c}$	$\frac{2+4a-c(a+1)}{2(3+c)}$
T1, T2	$0^\ddagger$	$0^\dagger$	$\frac{5+a-2ac}{2(3+c)}$	$0^\dagger$	$\frac{2+a}{3}$	$\frac{1+2a}{3}$

The left side of the table is labeled "Actions by B in stage two".

Table 2: Open Regime: Equilibrium actions of firm A in each subgame equilibrium of stage three, when both firms have entered the market, depending on technology choices made in stage two. † indicates that $q_{A2} = d_{B2} > 0$; ‡ indicates that $q_{A1} = d_{B1} > 0$.

Payoffs firm A		Actions by A in stage two		
		no development	T1	T1, T2
Actions by B in stage two	no development	0	$\frac{(1-ac)^2}{4}$	$\frac{1}{3+2c-c^2}\cdot$ $\big((1+a^2)(1-c+2c^2)$ $+a(1-5c+c^2-c^3)\big)$
	T2	$\frac{(a-c)(1-ac)}{2}$	$\frac{(1-ac)(1+a-c-c^2)}{(1+c)^2}$	$\frac{1}{4(3+c)^2}\cdot$ $\big(12+12a-42c-36ac-7c^2+22ac^2$ $-6a^2c+12a^2+13a^2c^2+4ac^3\big)$
	T1, T2	$\frac{1}{(3+2c-c^2)^2}\cdot$ $\big((1+a^2)(5-22c+c^5+3c^2-3c^3)$ $+a(17-19c+36c^2$ $+4c^3-5c^4-c^5)\big)$	$\frac{1}{4(3+c)^2}\cdot$ $\big(34a-32c-68ac+12c^2$ $+2c^3+40ac^2-56a^2c+13a^2$ $+12a^2c^2+4ac^3-2a^2c^3+25\big)$	$\frac{1+a+a^2}{3}-c\frac{8+11a+8a^2}{9}$

Table 3: Open Regime: Payoff matrix for firm A in second-stage subgame when both firms have entered the market.
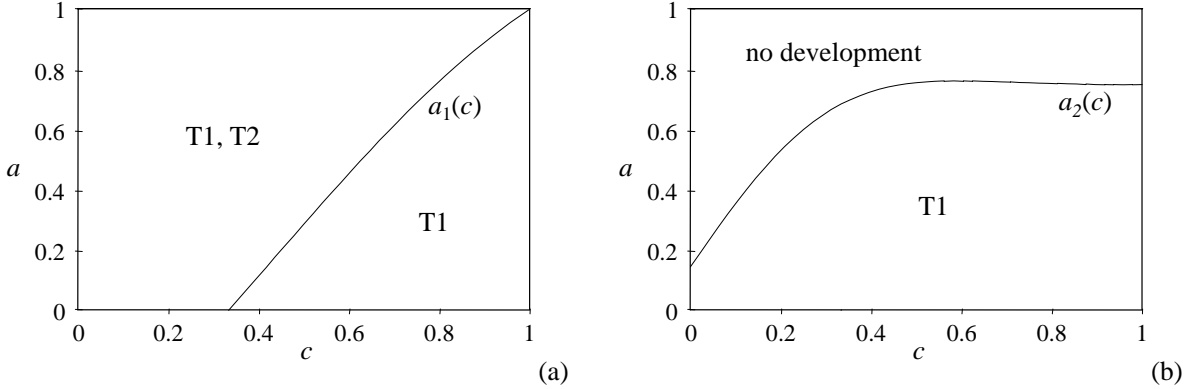
Figure 6: Open regime: Best responses by A to (a) no development by B; (b) development of T1 and T2 by B as functions of the parameters a, c. Border curves are given by equations (23) and (24), respectively.

$$-26\,204c^7 - 1073c^8 + 7606c^9 + 619c^{10} - 886c^{11} - 51c^{12} + 36c^{13} + c^{14}. \quad (25)$$

The curves a_1 (23) and a_2 (24) divide the (a, c) parameter space into four areas. Analysis of the best responses above shows that development of T1 by A is always a best response to development of T2 by B, and vice versa. Hence, a symmetric subgame equilibrium with each firm developing only one technology always exists. Development of both technologies by one firm and no development by its competitor is an equilibrium if $a > a_1(c)$ and

$a > a_2(c)$ (see Figure 2).

A.6 Proof of Proposition 7

It must be shown how the areas in parameter space that are relevant in Proposition 7 are defined. Two of the limiting curves have already been calculated. The areas where, under the proprietary regime, a duopoly/monopoly obtains as equilibrium are separated by the curve $c_b(a)$, see equation (4) and Figure 1. The corresponding curve for the open regime is described by equation (23).

The curve separating the areas in parameter space where total duopoly profits under the open regime are lower/higher than monopoly profits under the proprietary regime obtains by setting the relevant terms (see (6) and (7)) equal to each other and solving for a. This leads to the following equation (where the $\pm$ symbol indicates that the curve consists of two connected branches):

$$a_p(c) = \frac{5 + 5c^2 - 8c + 6c^3 \pm \sqrt{45 + 48c - 150c^2 - 276c^3 - 99c^4 + 60c^5 + 36c^6}}{2\left(8c + c^2 + 1\right)} \ . \quad (26)$$

The curve separating the areas where product qualities are higher under the respective regimes (see Figure 4b) is calculated by inserting the equilibrium technology levels into the equations (1), which describe product qualities. One obtains

$$a_q(c) = \frac{-2 - 40c - 20c^2 + 6\sqrt{9 + 26c + 29c^2 + 16c^3 + 4c^4}}{2\left(8 + 25c + 8c^2\right)} \ . \quad (27)$$

A.7 Proof of Proposition 8

The final-stage subgame equilibria for the case that only firm A reveals its developments are determined by standard calculus. The resulting actions and payoffs are given in tables 4 and 5, respectively.

The payoffs given in Table 5 allow to determine the players' best responses. As under the open regime, A's best response to no development by B is development of T1 when $a < a_1(c)$, and development of both technologies when $a > a_1(c)$. See equation (23). A's best response to development of T2 as well as to development of both technologies

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Actions in subgame equilibrium			Technologies firm A			
			T1		T1, T2	
			d_{X1}	d_{X2}	d_{X1}	d_{X2}
Technologies firm B — no devel.		d_{Ai}:	$\frac{1-ac}{2}$	0	$\frac{2+a-c(1+3a-c)}{3+2c-c^2}$	$\frac{1+2a-c(3+a-ac)}{3+2c-c^2}$
		d_{Bi}:	$0^\dagger$	0	$0^\dagger$	$0^\dagger$
	T2	d_{Ai}:	$\frac{2-c-2ca}{4+c}$	0	$\frac{2+a-c(2a+1)}{3+c}$	$\frac{2+4a-c(a+1)}{2(3+c)}$
		d_{Bi}:	$0^\dagger$	$\frac{3-ca}{4+c}$	$0^\dagger$	$\frac{5+a-2ac}{2(3+c)}$
	T1, T2	d_{Ai}:	$\frac{1}{2}$	0	$\frac{1+2a}{3}$	$\frac{2+a}{3}$
		d_{Bi}:	$\frac{2+a}{3}$	$\frac{1+2a}{3}$	$\frac{1+2a}{3}$	$\frac{2+a}{3}$

Table 4: Endogenous revealing: Actions in final-stage subgame equilibrium when only firm A reveals, depending on technology choices made in stage three. $\dagger$ indicates that B adopts the respective development from A.

Profits in subgame equilibrium			Technologies firm A	
			T1	T1, T2
Technologies firm B — no devel.		$\Pi_A =$	$\frac{(1-ac)^2}{4}$	$\frac{(1+a^2)(1-c+2c^2)+a(1-5c+c^2-c^3)}{3+2c-c^2}$
		$\Pi_B =$	$\frac{(a-c)(1-ac)}{2}$	$\frac{1}{(3+2c-c^2)^2}\cdot$ $\left((1+a^2)(5-22c+c^5+3c^2-3c^3)\right.$ $\left.+a(17-19c+36c^2+4c^3-5c^4-c^5)\right)$
	T2	$\Pi_A =$	$\frac{-2c^2-16c+4+8c^2a-8ca+c^3a+4c^2a^2}{(4+c)^2}$	$\frac{1}{4(3+c)^2}\cdot$ $\left(12+12a-42c-36ac-7c^2+22ac^2\right.$ $\left.-6a^2c+12a^2+13a^2c^2+4ac^3\right)$
		$\Pi_B =$	$\frac{1}{(4+c)^2}\cdot$ $\left(9+8a-8c+2c^2-8ca-8ca^2\right.$ $\left.7c^2a+c^3-c^2a^2+2c^3a\right)$	$\frac{1}{4(3+c)^2}\cdot$ $\left(34a-32c-68ac+12c^2+2c^3+40ac^2-56a^2c\right.$ $\left.+13a^2+12a^2c^2+4ac^3-2a^2c^3+25\right)$
	T1, T2	$\Pi_A =$	$\frac{1}{4}-c\frac{8+11a+8a^2}{9}$	$\frac{1+a+a^2}{3}-c\frac{8+11a+8a^2}{9}$
		$\Pi_B =$	$\frac{1+a+a^2}{3}-\frac{c}{2}$	$\frac{1+a+a^2}{3}-c\frac{8+11a+8a^2}{9}$

Table 5: Endogenous revealing: Payoffs in final-stage subgame equilibrium when only firm A reveals, depending on technology choices in stage three.
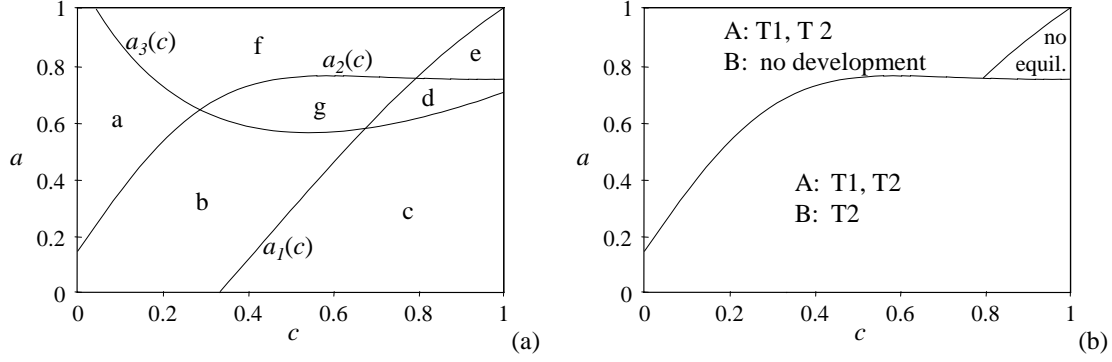
Figure 7: Revealing only by A: Parameter areas of different best-response functions in technology choices (a) and different third-stage subgame equilibria (b).

by B is always to develop both technologies. B's best response to development of both technologies by A: As in the open regime, B's best response is "no development" and adoption of both of A's technologies if $a > a_2(c)$, and development of T2 if $a < a_2(c)$. See equation (24). B's best response to development of T1 by A is either development of T2 or development of T1 and T2. Development of T2 is preferable if $a < a_3(c)$, see equation (28). Figure 7a shows the three curves that separate areas of different best response functions in parameter space, as well as the resulting seven segments a-g.

$$a < a_3(c) := \frac{16 - 64c + 40c^2 + 12c^3 + 4\sqrt{192 + 96c + 396c^2 + 288c^3 + 216c^4 + 78c^5 + 9c^6}}{2(32 + 64c + 8c^2)}$$

(28)

The curves $a_1(c)$, $a_2(c)$ and $a_3(c)$ divide the parameter space into seven segments. The best-response functions allow to determine the third-stage subgame equilibria for each segment. In segments a and f, development of both technologies by A and no development by B is the only equilibrium. In segments b, c, d, and g, development of both technologies by A and development of T2 by B is the unique equilibrium. In segment e, no equilibrium in pure strategies exists. Figure 7b shows which subgame equilibrium arises in each part of parameter space.

Finally, the payoffs that B receives in the third-stage subgame when only A has chosen to reveal (see Table 5) have to be compared to those under the open regime (see Table 3) in order to solve the second stage of the game. I first consider areas in parameter space where, when only A has chosen to reveal, B chooses "no development" (i.e., $a > a_3(c)$, see Figure 7). Setting B's payoffs equal to what the firm receives under the open regime and solving for a leads to the following condition for B's payoff to be higher under the

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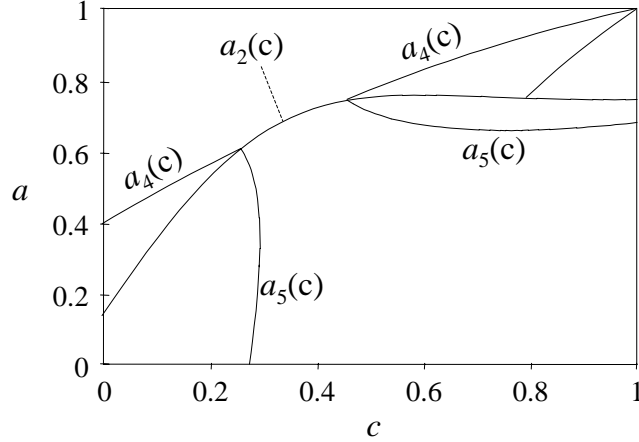
Figure 8: Comparison of B's payoffs for third-stage subgame equilibria when both reveal vs. when only A reveals. Revealing by both is preferable for B between the curves a_4 and a_5.

open regime than with unilateral secrecy:

$$a < a_4(c) := \frac{-8 + 4c - 20c^2 - 2c^3 + 2c^5 + 2\sqrt{V}}{2(5 - 13c - 3c^2 - 2c^3 + c^5)} \text{ , where} \tag{29}$$

$$V = 36 - 33c - 44c^2 + 44c^3 - 12c^4 + 10c^5 + 12c^6 - 20c^7 + 8c^8 - c^9 \ .$$

In case B chooses to develop T2 in the third-stage subgame equilibrium when only A reveals (i.e., for $a < a_3(c)$), B's payoffs under the open regime equal those when only A reveals if

$$a = a_5(c) := \frac{2 - 12c + 78c^2 + 40c^3 - 20c^4 \pm 4\sqrt{W}}{2(13 + 6c - 63c^2 - 30c^3 + 8c^4 - 2c^5)} \text{ , where} \tag{30}$$

$$W = 36 - 84c - 284c^2 + 168c^3 + 921c^4 + 882c^5$$
$$+ 339c^6 + 52c^7 + 11c^8 + 6c^9 + c^{10} \ .$$

Since the function $a_5(c)$ is defined piecewise, the condition for the open regime to be preferable for B cannot be formulated as "a greater ...". Instead, Figure 8 shows the corresponding areas in parameter space. The open regime yields a higher payoff for B for parameter values (a, c) between the curves a_4 and a_5 (except for the triangle top right where $a_1(c) > a > a_2(c)$ and no equilibrium exists). Hence, for these values "revealing by both firms" is a second-stage subgame equilibrium.

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References

Allen, R. C. (1983). "Collective Invention," *Journal of Economic Behavior and Organization* 4, 1–24.

Arora, A., Fosfuri, A. and Gambardella, A. (2001). *Markets for Technology: The Economics of Innovation and Corporate Strategy.*

Arrow, K. J. (1962). "Economic Welfare and the Allocation of Resources for Invention," in: R. Nelson (ed.), "The Rate and Direction of Inventive Activity," Princeton University Press, Princeton, NJ.

Arundel, A. (2001). "The Relative Effectiveness of Patents and Secrecy for Appropriation," *Research Policy* 30(4), 611–624.

Baake, P. and Wichmann, T. (2003). "Open Source Software, Competition and Potential Entry," Working Paper, IFO-Institut / Berlecon Research, http://www.berlecon.de/tw/osscompetition.pdf.

Balacco, S. and Lanfear, C. (2002). "The Embedded Software Strategic Market Intelligence Program 2002/2003, Volume I: Embedded Systems Market Statistics," White Paper, Venture Development Corporation (VDC), http://www.vdc-corp.com/embedded/white/02/02embeddedvol1.pdf.

Baldwin, C. Y. and Clark, K. B. (2003). "The Architecture of Cooperation: How Code Architecture Mitigates Free Riding in the Open Source Development Model," Working Paper, Harvard Business School.

Bessen, J. (2001). "Open Source Software: Free Provision of Complex Public Goods," Working Paper 5/01, http://www.researchoninnovation.org/opensrc.pdf, Zugriff am 07.10.2003.

Bessen, J. and Maskin, E. (2000). "Sequential Innovation, Patents, and Imitation," MIT Department of Economics Working Paper 00-01.

Boldrin, M. and Levine, D. K. (2002). "The Case against Intellectual Property," *American Economic Association Papers and Proceedings* May 2002, 209–212.

Cohen, W. M. and Levinthal, D. A. (1990). "The Implications of Spillovers for R&D Investment and Welfare: A New Perspective," *Administrative Science Quarterly* 35, 128–152.

Cohen, W. M., Nelson, R. R. and Walsh, J. P. (2000). "Protecting their Intellectual Assets: Appropriability Conditions and Why U.S. Manufacturing Firms Patent (or not)," NBER Working Paper No. w7552; revised version: September 2001.

Cowan, R. and Jonard, N. (2003). "The dynamics of collective invention," *Journal of Economic Behavior and Organization* 52(4), 513–532.

Dahlander, L. and Magnusson, M. G. (2005). "Relationships between open source software companies and communities: Observations from Nordic firms," *Research Policy* 34(4), 481–493.

Eaton, B. C. and Eswaran, M. (1997). "Technology-Trading Coalitions in Supergames," *RAND Journal of Economics* 28(1), 135–149.

Farrell, J. (1995). "Arguments for Weaker Intellectual Property Protection in Network Industries," in: B. Kahin & J. Abbate (eds.), "Standards Policy for Information Infrastructure," 368–377, MIT Press, Cambridge, MA.

Fershtman, C. and Kamien, M. I. (1992). "Cross Licensing of Complementary Technologies," *International Journal of Industrial Organization* 10(3), 329–348.

Franke, N. and von Hippel, E. (2003). "Satisfying Heterogeneous User Needs via Innovation Toolkits: The Case of Apache Security Software," *Research Policy* 32(7), 1199–1215.

Free Software Foundation (1991). "GNU General Public License," http://www.fsf.org/licenses/gpl.html (download 07/28/2003).

Gallini, N. T. and Scotchmer, S. (2002). "Intellectual Property: When is it the Best Incentive System?" in: A. Jaffe, J. Lerner & S. Stern (eds.), "Innovation Policy and the Economy, Vol. 2," MIT Press, Cambridge, MA.

Ganssle, J. and Barr, M. (2003). *Embedded Systems Dictionary*, CMP Books, Lawrence, KS.

Gerlach, H. A., Rønde, T. and Stahl, K. (2005). "Project choice and risk in R&D," *Journal of Industrial Economics* 53(1), 53–81.

Grossman, G. and Helpman, E. (1991). *Innovation and Growth in the Global Economy*, MIT Press, Cambridge, MA.

Gruber, M. and Henkel, J. (2005). "New ventures based on open innovation - an empirical analysis of start-up firms in embedded Linux," *International Journal of Technology Management* .

Harabi, N. (1995). "Appropriability of Technical Innovations – an Empirical Analysis," *Research Policy* 24(6), 981–992.

Harhoff, D., Henkel, J. and von Hippel, E. (2003). "Profiting from Voluntary Information Spillovers: How Users Benefit by Freely Revealing their Innovations," *Research Policy* 32, 1753–1769.

Heller, M. A. (1998). "The Tragedy of the Anticommons: Property in the Transition from Marx to Markets," *Harvard Law Review* 111, 621–688.

Henderson, R. and Cockburn, I. (1996). "Scale, Scope, and Spillovers: The Determinants of Research Productivity in Drug Discovery," *RAND Journal of Economics* 27(1), 32–59.

Henkel, J. (2003). "Software Development in Embedded Linux – Informal Collaboration of Competing Firms," in: W. Uhr, W. Esswein & E. Schoop (eds.), "Proceedings of the 6th International Conference on Business Informatics," Physica, Heidelberg (www.tim.wi.tum.de/paper/Henkel_Embedded_Linux_2003.pdf).

———— (2005). "Selective Revealing in Open Innovation Processes: The Case of Embedded Linux," Working Paper, Technical University of Munich (www.tim.wi.tum.de/paper/Henkel_Selective_revealing_2005.pdf).

Henkel, J. and von Hippel, E. (2005). "Welfare Implications of User Innovation," *Journal of Technology Transfer* 30(1/2), 73–87.

Johnson, J. P. (2001). "Economics of Open Source Software," Working Paper, http://opensource.mit.edu/papers/johnsonopensource.pdf, download 10/07/2003.

Kamien, M. I. and Zang, I. (2000). "Meet me halfway: research joint ventures and absorptive capacity," *International Journal of Industrial Organization* 18(7), 995–1012.

Lerner, J. and Tirole, J. (2002). "Some Simple Economics of Open Source," *Journal of Industrial Economics* 50(2), 197–234.

Lessig, L. (2001). *The Future of Ideas: The Fate of the Commons in a Connected World*, Random House, New York.

Levin, R. C. (1982). "The Semiconductor Industry," in: R. R. Nelson (ed.), "Government and Technical Progress: A Cross-Industry Analysis," 9–100, Pergamon Press, Oxford.

Levin, R. C., Klevorick, A., Nelson, R. R. and Winter, S. G. (1987). "Appropriating the Returns from Industrial Research and Development," *Brookings Papers on Economic Activity* 1987(3), 783–820.

Lombardo, J. (2001). *Embedded Linux*, New Riders, Boston.

Machlup, F. and Penrose, E. (1950). "The Patent Controversy in the Nineteenth Century," *Journal of Economic History* 10(1,2), 1–29.

Marti, D. (2002). "Use Binary-Only Kernel Modules, Hate Life," LinuxJournal.com, 19.06.2002, http://www.linuxjournal.com/article.php?sid=6152, Zugriff am 01.09.2003.

Mazzoleni, R. and Nelson, R. R. (1998). "The Benefits and Costs of Strong Patent Protection: A Contribution to the Current Debate," *Research Policy* 27(3), 273–284.

Meyer, P. B. (2003). "Episodes of Collective Invention," Working Paper 368, Bureau of Labor Statistics, U.S. Department of Labor, http://www.bls.gov/ore/pdf/ec030050.pdf, Zugriff am 22.09.2003.

Moody, G. (2001). *Rebel Code – Inside Linux and the Open Source Revolution*, Perseus Publishing, Cambridge, MA, 1. edn.

Nuvolari, A. (2001). "Open Source Software Development: Some Historical Perspectives," Working Paper, http://opensource.mit.edu/papers/nuvolari.pdf, Zugriff am 15.09.2003.

——— (2004). "Collective Invention During the British Industrial Revolution: The Case of the Cornish Pumping Engine," *Cambridge Journal of Economics* 28(3), 347–363.

Open Source Initiative (2003). "The Open Source Definition," http://www.opensource.org/docs/definition_plain.php, download 08/20/2003.

Osterloh, M. and Rota, S. G. (2004). "Open source software development - Just another case of collective invention?" Working paper, http://papers.ssrn.com/sol3/Delivery.cfm.

Romer, P. M. (1990). "Endogenous Technological Change," *Journal of Political Economy* 98(5), 71–102.

Sattler, H. (2003). "Appropriability of Product Innovations: An Empirical Analysis for Germany," *International Journal of Technology Management* 26(5-6), 502–516.

Selten, R. (1965). "Spieltheoretische Behandlung eines Oligopolmodells mit Nachfrageträgheit," *Zeitschrift für die gesamte Staatswissenschaft* 12, 301–324.

Spence, M. (1984). "Cost Reduction, Competition, and Industry Performance," *Econometrica* 52(1), 101–122.

VDC (2004). "White paper, Venture Development Corporation," Referenced in: "Linux now top choice of embedded developers", LinuxDevices.com, http://www.linuxdevices.com/news/NS2744182736.html.

von Hippel, E. (1988). *The Sources of Innovation*, Oxford University Press, New York.

——— (2001). "Innovation by User Communities: Learning from Open-Source Software," *MIT Sloan Management Review* 2001(Summer), 82–86.

Webb, W. (2002). "Pick and Place: Linux Grabs the Embedded Market," *EDN.COM, http://www.reed-electronics.com/ednmag/contents/images/253780.pdf* 10/31/2002.

——— (2003). "Unlocked – Embedding Open-Source Software," *EDN.COM, http://www.reed-electronics.com/ednmag/contents/images/296493.pdf* 05/15/2002.

Wiethaus, L. (2005). "Absorptive capacity and connectedness: Why competing firms also adopt identical R&D approaches," *International Journal of Industrial Organization* 23(5-6), 467–481.