DISCUSSION PAPER SERIES

No. 4507

THE JUKEBOX MODE OF INNOVATION – A MODEL OF COMMERCIAL OPEN SOURCE DEVELOPMENT

Joachim Henkel

INDUSTRIAL ORGANIZATION

Centre for Economic Policy Research

www.cepr.org

Available online at: **www.cepr.org/pubs/dps/DP4507.asp**

ISSN 0265-8003

THE JUKEBOX MODE OF INNOVATION – A MODEL OF COMMERCIAL OPEN SOURCE DEVELOPMENT

Joachim Henkel, Universität München and CEPR

Discussion Paper No. 4507
July 2004

Centre for Economic Policy Research
90–98 Goswell Rd, London EC1V 7RR, UK
Tel: (44 20) 7878 2900, Fax: (44 20) 7878 2999
Email: cepr@cepr.org, Website: www.cepr.org

CEPR Discussion Paper No. 4507

July 2004

ABSTRACT

The Jukebox Mode of Innovation – A Model of Commercial Open Source Development*

In this Paper, I explore the circumstances under which innovation processes without secrecy or intellectual property protection are viable, and where free revealing of innovations is a profit-maximizing strategy. Motivated by an empirical study of embedded Linux, I develop a duopoly model of quality competition. Firms require two complementary technologies as inputs, but differ with respect to the relative importance of these technologies. I find that a regime with compulsory revealing can lead to higher product qualities and higher profits than a proprietary regime. When the decision to reveal is endogenized, equilibria with voluntary revealing arise, again superior to the proprietary outcome.

JEL Classification: L11, L15 and L86
Keywords: development collaboration, embedded Linux, innovation and open source software

Joachim Henkel
Universität München
Kaulbachstr. 45
80539 Munich
GERMANY
Tel: (49 89) 2180 2986
Fax: (49 89) 2180 6284
Email: henkel@bwl.uni-muenchen.de

For further Discussion Papers by this author see:
www.cepr.org/pubs/new-dps/dplist.asp?authorid=146678

*I thank Eric von Hippel for his hospitality during my stay at MIT's Sloan School of Management. I am indebted to him, to Pio Baake, Dietmar Harhoff, Markus Reisinger, Chern Celine Schulz and Carolin Socker for valuable comments and discussions. Of course, all remaining errors are mine. Financial support by Deutsche Forschungsgemeinschaft is gratefully acknowledged.

Submitted 23 June 2004

1 Introduction

There is a long-standing debate on what the ideal incentive system for innovation would be. This debate has particular relevance given the current trend towards ever stronger intellectual property rights (e.g., Gallini 2002). For some industries, in particular pharmaceuticals, there is little disagreement that patents are an effective and indispensable means to set innovation incentives (e.g., Cohen, Nelson & Walsh 2000). For other industries, however, overly strong intellectual property rights have been criticized as a drag to innovation (e.g., Bessen & Maskin 2000, Boldrin & Levine 2002, Mazzoleni & Nelson 1998).

The surge of open source software adds new aspects to this debate. Open source licenses do not allow royalties to be charged. Furthermore, 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), and popular programs such as Linux and Apache have experienced tremendous success with rapid development. While hobby developers play an important role in many open source projects, they are of negligible importance in others (Henkel 2003).

This surprising observation has implications on the industry level and for the individual firm. On the industry level it demonstrates that IP protection is not always needed to spur innovation. Indeed, it may be an impediment. For the individual firm, it shows that voluntary revealing of developments can be consistent with profit-maximizing behavior. In fact, just as secrecy and legal protection in other situations, free revealing can be a *precondition* for certain ways to appropriate rents from innovation.

In this paper I analyze a situation where benefits from revealing arise from complementarity between the innovators' developments, while a loss of competitive advantage is alleviated by heterogeneity in technology needs and limited intensity of competition. The analysis is motivated by an empirical study of the development of "embedded Linux" (see Section 2 and Henkel 2003), which provides an ideal illustration of the general phenomenon. I develop a duopoly model of quality competition. Each firm's market offering requires two technologies as inputs, which are complementary to each other. They can be thought of as modules of the final product.[2] Firms can choose to develop one technology or both, and may make their developments public or not. I compare an "open" regime with compulsory revealing to a "proprietary" regime with no revealing, and then proceed to endogenize the decision to reveal. Open and proprietary regime can be seen as idealized models of open source and proprietary software development, respectively. I investigate if and under which conditions the open regime yields superior outcomes with respect to product qualities and profits, and compare its market structure to that of the proprietary regime. In an extension of the model, the firms actively decide whether to reveal their developments or not. I analyze under what conditions revealing by both firms constitutes an equilibrium, i.e., when an open regime arises endogenously.

The main results are the following. 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. In contrast, in a proprietary regime where all developments are kept secret, a duopoly is only viable at low intensities of competition. Duopoly profits are higher in the open than in the proprietary regime. For high heterogeneity and/or at low intensities of competition, also product qualities are higher in the open regime. When the choice between revealing and secrecy is endogenized, equilibria with both firms opting to reveal exist at low intensities of competition and medium to high heterogeneity of technology needs. Hence, under suitable circumstances, an informal division of labor arises both for exogenous and endogenous revealing. In the latter case, players are not caught in a prisoner's dilemma but are facing a coordination game in which revealing by both is the superior outcome. Thus, contrary to standard reasoning, it is individually rational to make one's developments public.

Revealing of innovation-related information is prevalent in open source development, but by no means restricted to this field. It has been observed, among others, in industries as diverse as iron making (Allen 1983), steam machines (Nuvolari 2001), scientific instruments (Riggs & von Hippel 1994), and sporting equipment (Franke & Shah 2003). However, the situation analyzed here differs from the above instances of free revealing, for the following reasons. Allen and Nuvolari describe situations of "collective invention", which "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). Furthermore, technology needs are homogeneous. In contrast, I analyze a situation where firms do allocate resources to R&D, and heterogeneity of their technology needs

[2] See Baldwin & Clark (2003) on the importance of code modularity for the open source development process.

plays a central role. The situation also differs from those described by Riggs & von Hippel (1994) and Franke & Shah (2003), where innovations are developed and revealed by *users* (individuals or firms). For the firms considered here, their developments are a part of their product or service offering, not something they use internally. Finally, the situation analyzed here also differs from open source development by hobbyists because all actors are profit-oriented firms.[3] Central to the situation I analyze is that there is publicly available technology to which each innovator adds according to its individual needs.

The situation described above is similar to that of a bar where several patrons feed the jukebox. Each contributor wishes to hear a particular song that is unlikely to be chosen by someone else. Still, all others also benefit from the song since both the patrons' musical taste as well as the jukebox's selection will be homogeneous to a good degree—otherwise, they would probably have their drinks at some other place. The public good problem is overcome by heterogeneity in taste. As a result, the patrons can enjoy music all night long, which may be one of the reasons why they go there. Due to this analogy, the innovation mechanism explored in this paper is dubbed the "jukebox mode of innovation".

The remainder of the paper is organized as follows. In Section 2, some background on the characteristics and the development process of embedded Linux is introduced. The model set-up is defined in Section 3. Section 4 presents the results from the model analysis. Section 5 discusses model assumptions, before conclusions are drawn in Section 6. Proofs are relegated to the Appendix.

[3] A number of theoretical contributions have analyzed under what conditions an open regime might be favorable to innovation. Bessen & Maskin (2000) present a duopoly model in which innovation is sequential and complementary. Under certain assumptions, they show that the availability of patent protection can be an impediment to innovation. In contrast to this paper, they consider complementarity not between technologies, but between different firms' consecutive R&D efforts. In addition, they do not endogenize firms' decision to reveal. This is done in the model by Baake & Wichmann (2003), which is similar in its timing structure to the model developed here. However, benefits of revealing in their model stem partly from development support by users, which is explicitly excluded here. A mix of user innovation—voluntarily made public—and subsequent, complementary manufacturer innovation is modeled by Harhoff, Henkel & von Hippel (2003). Free revealing of a supplier innovation, intended to increase demand for the required input, is analyzed by Harhoff (1996). Finally, Bessen (2001) focuses on need heterogeneity to show why debugging of open source software by its users may be superior to that by manufacturers. Further contributions on this topic, less closely related to this paper, are from Levin & Reiss (1988), de Fraja (1993), Eaton & Eswaran (1997), Johnson (2001), and Kuan (2000).

2 Embedded Linux—informal development collaboration

This paper is motivated by an empirical study of embedded Linux (Henkel 2003). "Embedded Linux" denotes variants of the Linux operating system that are tailored to embedded devices. Unlike general-purpose devices such as PCs, embedded devices are built for a specific purpose and have a "limited mission" (Lombardo 2001, p. xvi). Examples are mobile phones, VCRs, machine controls and power plants. Market analysis as well as everyday experience show that embedded devices, and with them the embedded software they contain, are steadily gaining importance (Balacco & Lanfear 2002). Embedded devices are extremely heterogeneous, which entails a large diversity of hardware and software. Depending on the field of application, embedded software has to fulfill particular requirements with respect to stability, real-time capability, and low memory needs. This heterogeneity has led to a relatively high industry fragmentation in the field of embedded operating systems, where no dominant player such as Microsoft in the desktop market exists. Adaptation of existing operating systems to individual needs is common, and even in-house development by device manufacturers is still rather widespread.

In recent years, increasing complexity of embedded devices has made in-house development less attractive (Webb 2002). This is one of the reasons why embedding the open source operating system Linux has emerged as an attractive option. Linux is a fully-fledged, stable, and well maintained operating system which, due to its modularity and its being open source software, is well suited for adaptation to individual needs. To clarify, the term "embedded Linux" does not denote a well-defined version of Linux, but rather all variants of the operating system that are in one way or another adapted to embedded applications. Correspondingly, "developing embedded Linux" refers to the development of 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 "shrinked" 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. Embedded Linux enjoys growing popularity and has experienced a fast development over the last years (Lombardo 2001, Balacco & Lanfear 2002, Webb 2003).

Embedded Linux is a peculiar case of open source software in two respects. First, nearly all developments come from firms, while hobbyists play only a minor role. Second, embedded Linux shows a high heterogeneity. Table 1 lists quotes taken from interviews conducted in 2002 and 2003 with firms involved in embedded Linux development (Henkel 2003). They will be used in the following to illustrate the characterization of embedded Linux and more generally the kind of informal development collaboration in this industry.

The first point—the dominant role of profit-oriented firms—is due to the fact that hobby developers normally have a PC based on an X86 processor at their disposal, and not the processors, boards and devices that make up embedded systems. Development of code that is specific to embedded Linux is driven by specialized software firms, board vendors, and device manufacturers.[4]

The commitment of commercial firms to embedded Linux is surprising, given the fact that Linux is licensed under the General Public License (GPL). This license requires that all developments based on software under the GPL be themselves licensed under the GPL (Free Software Foundation 1991). For embedded devices, this implies that by the time a device running embedded Linux comes onto the market, the source code of the specific version of Linux it contains must be made available to all buyers. Unless a device is sold only to very few customers this implies that it is all but publicly available—and competitors can use it without any restrictions imposed. Yet, a certain leeway with respect to revealing code does exist: code can be (voluntarily) made public right after its development, or (as the license requires it) only when the device comes to market; furthermore, it is accepted practice to make drivers available only as loadable binary modules, not as source code (Henkel 2003).

The second peculiarity of embedded Linux—high heterogeneity—limits the negative effects arising from free revealing (see Quote 1, Table 1). 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). Heterogeneity also prevents a waiting game since it is unlikely that someone else will develop and reveal the exact piece of software that a firm requires at a certain point in time (Quote 3). To come back to the jukebox analogy, I could wait all night for some other patron to choose my favorite song, or I could invest a quarter and make sure it is played now.

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

[4]Examples for specialized software vendors are FSMLabs, LynuxWorks, MontaVista, and TimeSys in the US and Denx Software, Emlix, Mind and Sysgo in Europe; for board vendors, Hitachi, Intel, and Motorola; for device manufacturers, Philips, Sharp, and Siemens.

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. 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 stability 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.

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

Table 1: Quotes from interviews carried out with firms involved in embedded Linux development (Henkel 2003).

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 (1 and 2) 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 basic software does not explicitly appear in the model. The firms' technology levels in technologies 1 and 2 are denoted by q_{Xi}, where $X \in \{A, B\}$, $i \in \{1, 2\}$. The technologies are assumed to be complementary to each other, which is modeled by a complementarity term $q_{X1}q_{X2}$ in the product quality functions Q_X (1).[5] Furthermore, it is assumed that firms A and B differ with respect to their technology needs: for A, technology 1 is more important than for B, and vice versa for technology 2. This can be due to differences in complementary hardware, human capital or the firms' market positioning. These differences are modeled by a "homogeneity parameter" $a \in [0, 1]$: $a = 1$ models identical technology needs, while there is maximum heterogeneity of needs for $a = 0$. The firms' product qualities as functions of their technology levels and of need homogeneity a are defined as

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

Firm A (analogously for firm B) can achieve a development level q_{Ai} in technology i by bearing the cost d_{Ai}^2 to attain the "development level" $d_{Ai} = q_{Ai}$.[6] Alternatively, if firm B has developed *and revealed* d_{Bi}, A can adopt B's development at no cost, yielding $q_{Ai} = d_{Bi}$ and $d_{Ai} = 0$. The cost of firm X is hence given by

$$K_X = d_{X1}^2 + d_{X2}^2 \; . \tag{2}$$

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 setting are not made explicit in order to keep the model tractable. Introducing a parameter

[5]It would be desirable to parameterize the strength of the complementarity effect. However, an additional parameter would render the analysis rather complex. Instead, a variation of the strength of this effect is discussed qualitatively in Section 5.

[6]Just as the complementarity term, the cost term does not carry a coefficient. However, this does not constitute a further restriction of generality, since by re-scaling technology levels and profits a coefficient β in the cost term can be removed (i.e., be scaled to $\tilde{\beta} = 1$). Alternatively, one could consider the complementarity term's coefficient to be *scaled* to 1 and the cost terms' coefficient to be *set* to 1.

$c \in [0, 1]$ that measures the degree of competition, profits are defined as

$$\Pi_A = Q_A - cQ_B - K_A \;, \qquad \Pi_B = Q_B - cQ_A - K_B \;. \tag{3}$$

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.

As to the game's timing structure, I analyze a three-stage and a four-stage simultaneous 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 one where all are revealed. In the four-stage game, revealing is endogenized. After the market-entry decisions, in the newly introduced stage two, firms have to commit to either reveal their developments or keep them secret. This timing is motivated by the observation that firms tend to have long-term strategies with respect to revealing their code. It can be explained by the fact that such a strategy depends on a firm's relationship to the open source community, on its culture, and on the people it has hired. All of these characteristics can not be easily 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 perfectness (Selten 1965).

4 Results

4.1 Proprietary regime

As a point of reference I first analyze the three-stage game in which revealing is excluded ("proprietary regime"). In this case, technological levels equal development levels, i.e., $q_{Xi} = d_{Xi}$ for all $X \in \{A, B\}$ and all $i \in \{1, 2\}$. If a firm has decided to enter the market in stage one, its subsequent decision on what technology to develop is trivial: since development levels enter the quality function Q_X (1) linearly but the cost function K_X (2) quadratically, it always makes sense to choose a positive development level for both technologies. Optimal development levels in stage three are obtained by simple maximization. Backward induction then allows to reduce the game to a symmetric 2×2 matrix game with strategies "entry" and "no entry". The payoffs for A in this reduced game are given by (4) if A enters the market, otherwise they are zero. From these payoffs best responses can be calculated, which leads to Proposition 1.

$$\Pi_A^{propr} = \begin{cases} \dfrac{1 + a + a^2}{3} & \text{if } B \text{ does not enter} \\ \\ \dfrac{1 + a + a^2}{3} - c\dfrac{8 + 11a + 8a^2}{9} & \text{if } B \text{ enters} \end{cases} \tag{4}$$

Proposition 1 *In the proprietary regime, there is a unique symmetric equilibrium in which both firms enter the market if*

$$c \leq c_b(a) := 3\frac{1 + a + a^2}{8 + 11a + 8a^2} \ . \tag{5}$$

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

$$d_{A1} = d_{B2} = (2 + a)/3 \ , \qquad d_{A2} = d_{B1} = (1 + 2a)/3 \ . \tag{6}$$

For $c > c_b(a)$, there are two equilibria with only one of the firms entering the market.[7] *Development levels are the same as in the duopoly case.*

[7] 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.

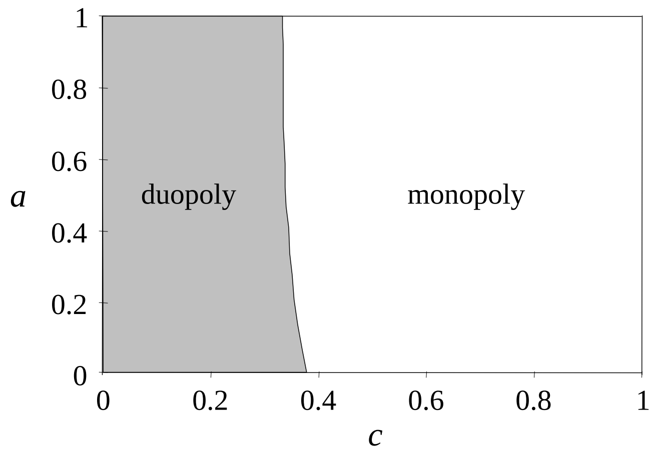

Figure 1: Proprietary regime: Areas of different equilibria (duopoly, monopoly) in parameter space (a, c). Border curve described by $c_b(a)$.

4.2 Open regime

The opposite case to a proprietary regime is an "open regime" where revealing is compulsory. It can be interpreted as an idealized type of open source development where no leeway exists with respect to keeping innovations secret. In this case, 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.[8] In the third and final stage, firms decide on the development levels of the technologies they have chosen. If one firm has chosen to develop technology i and the other has not, than the latter can adopt the development at no cost. If, for example, A adopts technology 2 from B, then $d_{A2} = 0$ and $q_{A2} = d_{B2}$. I assume that a technology can only either be completely adopted or be completely developed in-house.[9] The calculation of the final-stage subgame equilibria is presented in Appendix A.1. The resulting payoffs allow to reduce the stage-two subgame, assuming market entry by both firms, to a matrix game as shown in Table 4 in the Appendix. Concerning the equilibria of this subgame, the following proposition holds (proof: see Appendix A.2):

[8]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.

[9]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. In this case, the developer would in most cases not reveal a half-finished version but only the completed development.

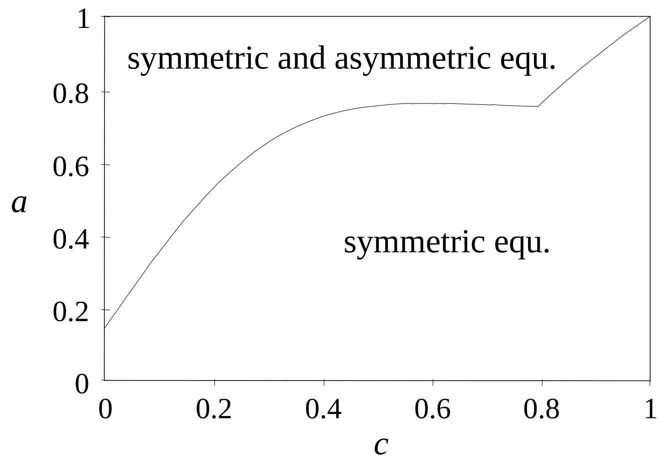

Figure 2: Open regime: Types of second-stage subgame equilibria in (a, c)-parameter space after market entry by both firms.

Proposition 2 *When, in 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 (9) and (10) 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 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.[10] 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 immediately leads to Proposition 3 concerning the existence of symmetric equilibria.

[10] The free rider in the asymmetric equilibrium fares better than each firm in the symmetric equilibrium if $a > \left(-2c^3-20c^2+2c^5+4c-8+2\sqrt{36-44c^2-33c+10c^5+44c^3+8c^8+12c^6-20c^7-12c^4-c^9}\right)/\left(2\left(c^5-2c^3-3c^2-13c+5\right)\right)$ or, roughly, $a > 0.4 + 0.6c$.

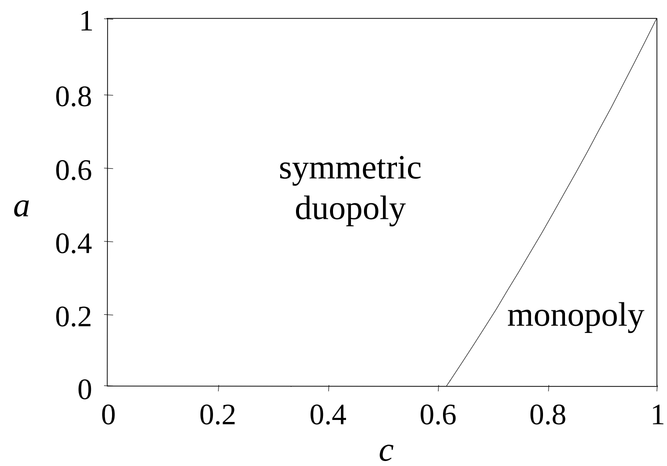

Figure 3: Open regime: Areas of different equilibria (duopoly, monopoly) in parameter space (a, c). Border curve described by equation (8).

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

Proposition 3 *(i) In 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. The only viable outcome is that for a monopoly to exist.[11]

Hence, in a large part of the parameter space an equilibrium with informal division of labor between the firms exists. It does not rest on explicit coordination but arises from individual, non-cooperative profit maximization. While free riding is possible, it would imply that the respective firm—firm B, say—has only the less important technology 1

[11] One has to check that for $a < c^2 + c - 1$ no duopoly equilibrium exists when in the stage-two subgame asymmetric subgame equilibria are considered (see Proposition 2ii). One can show (and it is rather intuitive) that the firm which develops both technologies in such an equilibrium makes lower profits than each firm in a symmetric duopoly. Hence, when payoffs are negative in the latter case, they are also negative for the developing firm in an asymmetric duopoly which thus can not constitute an equilibrium.

at its disposal. Additionally, the complementarity term in its quality function vanishes, reducing B's product quality further. It is true that the competing firm A also benefits from B's developing and revealing technology 2, but the negative impact this has on B's profits is mitigated by heterogeneity in technology needs ($a < 1$) and by low intensity of competition ($c < 1$).[12]

A monopoly equilibrium (see Proposition 3ii) arises when competition is strong, which is intuitive. In addition, high heterogeneity in technology needs (low a) favors such equilibria. This is due to the fact that efficiency gains in a symmetric duopoly which arise from the possibility to adopt the competitor's developments are lower the more heterogeneous the technology needs are. Hence, for constant intensity c of competition, duopoly profits increase as a function of a.

4.3 Comparison of proprietary and open regimes

In the open regime's duopoly outcome, a firm's development efforts also benefit its competitor, which in turn has a negative impact on the developing firm. Incentives to innovate should thus be reduced, and development levels be biased downwards. However, the following proposition shows that the open regime can yield outcomes that are superior to those of the proprietary regime with respect to both product quality and profits. Proofs can be found in Appendix A.3.

Proposition 4 *(i) A duopoly exists in the proprietary regime only for low intensity of competition (area V in Figure 4a), while in the open regime it exists in most parts of the parameter space (areas V, W, X).*
(ii) Duopoly profits in the open regime are higher than in the proprietary regime (applies to area V in Figure 4a).
(iii) Where the proprietary regime yields a monopoly, and the open regime leads to a duopoly (areas W and X in Figure 4a), total duopoly profits in the open regime are higher than monopoly profits in the proprietary regime when competition is not too strong (in area W).
(iv) For strong heterogeneity in technology needs and/or low intensity of competition, equilibrium product qualities are higher in the open regime than in the proprietary regime (see Figure 4b).

[12] The development level d_{B2} enters positively into B's profits ($d_{B2} + d_{A1}d_{B2}$) as well as negatively, via the competition term ($c(ad_{B2} + d_{A1}d_{B2})$). The second term's impact increases in a and c.

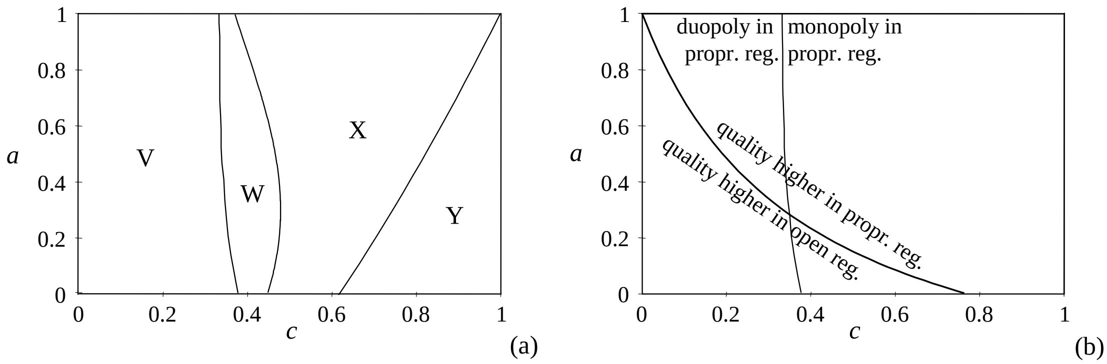

Figure 4: Comparison of equilibria in proprietary and open regime. (a): Market structure and profits. In proprietary regime: duopoly in V, monopoly in W, X, Y. In open regime: Duopoly in V, W, X, monopoly in Y. (b) Comparison of product qualities. Border curve given by $A_g^{qual}(c)$, equation (13).

Part (i) of the Proposition corresponds to the observation that market entry into the embedded Linux industry, and into open-source-based industries in general, is easier than entry into an industry under a proprietary regime. 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 of that 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 entry and also the continuation of market participation more costly. A quote from an expert interview illustrates this for the case of embedded Linux:

"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 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."[13]

Part (ii) of the Proposition—higher duopoly profits in the open than in the proprietary regime—may or may not be surprising at first glance. It is plausible since, in 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

[13] The quote is taken from an interview by the author conducted in 2002 with a US software firm dedicated to the development of embedded Linux (Henkel 2003). WindRiver and QNX are important vendors of proprietary embedded operating systems. While the interviewee likely has a biased position concerning proprietary versus open source operating systems, the statement is extremely plausible.

incentives, potentially to such a degree that profits, despite cost savings on development, are lower than in the proprietary regime. This is not the case, though—the incentive-reducing effect of openness is overcompensated by efficiency gains which result from the avoidance of parallel developments.

Proposition 4(iii) is unusual: theoretically, a monopolist should be able to replicate the duopolists' actions and hence to earn at least their joint profits. The result that total duopoly profits may be higher than profits in monopoly is driven by two model assumptions. First, not only the duopolists but also the monopolist is specialized on one of the two technologies, as expressed by the parameter $a < 1$ in equation (1). This assumption is not very plausible in the long run, but it does make sense in the short- and medium-term. Second, the definition (3) of the profit functions implicitly contains capacity restrictions: given identical quality levels Q, total sales equal $2Q(1 - c)$ in the duopoly and Q in the monopoly case. Hence, for low to medium intensities of competition ($c < 1/2$), total sales in the duopoly case are higher than in the monopoly case, which can be interpreted as a capacity restriction of the monopolist. Again, in the medium-term, and especially for service-oriented software firms, this is plausible. Still, comparisons between the monopoly case in the proprietary regime and the duopoly case in the open regime must be interpreted carefully.

Part (iv) of Proposition 4 contains a central result: The open regime can yield technology levels superior to those that obtain in 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 the complementarity between technologies. Since, in the open regime, A can adopt B's technology level d_{B2}, which is superior to what A would have developed in 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. This is an important finding since one should expect that a more complete allocation of property rights increases incentives to innovate and hence innovation efforts. It means that under realistic conditions the positive effects of compulsory openness on innovation can more than outweigh its negative effects.

The result helps to understand the fast technological development that embedded Linux has experienced in recent years. The following quote from an expert interview concerning the use of a proprietary embedded operating system illustrates the findings from the model, and in addition lends support to the implicit assumption of capacity restrictions discussed above:

"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."[14]

4.4 Endogenous choice between revealing and secrecy

The regimes analyzed above can be interpreted as idealized models of proprietary and open source software production. However, in the real world proprietary software developers sometimes do make code public, while on the other hand also for open source software—even if it is licensed under the GPL—there exist ways to keep developments secret. In both cases it is at the agent's discretion to reveal a development or not. The next logical step in the model analysis is thus to endogenize the choice between revealing and secrecy.

To that end, I introduce an additional stage into the game in which firms have to commit to either reveal their subsequent developments or to keep them secret. This choice takes place in stage two, after the decision to enter the market and before the choice of technologies and development levels. In order to solve the game by backward induction, each final-stage subgame equilibrium needs to be determined. Tables 5 and 6 in Appendix A.4 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, since developing only technology 1 is always preferable for A. In Appendix A.4, the best responses for both players in the third-stage subgame are determined. Comparing the payoffs with those in 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.4. The border curves $a_4(c)$ and $a_5(c)$ of the shaded areas are described by equations (15) and (16) in the Appendix.

Proposition 5 *When the choice between revealing and secrecy is endogenous, an equi-*

[14]The quote (translated by the author) is taken from an interview by the author conducted in 2002 with a German software firm specializing on the development of embedded Linux (Henkel 2003).

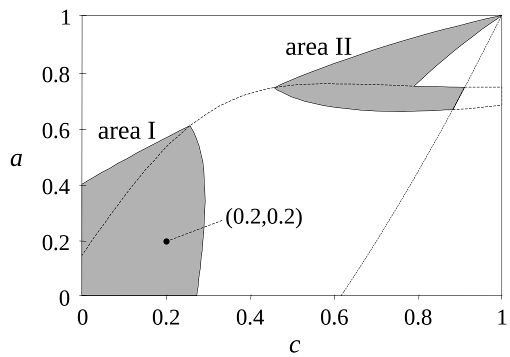

Figure 5: Endogenous revealing: Existence of equilibria with both firms choosing to reveal (shaded areas).

librium 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.

Hence, despite competition it can be individually rational for firms to make their innovations publicly available. To illustrate Proposition 5, Table 2 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 to "secrecy", A can no longer adopt T2 from B, but develops it in-house. However, since for A T2 is less important than for B, A chooses a development level of 0.4, far below what A can adopt from B when both reveal. 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. 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.

	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	0.73
d_{X2}	$0^{\dagger}$	0.8	0.4	0.8	0.47	0.47
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 2: 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.

A closer inspection of subgame equilibria in area II of parameter space reveals that they strongly differ from those in area I. Since both a and c have high values, the competition effect of revealing is strong, and the marginal benefit from investing in one's more important technology is strongly reduced. Equilibrium development levels are correspondingly low, and a deviation to "secrecy" in stage two—by B, say—increases B's incentives to invest in technology 2 strongly. In case B deviates, also A's quality increases: now A develops also T2, but without spill-overs to B. The existence of these equilibria is not so much driven by beneficial 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 outcome seems far more likely.

5 Discussion of model assumptions

Several modeling assumptions merit discussion. First, market entry has been excluded. This is justified by the observation made in the qualitative study of embedded Linux that competitive positions are often protected much more by complementary assets, in particular hardware and personnel, than by keeping the software secret. 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 et al. 2000, Arundel 2001). Hence, even though the software is freely available, entrants can not easily replicate the incumbents' market position.

The possibility of licensing was not considered. In the particular case of embedded Linux, this is correct since 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, device 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) and Henkel & von Hippel (2003) on the difficulties involved in changing functional roles in the context of innovation).

The coefficient of the complementarity term in the firms' quality functions was set to one. It is hard to say if this value is "big" or "small" compared to real complementarity effects in embedded Linux. It is clear that when the coefficient goes to zero (i.e., when the complementarity effect vanishes), then equilibria with endogenous revealing disappear since there is no downside of unilaterally deviating to secrecy. However, the duopoly outcome in the open regime will remain superior to that in the proprietary regime at least in some parts of parameter space, since heterogeneity of needs and efficiency gains from revealing remain.

The number of firms was restricted to two. One might conjecture that the likelihood of equilibria with endogenous revealing decreases in the number N of firms, since a unilateral deviation from "revealing" might be less harmful to the respective player the larger N.

However, while the effect that such a deviation would have on each of the other firms decreases in N, the negative repercussions on the deviating firm add up over all other firms. Hence, the result of endogenous revealing is not likely to vanish for larger number of firms.

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 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. 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, yet, secrecy is individually rational. Such a situation is indeed prevalent in large parts of the parameter space. However, for low degrees of competition and middle to high values of technical heterogeneity, a coordination game arises: both free revealing and secrecy are equilibria. In the open equilibrium, product qualities as well as profits are higher. Thus, under certain conditions not secrecy or IP protection, but free revealing of an innovation constitutes the precondition for an optimal appropriation of rents from this innovation.

It is plausible that firms in the embedded Linux industry are "used" to revealing due to the open source culture. Despite a certain leeway to keep developments secret, they are coordinated on the revealing equilibrium of the coordination game. Arguably, similar conditions as in embedded Linux with respect to heterogeneous technology needs and complementarity between technologies should also exist in other industries, especially in other segments of the software market. However, the relevant actors might be 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 developed here captures the essence of this innovation process. It thus contributes to the understanding of innovation processes that are driven by voluntary spillovers.

A Appendix

A.1 Third-Stage Subgame Equilibria in 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 3. The corresponding actions of firm B obtain from symmetry considerations. Firm X's technology level q_{Xi} equals its development level d_{Xi} if the firm has chosen to develop technology i. If not, but its competitor has done so, then X adopts its competitor's development level. That is, $q_{Xi} = d_{Yi}$ (indicated by † resp. ‡ in Table 3). 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 9 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 3 payoffs can be calculated. They are given, for firm A, in Table 4.

A.2 Second-Stage Subgame Equilibria in the Open Regime

Given the payoffs obtained by solving the game's third and final stage (see Table 4), 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 in the proprietary regime, with equilibrium development levels given by (6) and payoffs by (4). 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)

$$a < a_1(c) := \frac{3c-1}{2-c+c^2} \,. \tag{9}$$

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)

$$a < a_2(c) := \frac{-306+72c-1432c^2-416c^3+214c^4-96c^5+68c^6+8c^7+4\sqrt{V}}{2\,(63-324c+190c^2-310c^3-249c^4+124c^5+4c^6+6c^7)} \,, \tag{10}$$

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}
Actions by B in stage two	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	$0^{\ddagger}$	$0^{\dagger}$	$\frac{5+a-2ac}{2(3+c)}$	$0^{\dagger}$	$\frac{2+a}{3}$	$\frac{1+2a}{3}$

Table 3: 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 B in stage two	Actions by A in stage two: no development	T1	T1, T2
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 4: Open Regime: Payoff matrix for firm A in second-stage subgame when both firms have entered the market.

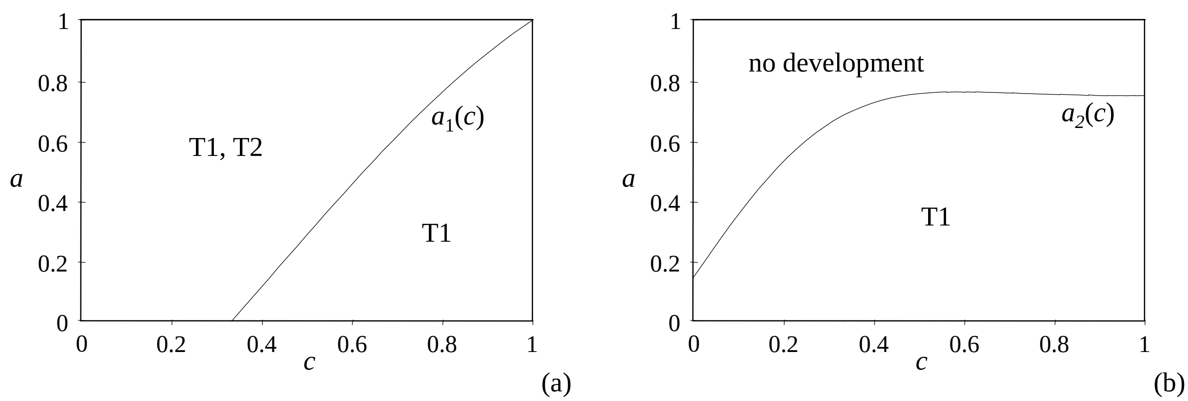

Figure 6: Open regime: Best responses by A to (a) no development by B; (b) development of T1 and T2 by B as functions of the parameters a, c. Border curves are given by equations (9) and (10), respectively.

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

The curves a_1 (9) and a_2 (10) 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.3 Proof of Proposition 4

It must be shown how the areas in parameter space that are relevant in Proposition 4 are defined. Two of the limiting curves have already been calculated. The areas where, in the proprietary regime, a duopoly/monopoly obtains as equilibrium are separated by the curve $c_b(a)$, see equation (5) and Figure 1. The corresponding curve for the open regime is described by equation (9).

The curve separating the areas in parameter space where total duopoly profits in the open regime are lower/higher than monopoly profits in the proprietary regime (areas W, X in Figure 4) obtains by setting the relevant terms (see (4) 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):

$$a_p(c) = \frac{5 + 5c^2 - 8c + 6c^3 \pm \sqrt{45 + 48c - 150c^2 - 276c^3 - 99c^4 + 60c^5 + 36c^6}}{2\,(8c + c^2 + 1)} \ . \tag{12}$$

In an analogous way, the curve separating the areas where product qualities are higher in the respective regimes is calculated (see Figure 4b). Inserting the equilibrium technology levels into the equations (1), which describe product qualities, one obtains

$$a_q(c) = \frac{-2 - 40c - 20c^2 + 6\sqrt{9 + 26c + 29c^2 + 16c^3 + 4c^4}}{2\,(8 + 25c + 8c^2)} \ . \tag{13}$$

A.4 Proof of Proposition 5

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 5 and 6, respectively.

The payoffs given in Table 6 allow to determine the players' best responses. As in 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 (9).

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

A's best response to development of T2 as well as to development of both technologies 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 (10). 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 (14). 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.

$$a < a_3(c) := \frac{16 - 64c + 40c^2 + 12c^3 + 4\sqrt{192 + 96c + 396c^2 + 288c^3 + 216c^4 + 78c^5 + 9c^6}}{2(32 + 64c + 8c^2)} \tag{14}$$

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 6) have to be compared to those in the open regime (see Table 4)

Profits in subgame equilibrium			Technologies firm A: T1	Technologies firm A: T1, T2
Technologies firm B	no devel.	$\Pi_A =$	$\frac{(1-ac)^2}{4}$	$\frac{(1+a^2)(1-c+2c^2)+a(1-5c+c^2-c^3)}{3+2c-c^2}$
		$\Pi_B =$	$\frac{(a-c)(1-ac)}{2}$	$\frac{1}{(3+2c-c^2)^2} \cdot \Big((1+a^2)(5-22c+c^5+3c^2-3c^3) +a(17-19c+36c^2+4c^3-5c^4-c^5)\Big)$
	T2	$\Pi_A =$	$\frac{-2c^2-16c+4+8c^2a-8ca+c^3a+4c^2a^2}{(4+c)^2}$	$\frac{1}{4(3+c)^2} \cdot \Big(12+12a-42c-36ac-7c^2+22ac^2 -6a^2c+12a^2+13a^2c^2+4ac^3\Big)$
		$\Pi_B =$	$\frac{1}{(4+c)^2} \cdot \Big(9+8a-8c+2c^2-8ca-8ca^2 \; 7c^2a+c^3-c^2a^2+2c^3a\Big)$	$\frac{1}{4(3+c)^2} \cdot \Big(34a-32c-68ac+12c^2+2c^3+40ac^2-56a^2c +13a^2+12a^2c^2+4ac^3-2a^2c^3+25\Big)$
	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 6: Endogenous revealing: Payoffs in final-stage subgame equilibrium when only firm A reveals, depending on technology choices in stage three.

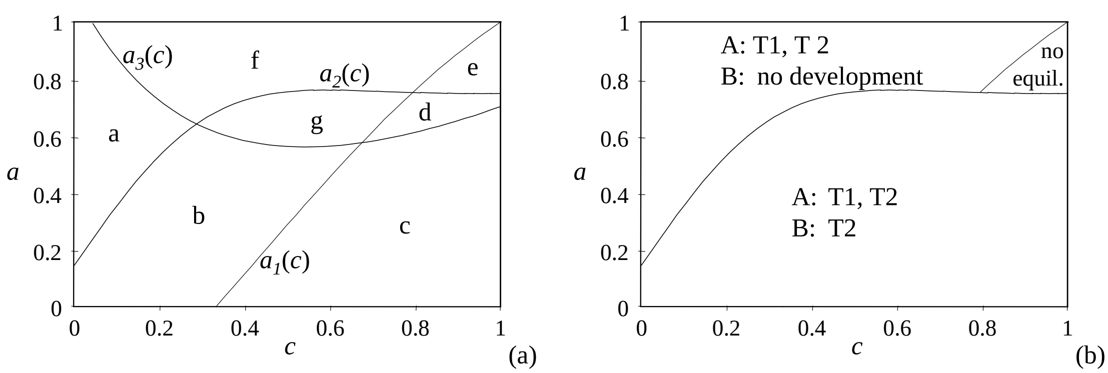

Figure 7: Revealing only by A: Parameter areas of different best-response functions in technology choices (a) and different third-stage subgame equilibria (b).

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 in the open regime and solving for a leads to the following condition for B's payoff to be higher in the open regime than with unilateral secrecy:

$$\begin{aligned} a < a_4(c) &:= \frac{-8+4c-20c^2-2c^3+2c^5+2\sqrt{V}}{2(5-13c-3c^2-2c^3+c^5)}\text{ , where} \\ V &= 36-33c-44c^2+44c^3-12c^4+10c^5+12c^6-20c^7+8c^8-c^9\;. \end{aligned} \tag{15}$$

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 in the open regime equal those when only A reveals if

$$a = a_5(c) := \frac{2-12c+78c^2+40c^3-20c^4 \pm 4\sqrt{W}}{2(13+6c-63c^2-30c^3+8c^4-2c^5)}\text{ , where} \tag{16}$$

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

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.

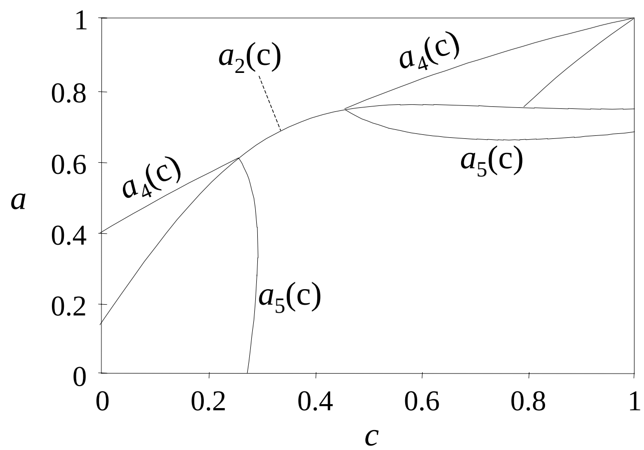

Figure 8: Comparison of B's payoffs for third-stage subgame equilibria when both reveal vs. when only A reveals. Revealing by both is preferable for B between the curves a_4 and a_5.

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 und Berlecon Research.

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., 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.

de Fraja, G. (1993). "Strategic Spillovers in Patent Races," *International Journal of Industrial Organization* 11(1), 139–146.

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.

Franke, N. and Shah, S. (2003). "How Communities Support Innovative Activities: An Exploration of Assistance and Sharing among End-Users," *Research Policy* 32(1), 157–178.

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

Gallini, N. T. (2002). "The Economics of Patents: Lessons from Recent U.S. Patent Reform," *Journal of Economic Perspectives* 16(2), 131–154.

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.

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

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

Harhoff, D. (1996). "Strategic Spillovers and Incentives for Research and Development," *Management Science* 42(6), 907–925.

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.

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.

Henkel, J. and von Hippel, E. (2003). "Welfare Implications of User Innovation," CEPR Discussion Paper No. 4063.

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

Kuan, J. (2000). "Open Source Software As Consumer Integration into Production," Working Paper, University of California at Berkeley.

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.

Levin, R. C. and Reiss, P. (1988). "Cost-Reducing and Demand-Creating R&D with Spillovers," *RAND Journal of Economics* 19(4), 538–556.

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.

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.

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

Nuvolari, A. (2001). "Collective Invention During the British Industrial Revolution: The Case of the Cornish Pumping Engine," Working Paper 01.04, Version Juli 2002, Eindhoven Center for Innovation Studies, http://www.tm.tue.nl/ecis/Working%20Papers/eciswp37.pdf.

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

Riggs, W. and von Hippel, E. (1994). "Incentives to Innovate and the Sources of Innovation: the Case of Scientific Instruments," *Research Policy* 23(4), 459–469.

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

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

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

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.