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

March 2004

Joachim Henkel[1]

University of Munich, CEPR

Abstract

The success of open source software highlights the fact that innovation can take place without secrecy or intellectual property protection. In this paper, I explore the circumstances under which such innovation processes are possible. Motivated by an empirical study of embedded Linux, I develop a duopoly model of quality competition. Each firm requires two technologies as inputs. The technologies are complementary to each other and of different relative importance to the firms. I find that a regime with compulsory revealing can lead to higher product qualities and higher profits than a proprietary regime. When the choice between revealing and secrecy is endogenous, equilibria with voluntary revealing arise.

JEL classification: L11, L15, L86

Keywords: Innovation; Development collaboration; Open source software; Embedded Linux

[1]Institute for Innovation Research, Technology Management and Entrepreneurship, Ludwig Maximilians University Munich, Kaulbachstr. 45, D – 80539 Munich, Germany. Phone: +49 - 89 - 2180 2986, fax: +49 - 89 - 2180 6284, email: henkel@bwl.uni-muenchen.de.

1 Introduction

The surge of open source software has added new aspects to the debate on what would be the ideal incentive system for innovation. Open source licenses to not allow to charge royalties. 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 should correspondingly expect reduced incentives to innovate. Nonetheless, commercial firms make many and in some cases large contributions to this type of software (e.g., Moody 2001), and popular programs such as Linux and Apache have experienced tremendous success and fast development.

This observation has implications on the industry level and for the individual firm. On the industry level it demonstrates that, while public policy has tended to strengthen intellectual property protection in recent years (e.g., Gallini 2002), IP protection is not always needed to spur innovation. For the individual firm it shows that free revealing of developments can be consistent with profit-maximizing behavior. In fact, just as secrecy and legal protection, free revealing can be a *precondition* for certain ways to appropriate rents from innovation.

Circumstances under which revealing might be preferable to secrecy and legal protection can be identified by considering its potential benefits and downsides. Among the benefits are external development support, increased demand for commercially sold complementary goods, development of complements to the respective innovation, standard setting, and signalling of competencies (e.g., Behlendorf 1999, Henkel 2004, Lerner & Tirole 2002, Raymond 1999, von Hippel & von Krogh 2003). The biggest potential downside is a loss of differentiation and competitive advantage.

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. Using a game-theoretic model I compare an "open" regime with compulsory revealing to a "proprietary" one with no revealing. These regimes 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. This endogenization takes account of the fact that also proprietary software developers may make their code public, while on the other hand also open source developers have some leeway in keeping their code secret. I analyze whether and under what conditions revealing by both firms constitutes an equilibrium, i.e., when an open regime arises endogenously. The model is motivated by an empirical study of the development of "embedded Linux" (Henkel 2003) which is described in detail in Section 2.

The main results are the following. When revealing is compulsory, an equilibrium with each firm specializing on one technology exists in large parts of parameter space. In contrast, in a proprietary regime where all developments are kept secret a duopoly is only viable for low intensity of competition. Duopoly profits are higher in the open than in the proprietary regime. For high heterogeneity and/or low intensity 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 for low intensity 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.

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. Allen and Nuvolari describe situations of "collective invention", which "differs from R&D since the firms [do] not allocate resources to invention – the new technical knowledge [is] 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 plays a central role. The situation also differs from those described by Riggs & von Hippel and Franke & Shah, where innovations are developed and revealed by *users*. For the firms considered here, their developments are a part of their product or service offering, not something they use in their internal processes. Finally, the situation analyzed here also differs from community-based open source development in that all actors are profit-oriented firms.[2]

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 is hence 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 characteristics and the development process of embedded Linux is given. 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

[2]A number of theoretical contributions has analyzed under what conditions an open regime might be favorable to innovation. Among them are Baake & Wichmann (2003), Bessen (2001), Bessen & Maskin (2000), de Fraja (1993), Eaton & Eswaran (1997), Harhoff, Henkel & von Hippel (2003), Johnson (2001), and Kuan (2000).

can be found in the Appendix.

2 Embedded Linux – informal development collaboration

This paper was 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 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, 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 (Balacco & Lanfear 2002, Lombardo 2001, 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, due to high heterogeneity of hardware and functional requirements in embedded systems, embedded Linux shows a high heterogeneity.

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.[3] The commitment of commercial firms to embedded Linux is somewhat 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.

However, the second peculiarity of embedded Linux – high *heterogeneity* – limits the negative effects arising from free revealing. 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. 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. 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. 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. 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 this paper.

Table 1 lists several quotes taken from interviews conducted by the author in 2002 and 2003 with firms involved in embedded Linux development (Henkel 2003). They support the characterization of embedded Linux given above and more generally illustrate the kind of informal development collaboration that takes place in this industry.

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. The firms' technology levels are denoted by q_{Xi}, where $X \in \{A, B\}$, $i \in \{1, 2\}$. The

[3] 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.

"...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)
"When you look at it closely you find that many 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 specialized on embedded Linux, Europe)
"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)
"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)
"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)

Table 1: Quotes from interviews with firms involved in embedded Linux development.

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).[4] For embedded Linux, e.g., further investments in the system's real-time capabilities make the more sense the better its networking features. 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 motivated by 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" $d_{Ai} = q_{Ai}$.[5] Alternatively, if firm B has developed *and revealed* d_{Bi}, A can adopt B's development at no cost, yielding

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

[5] Just as the complementarity term, the cost term does not carry a coefficient. However, this does not

$q_{Ai} = d_{Bi}$ and $d_{Ai} = 0$. The firms' cost are 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 at least to 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 $c \in [0, 1]$ that measures the degree of competition, profits are defined as

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

A comment concerning the two parameters a and c is in place. 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 even market offerings. In turn, 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.

As to the game's timing structure, I analyze a three-stage and a four-stage 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. Nonetheless, a long-term strategy typically underlies the individual decisions what to reveal and what to keep secret. The equilibrium concept employed is subgame perfectness (Selten 1965, Fudenberg & Tirole 1991, pp. 69).

---

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.

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 (1) linearly but the cost function (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 game are shown in Table 2 for the case that A enters the market (otherwise A's payoff equals zero).

	Strategy B: no entry	Strategy B: entry
Payoff A	$\frac{1+a+a^2}{3}$	$\frac{1+a+a^2}{3} - c\frac{8+11a+8a^2}{9}$

Table 2: Payoffs for A in proprietary regime if A enters the market. Reduced game, second- and third-stage subgames solved.

From the payoffs shown in Table 2, best responses can be calculated, which leads to the following Proposition.

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

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

See shaded area in Figure 1. In this equilibrium, A chooses the development levels

$$e^{pd}_{A1} = e^{pd}_{B2} = (2+a)/3 , \qquad e^{pd}_{A2} = e^{pd}_{B1} = (1+2a)/3 . \quad (5)$$

For $c > c_g(a)$, there are two equilibria with only one of the firms entering the market.[6] *Development levels are the same as in the duopoly case.*

[6]These are equilibria in pure strategies. Equilibria in mixed strategies exist, but are indifferent and instable. They are not explored further.

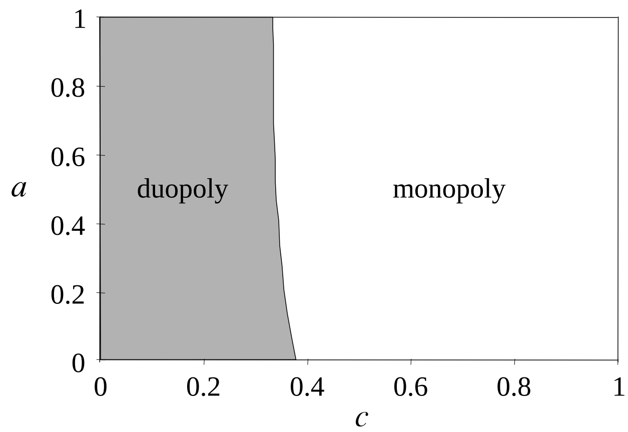

Figure 1: Proprietary regime: Areas of different equilibria (duopoly, monopoly) in parameter space (a, c). Border curve described by $c_g(a)$.

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.[7] 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, $d_{A2} = 0$ and $q_{A2} = d_{B2}$. I assume that a technology can only either be completely adopted or be completely developed in-house.

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 6 in the Appendix. Concerning the equilibria of this subgame, the following proposition holds (proof: see Appendix A.2):

Proposition 2 *When, in the open regime, both firms have entered the market, then the second-stage subgame has the following equilibria:*
(a) Development of only the respective more important technology by each firm is a subgame equilibrium for all parameter values.
(b) Development of both technologies by one firm and free riding by the other firm is a subgame equilibrium in segment A of parameter space (see Figure 2 and equations (7) and

[7] 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.

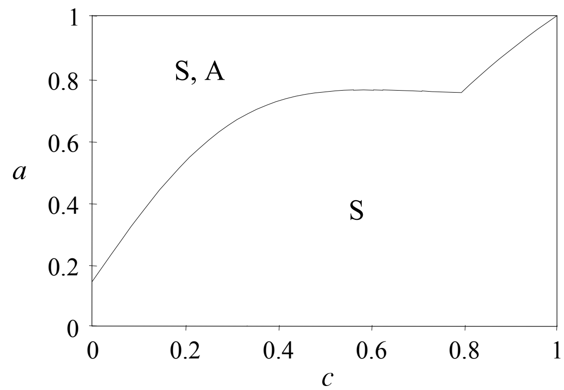

Figure 2: Open regime: Second-stage subgame equilibria in (a, c)-parameter space after market entry by both firms. S: symmetric equilibrium, development of the respective more important technology by each firm. A: asymmetric equilibrium, development of both technologies by one firm, free riding by the other firm.

(8) in the Appendix).

The above solution of the second-stage subgame allows to reduce 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 (segment A in parameter space, see Proposition 2). 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.[8] Under this assumption, payoffs for firm A as a function of market entry decisions are given by Table 3 (symmetrically for firm B). This table immediately leads to Proposition 3 concerning existence of symmetric equilibria.

Proposition 3 *(a) In the open regime, a symmetric duopoly equilibrium exists if*

$$a \geq c^2 + c - 1 \ . \tag{6}$$

In this equilibrium, each firm develops only the respective more important technology and adopts the other technology from its competitor.
(b) For $a < c^2 + c - 1$, no duopoly equilibrium exists. The only viable outcome is a monopoly.[9]

[8] 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, $a > 0.4 + 0.6c$.

[9] 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 2b). 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.

	Strategy B: no entry	Strategy B: entry
Payoff A	$\frac{1+a+a^2}{3}$	$\frac{(1-ac)(1+a-c-c^2)}{(1+c)^2}$

Table 3: Payoffs for A in open regime if A enters the market. Reduced game, second- and third-stage subgames solved. In case of multiple equilibria in the second-stage subgame, the symmetric equilibrium is assumed.

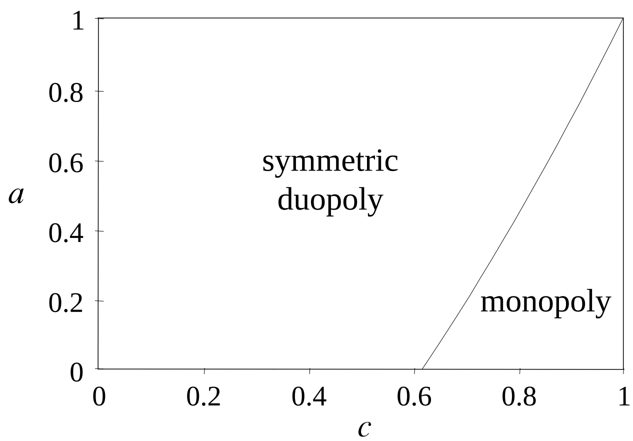

Figure 3: Open regime: Areas of different equilibria (duopoly, monopoly) in parameter space (a, c). Border curve described by equation (6).

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 utility maximization. While free riding is possible, it would imply that the respective firm – firm B, say – has only the less important technology 1 at its disposal. Additionally, the complementarity term in its quality function vanishes, reducing B's product quality further. It is true that also the competing firm A 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 ($c < 1$).[10]

A monopoly equilibrium (see Proposition 3b) 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 hetero-

[10] 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.

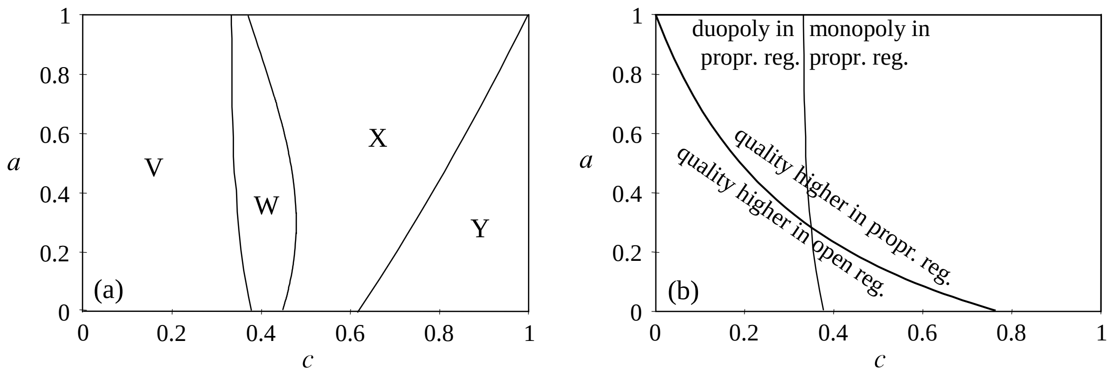

Figure 4: Comparison of equilibria in proprietary and open regime. (a): Market structure and profits. In proprietary regime: duopoly in V, monopoly in W, X, Y. In open regime: Duopoly in V, W, X, monopoly in Y. (b) Comparison of product qualities. Border curve given by $A_g^{qual}(c)$, equation (11).

geneous the technology needs. 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 downward. However, the following Proposition shows that the open regime can yield outcomes preferable to those of the proprietary regime. Proofs can be found in Appendix A.3.

Proposition 4 *(a) 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).*
(b) Duopoly profits in the open regime are higher than in the proprietary regime (applies to area V in Figure 4a).
(c) When the proprietary regime yields a monopoly, while 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).
(d) For strong heterogeneity in technology needs and low intensity of competition, equilibrium product qualities are higher in the open regime than in the proprietary regime (see Figure 4b).

Part (a) 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 nicely 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."*[11]

Part (b) 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 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(c) 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- or 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 duopoly and Q in monopoly. Hence, for low and medium intensity c of competition ($c < 1/2$), total sales in duopoly are higher than in duopoly, 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 monopoly in the proprietary regime and duopoly in the open regime must be interpreted carefully.

Part (d) of Proposition 4 contains a central result: The open regime can yield technology levels superior to those that obtain in the proprietary regime. Condition for this result is that technology needs are sufficiently heterogeneous (a small) and/or the intensity c of competition is low. It 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

[11] 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.

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. Since one should expect that a more complete allocation of property rights increases incentives to innovate and hence innovation efforts, this is an important finding. It means that under realistic conditions the negative effects of compulsory openness on innovation can be more than outweighed by its positive effects.[12]

The conditions under which this result arises – heterogeneous technology needs, not-too-strong competition, and complementarity between technologies – are plausible for many firms in the field of embedded Linux. In particular, the assumption of heterogeneous technology needs is often extremely realistic. "Heterogeneous" means heterogeneous *at a certain point in time*: it may be that other firms have a high need for a certain development one year after it was made public. Still, at the moment under consideration, needs are heterogeneous. This fact both precludes free-riding by the developing firm and mitigates the negative competitive effect from revealing.

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."*[13]

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 open source software offers ways to keep one's 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

[12] A similar result is shown by Bessen & Maskin (2000) in the context of a repeated game, based on somewhat different assumptions.

[13] 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).

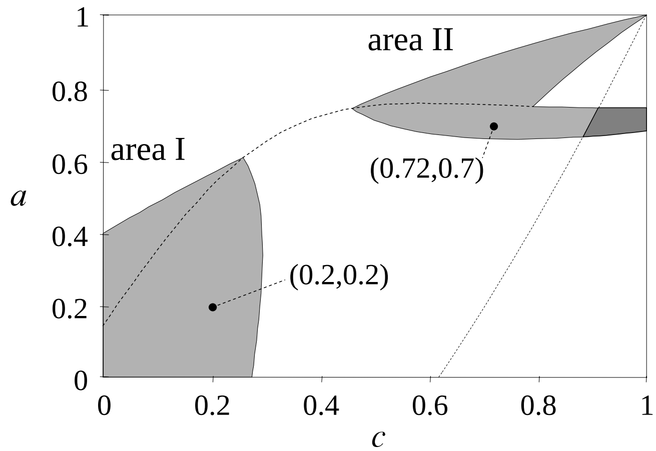

Figure 5: Endogenous revealing: Existence of equilibria with both firms choosing to reveal (shaded areas).

induction, each final-stage subgame equilibrium needs to be determined. Tables 7 and 8 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 the Appendix, the best responses for both players in the third-stage subgame are determined, leading to subgame equilibria as shown in Figure 7b. Comparing the payoffs with those in the open regime and the proprietary regime allows to solve the entire game. The results are summarized in the following Proposition, which is illustrated by Figure 5 and proved in Appendix . The border curves $A_{g4}(c)$ and $A_{g5}(c)$ of the shaded areas are described by equations (13) and (14) in the Appendix.

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

To illustrate Proposition 5, Table 4 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. Columns three/four show the outcome in case a firm deviates from one of the equilibria. When B unilaterally deviates in stage two 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. 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.

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 4: 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 better to the situation at hand.

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 usually 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, Nelson & Walsh 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 obviously correct since royalties are excluded by the applicable open source license. More generally, the assumption is justified by the fact that the developments under consideration are typically 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 difficulty to change 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 at least to Arrow (1962). IPRs in general 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).

This paper adds to the debate mentioned above. Furthermore, it explores particular 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 – conditions that are realistic in the case of embedded Linux – an open regime yields higher product qualities as well as higher profits than a proprietary regime. The results are driven by specialization and complementarity between the technologies.

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, quality as well as profits are higher.

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. They might just be stuck 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 nicely captures the essence of this innovation process. It thus contributes to the understanding of innovation processes that are driven by voluntary spillovers.

Actions firm A in third-stage subgame equ.	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: no devel.	0	0	$\frac{1-ac}{2}$	0	$\frac{2+a-c(1+3a-c)}{3+2c-c^2}$	$\frac{1+2a-c(3+a-ac)}{3+2c-c^2}$
Actions by B: T2	0	$0^\dagger$	$\frac{1-ac}{1+c}$	$0^\dagger$	$\frac{2+a-c(2a+1)}{3+c}$	$\frac{2+4a-c(a+1)}{2(3+c)}$
Actions by B: T2, T1	$0^\ddagger$	$0^\dagger$	$\frac{5+a-2ac}{2(3+c)}$	$0^\dagger$	$\frac{2+a}{3}$	$\frac{1+2a}{3}$

Table 5: 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. "Ti" stands for "development of technology i". † indicates that $q^*_{A2} = d^*_{B2} \neq 0$; ‡ indicates $q^*_{A1} = d^*_{B1} \neq 0$.

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 5. 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, $q^*_{Xi} = d^*_{Yi}$. The symbol † in Table 5 indicates that, while $d^*_{A2} = 0$ in the respective subgame, $q^*_{A2} = d^*_{B2} > 0$. That is, A adopts B's development of technology 2. The symbol ‡ indicates that A adopts B's development of technology 1. 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 7 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 5 payoffs can be calculated. They are given, for firm A, in Table 6.

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 6), 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 (5) and payoffs by the top right entry in Table 2. 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)

$$a < A_{g1}(c) := \frac{3c-1}{2-c+c^2} \,. \tag{7}$$

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)

$$a < A_{g2}(c) := \frac{-306 + 72c - 1432c^2 - 416c^3 + 214c^4 - 96c^5 + 68c^6 + 8c^7 + 4\sqrt{V}}{2\,(63 - 324c + 190c^2 - 310c^3 - 249c^4 + 124c^5 + 4c^6 + 6c^7)} \,, \tag{8}$$

where

$$\begin{aligned} V \;=\; & +6561 + 4374c + 2997c^2 + 29\,970c^3 + 47\,043c^4 + 26\,064c^5 - 15\,137c^6 \\ & -26\,204c^7 - 1073c^8 + 7606c^9 + 619c^{10} - 886c^{11} - 51c^{12} + 36c^{13} + c^{14}. \end{aligned} \tag{9}$$

The curves A_{g1} (7) and A_{g2} (8) 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 duopoly equilibrium with each firm developing only one technology always exists. Development of

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

Table 6: Open Regime: Payoff matrix for firm A in second-stage subgame, when both firms have entered the market. “Ti” stands for “development of technology i”.

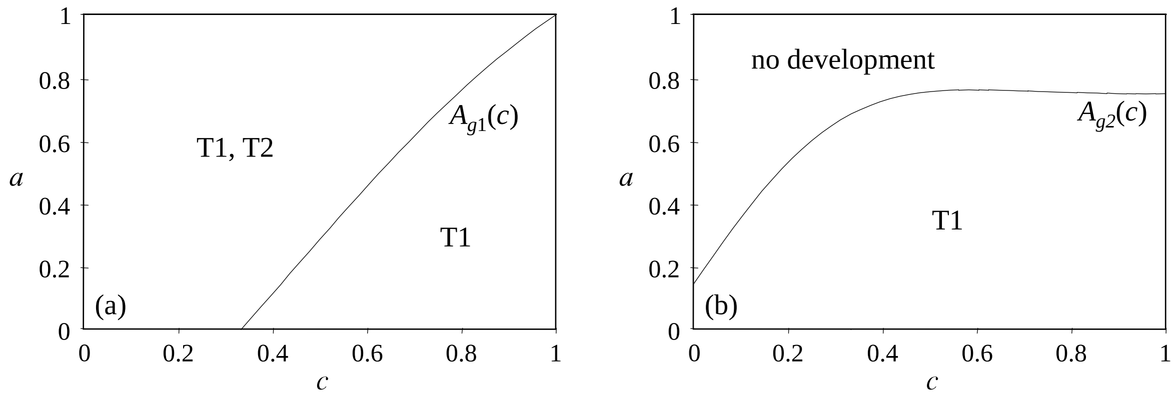

Figure 6: Best responses by A to (a) no development by B; (b) development of T1 and T2 by B as functions of the parameters a, c. Border curves are given by equations (7) and (8), respectively.

both technologies by one firm and no development by its competitor is an equilibrium if $a > A_{g1}(c)$ and $a > A_{g2}(c)$. These inequalities are fulfilled in the area denoted by A in 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 been calculated already. The areas where, in the proprietary regime, a duopoly/monopoly obtains as equilibrium are separated by the curve $c_g(a)$, see equation (4) and Figure 1. The corresponding curve for the open regime is described by equation (7).

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) obtains by setting the relevant terms (see Tables 2 and 6, resp.) equal to each other and solving for a. This leads to the following equation (where the $\pm$ symbol indicates that the function is defined in two branches):

$$A_g^{prof}(c) = \frac{5 + 5c^2 - 8c + 6c^3 \pm \sqrt{45 + 48c - 150c^2 - 276c^3 - 99c^4 + 60c^5 + 36c^6}}{2\,(8c + c^2 + 1)}\ . \quad (10)$$

In an analogous way the curve separating the areas where product qualities are higher/lower in the open than in the proprietary regime is calculated. Inserting the equilibrium tech-

Actions in subgame equilibrium			Technologies, A			
			T1		T1, T2	
			d^*_{X1}	d^*_{X2}	d^*_{X1}	d^*_{X2}
Technologies, 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 7: Endogenous revealing: Actions in final-stage subgame equilibrium when only firm A reveals, depending on technology choices in stage three. † indicates that B adopts the respective development from A.

nology levels into the equations (1) describing product quality, one obtains

$$A_g^{qual}(c) = \frac{-2 - 40c - 20c^2 + 6\sqrt{9 + 26c + 29c^2 + 16c^3 + 4c^4}}{2\,(8 + 25c + 8c^2)}\,. \tag{11}$$

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 7 and 8, respectively.

The payoffs given in Table 8 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 $a < A_{g1}(c)$, and development of both technologies when $a > A_{g1}(c)$. See equation (7). 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 $a > A_{g2}(c)$, and development of T2 if $a < A_{g2}(c)$. See equation (8). 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 $a < A_{g3}(c)$, see equation (12). Figure 7a shows the three curves that separate areas of different best

Profits in subgame equ.			Technologies, A	
			T1	T1, T2
Technologies, B	keine Entw.	$\Pi_A =$	$\frac{(1-ac)^2}{4}$	$\frac{(1+a^2)(1-c+2c^2)+a(1-5c+c^2-c^3)}{3+2c-c^2}$
		$\Pi_B =$	$\frac{(a-c)(1-ac)}{2}$	$\frac{1}{(3+2c-c^2)^2} \cdot \big((1+a^2)(5-22c+c^5+3c^2-3c^3) +a(17-19c+36c^2+4c^3-5c^4-c^5)\big)$
	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 8: Endogenous revealing: Payoffs in final-stage subgame equilibrium when only firm A reveals, depending on technology choices in stage three.

response functions in parameter space, as well as the resulting seven segments a-g.

$$a < A_{g3}(c) := \frac{16 - 64c + 40c^2 + 12c^3 + 4\sqrt{192 + 96c + 396c^2 + 288c^3 + 216c^4 + 78c^5 + 9c^6}}{2(32 + 64c + 8c^2)} \tag{12}$$

The curves A_{g1}, A_{g2} and A_{g3} 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 8) have to be compared to those in the open regime (see Table 6) 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., $a > A_{g3}(c)$, see Figure 7). Setting B's payoffs equal to what the firm receives in the open regime

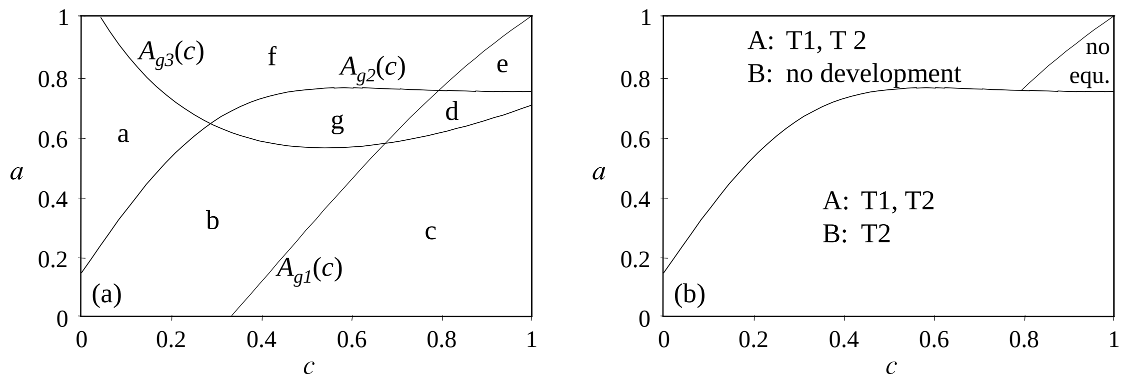

Figure 7: Revealing only by A: Parameter areas of different best-response functions (a) and different third-stage subgame equilibria (b).

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

$$a < A_{g4}(c) \quad := \quad \frac{-8 + 4c - 20c^2 - 2c^3 + 2c^5 + 2\sqrt{V}}{2(5 - 13c - 3c^2 - 2c^3 + c^5)} \ \text{, where} \tag{13}$$
$$V \quad = \quad 36 - 33c - 44c^2 + 44c^3 - 12c^4 + 10c^5 + 12c^6 - 20c^7 + 8c^8 - c^9 \ .$$

In case B chooses to develop T2 in the third-stage subgame equilibrium when only A reveals (i.e., for $a < A_{g3}(c)$), B's payoffs in the open regime equal those when only A reveals if

$$a = A_{g5}(c) \quad := \quad \frac{2 - 12c + 78c^2 + 40c^3 - 20c^4 \pm 4\sqrt{W}}{2(13 + 6c - 63c^2 - 30c^3 + 8c^4 - 2c^5)} \ \text{, where} \tag{14}$$
$$W \quad = \quad 36 - 84c - 284c^2 + 168c^3 + 921c^4 + 882c^5 + 339c^6 + 52c^7 + 11c^8 + 6c^9 + c^{10} \ .$$

Since the function $A_{g5}(c)$ is defined piece-wise, the condition for the open regime to be preferable for B can not 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_{g4} and A_{g5}. Hence, for these values "revealing by both firms" is a second-stage subgame equilibrium.

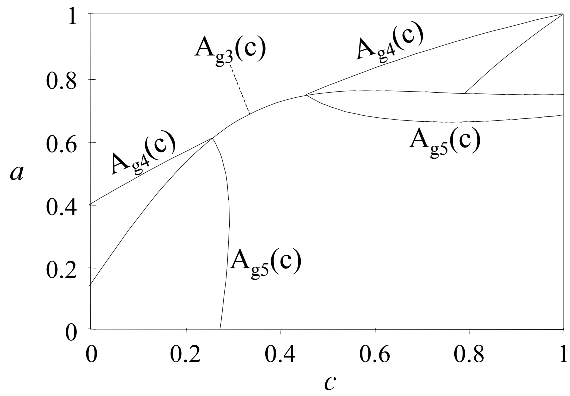

Figure 8: Comparison of B's payoffs for third-stage subgame equilibria when both reveal vs. when only A reveals. Revealing by both is preferable for B between the curves A_{g4} and A_{g5}.

Acknowledgements

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

References

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

Arora A., Fosfuri A., 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: Nelson R. (Ed.), The Rate and Direction of Inventive Activity, Princeton University Press, Princeton, N.J.

Arundel A. (2001). The relative effectiveness of patents and secrecy for appropriation. Research Policy 30(4), 611–624.

Baake P., Wichmann T. (2003). Open source software, competition and potential entry. Working Paper, IFO-Institut und Berlecon Research.

Balacco S., 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.

Behlendorf B. (1999). Open source as a business strategy. In: Dibona C., Ockman S., Stone M. (Eds.), Opensources: Voices from the Open Source Revolution, O'Reilly, Sebastopol, CA, 149–170.

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., Maskin E. (2000). Sequential innovation, patents, and imitation. MIT Department of Economics Working Paper 00-01.

Boldrin M., 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., 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., 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: Kahin B., Abbate J. (Eds.), Standards Policy for Information Infrastructure, MIT Press, Cambridge, MA, 368–377.

Franke N., 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).

Fudenberg D., Tirole J. (1991). Game Theory. MIT Press, Cambridge, MA, 3. ed.

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., Scotchmer S. (2002). Intellectual property: When is it the best incentive system? In: Jaffe A., Lerner J., Stern S. (Eds.), Innovation Policy and the Economy, Vol. 2, MIT Press, Cambridge, MA.

Grossman G., 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., Henkel J., 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: Uhr W., Esswein W., Schoop E. (Eds.), Proceedings of the 6th International Conference on Business Informatics, Physica, Heidelberg.

Henkel J. (2004). Open source software from commercial firms – tools, complements, and collective invention. Zeitschrift für Betriebswirtschaft, accepted for publication.

Henkel J., 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, Zugriff am 07.10.2003.

Kuan J. (2000). Open source software as consumer integration into production. Working Paper, University of California at Berkeley.

Lerner J., 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: Nelson R.R. (Ed.), Government and Technical Progress: A Cross-Industry Analysis, Pergamon Press, Oxford, 9–100.

Levin R.C., Klevorick A., Nelson R.R., 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.

Mazzoleni R., 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. ed.

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.

Raymond E.S. (1999). The Cathedral and the Bazaar: Musings on Linux and Open Source by an Accidental Revolutionary. O'Reilly, Sebastopol, CA, 1. ed.

Riggs W., 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.

von Hippel E., von Krogh G. (2003). Open source software and the "private-collective" innovation model: Issues for organization science. Organization Science 14(2), 209–223.

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.

Webb W. (2003). Unlocked – embedding open-source software. EDN.COM, http://www.reed-electronics.com/ednmag/contents/images/296493.pdf 05/15/2002.