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Essays on the Economics of Information and Communication Technologies: Copyleft, Networks and Compatibility

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Preface

The thesis consists of an introductory chapter and four essays. The first essay is forthcoming in *Information Economics and Policy* and appears here with the permission of Elsevier Science. The third essay has been published in *EURAS Yearbook of Standardization* and is reprinted here with the permission of Accedo Verlag.

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The research and studies leading to this thesis have been a fascinating experience. After a long period in business life where the span of thinking is short, sometimes almost nonexistent, it was both difficult and invigorating to concentrate on a problem and then take all the patience needed to report carefully the results arising. One of the surprises of this undertaking was to note how powerful inner motives can be. The incentives in business can be strong but the need to find out and say something, which hopefully turns out to be meaningful, may, in my experience, be an even stronger driver of man.

I am most grateful to the supervisor of the thesis, Professor Vesa Kanniainen. His guidance, always subtle, led me to find the interesting and relevant building blocks for my research from the vast realm of economics. His enthusiasm and 'do-it-now' attitude were both contagious and contributed to the rapid completion of the thesis.

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Helsinki, January 2003

Mikko Mustonen

Contents

The economics of ICT: An overview

1 Introduction

- *What is the interaction of a software firm developing a copyright program when programmers are motivated not only by wage but may be involved in the development of free competing copyleft programs like Linux?*
- *Under what conditions would a software firm support the development of a compatible program by a copyleft community? Would society benefit from imposing a standard or from supporting the scientific use of copyleft programs?*
- *If firms compete by investing in vertical compatibility between vintages of their products and buyers of IT-systems value the compatibility, is the market outcome efficient? How can society improve on it?*
- *If a firm signals its private information of its production cost to a rival by developing compatibility, how does this affect the market outcome?*

Creation of new knowledge and innovations that turn into new products and processes are fundamental to the growth of the economy[1]. Firms invest in research and development projects to increase the value of their goods in the eyes of consumers or to decrease the costs of production[2]. Maximization of expected profits drives the firms' decisions on investments in R&D. In this thesis, we explore the R&D strategies of firms when markets and products exhibit properties, which are typical in information and communication technology (ICT) industries. The aim of the study is to analyse the outcomes of market mechanisms and see whether they can be improved

[1] This view has been formalized in the endogenous growth theory, which stresses the importance of new knowledge. See eg. Jones (1995) and Romer (1986).
[2] In practice, this distinction is, however, blurred. See Levin and Reiss (1988) for a discussion.

by technology, science and competition policies to yield a higher level of welfare. In the era of the 'New Economy' (The Economist 2000) products and markets tend to have several common characteristics. Because of the heavy development investments, production of goods exhibits increasing returns to scale. The rapid progress of technology shortens product cycles. At the same time consumers face an increasingly complex environment where many different products need to work together. The development of new products and services is dependent of skills, human capital. Thus, the incentives for development work become important. According to OECD (2000a), the increasingly important sources of economic growth are increasing returns to scale, network effects and externalities. The motivation for the research stems from the significance of the ICT-industry to the creation of new knowledge and importance of product compatibility. Incentives for software development are becoming an important issue for the society. In developed countries a large fraction of investments is directed to software development, for example in Sweden 11 percent (Jagren and Morell 2000). The development work is for the most part knowledge creation in contrast to many other types of investment; hence, its relative contribution to new knowledge probably exceeds its share of investments. Compatibility between product vintages has become an issue for users of large IT-systems due to the cumulative investments to applications that need to be modified if the system environment changes. The cost of a conversion, i.e. switching the supplier of the system or moving to an incompatible new system from the current supplier, can be significant. Greenstein (1997) provided unique cost data of conversions of mainframe systems of US Federal Agencies. Already in the 1980s, the cost of conversion was up to 250 percent of the cost of the hardware system.

The information and communication technology (ICT) industry has not only grown but also been subject to rapid transformation during the recent decades. ICT includes the manufacturing of equipment for computing and communications, the software industry and a broad variety of services from consulting to telecommunications. The ICT sector has become a major contributor of economic activity[3]. It contributed from five to fourteen percent of the total business sector value added in OECD countries in 1999. More importantly, the ICT sector has been growing faster than most other

[3] Sources: OECD 2001a, b, c and ITU 2002.

sectors of the economy. This is illustrated by the fact that while the share of ICT investment was below fifteen percent of the total non-residential investment in the OECD business sector in the 1980s, its share has reached fifteen to thirty-five percent in 1999. OECD countries like Australia, Finland and USA had the highest shares by 1999. The share of ICT expenditures of GDP varies between countries in the OECD area. High intensities in the neighbourhood of nine percent can be found in, for example, the Nordic countries and lower intensities are found in the Southern European countries with the OECD average in 1999 being about six percent. In Finland, the contribution of ICT use to the growth of the economy has increased dramatically during the last ten years. Jalava and Pohjola (2002) reported that the contribution was 0,3 percentage points in the beginning of 1990s and 0,7 percentage points in the late 1990s. During the period, the products of the ICT industry have become common in the consumer markets. The proliferation of the Personal Computer and especially of mobile phones has changed not only the communications but also the consumption habits of consumers. Mobile phones serve as an example: in the last ten years the global use of mobile phones has grown hundredfold from ten million to thousand million users in the world. Internet, the decentralized network for information sharing and transfer, has facilitated the spread of the ICT technology to a large number of consumers. In 1999 there was, on average, one subscriber per ten inhabitants in OECD countries and in the most advanced countries one subscriber per four inhabitants. To highlight the breadth of services available in Internet, consider the fact that there were 100 million web sites in OECD countries in 2000. Of these, 63 percent were based on open source *copyleft* web server software, Apache (Netcraft 2001).

In the theoretical essays of this study, we identify prominent features of the ICT industries: copyleft, network effects and compatibility and analyse how they affect the economics of the industry. A novel licensing scheme, copyleft, creates an alternative incentive structure for open source programming work. In a copyleft license, the author withholds the copyright to the program but permits the use, distribution and further development of the program by everyone who in turn must license his own additions or enhancements to the program using the same copyleft agreement. The copyleft license implies that the program is free i.e. has zero price, since the authors cannot claim any rents from the program (GNU Project 2000a,b, Open Source

Initiative 2000). The first essay explores how the existence of a copyleft programming community, motivated not by profit, influences the behaviour of a software firm with copyright to a rival program in the same market. The firm faces an employment decision, which determines the qualities of both its own and the copyleft program. The second essay expands the analysis by introducing network effects in the market of programs. Goods are said to exhibit network effects when the number of agents taking similar action affects the net value of acquiring a good[4]. We characterize the conditions for the firm to support the copyleft community even if it develops a competing program. Compatibility between sequential vintages of a product, i.e. vertical compatibility, has become a crucial issue with the advent of complex information systems, in which the life spans of application programs, operating systems and hardware vary. Discontinuity in the compatibility of 'a piece of the puzzle' can have serious implications to the usability of the service. In the third and fourth essay, we analyse such vertical compatibility and the performance of the market solution in providing vertical compatibility and the ways to increase welfare. The fourth essay we expand the framework by introducing a firm's uncertainty over the rival's marginal costs and analyse the resulting signalling behaviour.

In all essays of the thesis, we try to unearth the factors influencing the market outcome and their contribution to market failures. For the society to be able to assess the requirements for policy actions to increase welfare it is necessary to know not only the underlying mechanisms of the ICT industries' markets but also the effects of policy. The insintric properties of the 'new economy' or ICT industries, i.e. increasing returns to scale, limited appropriability, externalities and uncertainty, are all sources of market failures (Mas-Colell et al. 1995, Martin and Scott 2000)[5]. A market failure implies that rational actions of private agents, firms and consumers result in an outcome that is not the first best. This potentially leaves room for corrective actions of the society. The influence of selected policy actions within the industry is assessed. In the case of the copyleft license, which is a new device, a distinct aim of the study is to provide policy analysis and recommendations. We resort to the methodology and

[4] The network effect can also contain a network externality if the interdependence of value and number of users of the network is not resolved by the market mechanism, implying a market failure. In this thesis, the terms are used interchangeably as the firms own the networks and can internalise the inherent externality. See more on this distinction in Liebowitz and Margolis (1994).

[5] For a critical view to the occurrence of market failures, see Zerbe and McCurdy (2000).

framework of traditional microeconomics, typical in industrial economics[6]. This approach stands in contrast to the alternative view that the analysis of such a new phenomenon requires a completely new theoretical framework. Some of those suggestions are mentioned in the following chapter. Using the seminal structure-conduct-performance framework of Scherer (1970), we can outline our potential contribution. We introduce and analyse a new type of economic agent, a copyleft programming community. We also introduce a new attribute of goods to the industry structure, i.e. vertical compatibility. Copyleft programming incentives and the use of compatibility R&D as a signal both contribute to the industry conduct. With those extensions, we study the industry performance in terms of welfare, measured as social surplus.

2 The analytical framework

Information, the basic ingredient of goods in the ICT industries, has intriguing economic properties. It is often indivisible, like for example, a computer program. The marginal cost of reproduction of information is minimal or non-existent. These properties imply a fundamental market failure in the production of new information as noted by Arrow (1962). In the absence of subsidies, imperfect competition is essential for the incentives of knowledge production and it leads to strategic behaviour. R&D investments are viewed as commitment instruments in the game between firms. Brander and Spencer (1983) presented a framework of strategic commitments into R&D investments. The framework has been used extensively to study strategic trade policy (see e.g. Spencer and Brander 1983, Leahy and Neary 1999) and knowledge spillovers between rival firms (see for example d'Aspremont and Jacquemin 1988 and the survey by De Bondt 1997). We work with this framework in the context of compatibility between product vintages.

We can link the analysis of copyleft licensing to some of the literature of copyright protection in markets with free copies. The incentives of information production require appropriability, i.e. intellectual property rights. Costless reproduction, however, suggests that it is welfare enhancing to distribute information freely.

[6] For a characterization of industrial economics as a field of study, see Martin (1993).

Copyright and the patent institution have been developed to find a solution to this dilemma. Landes and Posner (1989) identified this trade-off in copyright protection for the society. If copyright protection is very strict, it restricts the production of new works, as authors are not allowed to use the existing knowledge base. A low level of protection, on the other hand, reduces the incentives for creation. Kobodt (1995) extended the analysis to a consumer market with originals and imperfect copies. In our work, we analyse consumer behaviour in the market with copyright and copyleft programs. Conner and Rumelt (1991) and Shy and Thisse (1999) studied markets with both legal copyright programs and illegal free or inexpensive copies of the programs. They analysed the firms' incentives to protect their programs from copying and discovered that under strong network effects firms may find it profitable to allow for illegal free copies. General descriptions of copyleft or open source software, like Raymond's (1998) 'The Cathedral and the bazaar' and 'Hackers ethic and the spirit of the information age' by Himanen et al. (2001) explored the fundamental differences in the incentives and structure of the development work of developers of copyright and copyleft programs. They stressed the decentralized nature of copyleft development and the lack of direct pecuniary benefits to contributors. Söderberg (2002) presented a Marxian political economy analysis of copyleft, viewing it as a counterforce to capitalism, which to him is represented by copyright.

The economic literature on copyleft can be grouped into descriptive case studies of open source projects, analysis of the copyleft development process and research on firm behaviour in the presence of copyleft. Lerner and Tirole (2001, 2002) collected facts of several copyleft projects, provided general characterizations and suggested a research agenda. Among the issues they raised was skill signalling in copyleft programming and the co-operation between firms and copyleft communities. Schiff (2002) provided a survey of the early literature on the economics of open source software and presented the model of Mustonen (2000)[7] where a firm and a copyleft community interact in labour and product markets. McKelvey (2001) provided taxonomy of business models for innovation in knowledge intensive goods and services. She proposed three basic models by which development could be organized: firm-based control, hybrid control and network-based control. She used Microsoft,

[7] This is an earlier version of the model of the first essay.

Netscape and Linux, respectively, as examples. The first and the second essay essentially analyse the rivalry and eventual collaboration of programs developed under firm control and under network control. We, however, abstract from the hybrid control model, where a firm develops internally program components and relies to network-controlled copyleft development for complementary components. Kogut and Metiu (2001) provided an extensive overview of copyleft and discussed the structure of the development process. The decentralized nature and the missing direct incentives of copyleft programming led Johnson (2001) and Bessen (2001) to model it as private provision of a public good. They assumed that all users could also develop the program. Ghosh (1998) presented copyleft programming as an example of a novel incentive structure, 'Cooking pot markets', defined as an implicit barter economy with asymmetric transactions. Firm behaviour in the presence of copyleft programming communities has received some attention it the literature. One of the first to notice the implications of copyleft and open source to firms were Garud and Kumaraswamy (1993). Their paper analysed the motives and incentives of SUN Microsystems to open some of its program code. Kende (1998) did not mention copyleft explicitly, but provided a model, where a firm found it profitable to keep a primary component proprietary and open the specifications of a secondary complement. Subramanian (2000) considered a firm, the incumbent, that copylefted a part of its program to induce development activity to enhance the firm's program. Under network effects, the firm's profits may be higher if copylefting deters the entrants from the market. Dalle and Jullien (1999) and Khalak (2000) presented evolutionary models where consumers acquired a copyright or a copyleft program according to a diffusion process. They concluded that a copyleft program might capture the market even if it starts from a small user base. In summary, the current literature acknowledges skill-signalling as a motive for copyleft, verifies the support of firms to copyleft communities but it mostly concentrates on the development process of copyleft programs. As there are consumers that only utilize a copyleft program but do not take part in the development process, our interest here is directed towards firm behaviour and consumer market outcomes resulting from copyleft activity.

Goods in the ICT industry exhibit often network effects, so compatibility of products and standardization are relevant issues. In our essays, we draw on the research on firms' incentives and behaviour in markets with network effects and firms' choices of compatibility and standardization[8]. The original analysis by Rohlfs (1974) of network effects was extended by Katz and Shapiro (1985), who investigated firms' incentives for compatibility. They brought up the potential issue of possible multiplicity of equilibria since consumers can have only expectations of the size of network when buying the good. Katz and Shapiro introduced the concept of fulfilled expectations equilibrium, where the expectations of consumers are consistent with the market outcome. They and for example Economides (1996a) worked with a network effect having decreasing marginal value. DePalma and LeRuth (1996) considered a market where the marginal value of other users is constant but varies among consumers. Network effects can be classified as direct, resulting from the properties of the good, or indirect, when the value of the network increases due to enhanced complementary services. In our analysis, consumers are homogeneous with respect to network valuation and for simplicity, the marginal valuation of network is constant as proposed by Matutes and Regibeau (1996). Wiese (1997) presented a classification of compatibility between goods[9]. Compatibility, "fit between things enabling them to work together" (Wiese, p. 285) is called horizontal if goods from different producers are compatible and form a common network as in the model of our second essay. According to Wiese, compatibility between the main component and the secondary complementary components is vertical. One form of vertical compatibility is compatibility between the intertemporal vintages of a good from a single producer. In our third and fourth essay, we study this type of vertical of compatibility, which can also be described as vertical ex post quality differentiation of goods that are homogeneous ex ante.

Common to all essays of the thesis is the partial equilibrium nature of the analysis. We consider an industry and a relevant market where we can distinguish firms, consumers and goods. As our interest lies in the efficiency and welfare consequences of market outcomes and corrective policy actions, we abstract from the general equilibrium analysis. We assume that the industry and firms studied are small compared to the whole economy and do not consider the implications of firm

[8]See surveys on network effects by Economides (1996b), Katz and Shapiro (1994), Koski (1998), Matutes and Regibeau (1996) and Perrot (1993).
[9] Other surveys on compatibility are e.g. Quelin (2001) and Klemperer (1995).

behaviour on e.g. consumer income. As Tirole (1988, p.11) noted, partial equilibrium analysis is appropriate if income effects are small, implying that the demand for goods is downward sloping and the surplus of firms and consumers is an appropriate measure of welfare. This is motivated by the observation that the consumption of ICT related goods is not dominating the consumption of consumers and industrial buyers. Defining the appropriate market can be difficult (Tirole 1988, p.12). A good in an ICT industry may be for a general purpose and have substitutes depending on its users' environment. It may also be highly specialized so that users are an easily identifiable market. In the essays, we try to overcome the challenge of market definition by providing examples of products and user groups that form an industry coherent enough to be analysed.

We characterize the ICT industries with the following properties. There are few firms entering or active in a single market. Often the markets are niche-like and distinguishable. Consumers use a small share of their income to ICT related goods and the number of consumers in each market is large. The following unified approach to industry analysis covers the essential elements of the models in the essays and focuses on firm behaviour. The firms decide whether to enter the industry. If they enter, they determine how much they invest in the research and development of the product at the R&D stage. The investments determine the qualities of the products. Once the decisions are made they become public knowledge for consumers and rival firms. After the development period products are ready for production. Consumers value the products and determine their willingness to pay for them. The valuation is based on the perceived quality of the product and the size of the network it is expected to have. Firms determine the outputs and prices of the products. The marginal costs of products are low or zero, but output requires capacity commitment in the form of subcontracting or physical investment with fixed cost. Finally at the output stage, products are sold in the market and a finite number of consumers decide whether to buy one unit of the product from either firm or buy nothing. Figure 1 outlines the process under analysis.

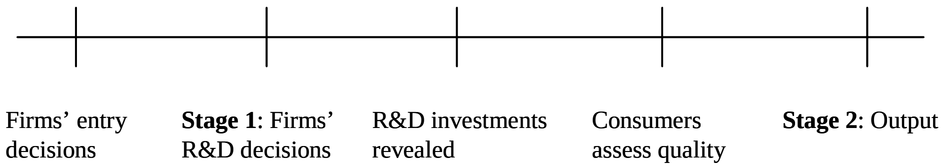

Figure 1: The generalized time line

In the first essay, we analyse the decision of a firm to employ programmers. This is essentially an R&D decision, since it determines the quality of the program. The firm's program competes with a copyleft program. The quality of the latter is indirectly also determined by the firm's decision. The firm's monopoly position implies absence of strategic behaviour and the firm chooses an optimal price. At the output stage, the copyleft program has zero price but both programs are subject to an implementation cost. Programs do not exhibit network effects. In the second essay, we do not explicitly model the entry and the R&D stage, but take programs and their qualities as given. Again, there is no strategic behaviour, as one firm makes decisions. At the output stage, however, we assume network effects among consumers. We also assume that the copyleft development community belongs to a network. We apply the unified approach in the third and fourth essay, but exclude network effects to analyse a particular dimension of quality: vertical compatibility between vintages of products. In the fourth essay, we assume that it is costly to produce but that the marginal cost of one firm is private information.

The chosen two-stage approach (see figure 1) facilitates the analysis of dynamic aspects of firm behaviour. The model views R&D activity subject to an indivisible sunk cost. This means that firms can use R&D investment as a strategic instrument. The two-stage model leads to sharp results. However, it does not allow for growth analysis (see Saint Paul, 2001 for growth aspects of copyleft activity). It also abstracts from, for example, the option value of R&D investments (see e.g. Takalo and Kanniainen, 2000). We consider copyleft development as a 'black box' and abstract from its properties[10]. The solution concept in the game between firms at the output stage is based on competition in quantities leading to Cournot-Nash equilibrium. An argument could be made for considering, say competition in prices (Bertrand) as the solution concept instead, especially in the case of products of the ICT industries. However, it is natural to interpret the quantity competition as price competition with capacity commitments (for proof, see Kreps and Scheinkman, 1983). Furthermore, assuming price competition necessitates that each firm is able to cover the whole market. In many ICT industries, firms must commit themselves to subcontracting or physical investment and we see, however, high profits even if products are relatively homogeneous.

The partial equilibrium approach to industry analysis hides some mechanisms behind the incentive structures for scientific, say copyleft, activity. General equilibrium modelling would bring out the question of financing the science sector. We regard the complementary income in copyleft programming as exogenous but in science, it has to be financed by taxation. A trade-off may occur: if copyleft products dominate many industries, the tax revenue is low and incentives for copyleft activity must be small.

This thesis is about the economics of the Information and Communication Technology industry. It is the area where the questions raised in the study are most relevant. The same issues, however, arise in other contexts. There are compatibility issues e.g. in many products with human user-interfaces. The copyleft approach is relevant also in several other fields of knowledge creation, for example, in pharmaceutical research.

3 The essays

Essay 1: Copyleft – the economics of Linux and other open source software

We introduce a novel model of a software industry dominated by a single firm where a community of copyleft programmers co-exists. Our basic premise is that copyleft

[10] See Aghion and Tirole (1994) for an analysis of the research and development process. Bessen (2001) and Johnson (2001) research the internal workings of a copyleft community.

creates an alternative incentive structure for the programmers. Instead of being employed in a firm, a capable programmer can signal his ability by being engaged in copyleft programming. Due to the nature of copyleft licensing, the ability of a programmer becomes publicly known and leads to complementary income. The copyleft community develops a zero-priced substitute for the monopolist's program. The employment decision of the monopolist is endogenous and depends on the outcome of the competition in the consumer market. The model has two stages. At the first stage, the firm determines the share of programmers it will employ by choosing the wage. Programmers not hired by the firm are engaged in developing the copyleft program. The firm and the copyleft community commit themselves to the projects. The consumers assess the programs once they exist. The qualities of the programs are increasing in the development efforts. At the second stage, consumers determine whether to buy the firm's copyright program or to acquire the free copyleft program or to acquire nothing. The decision depends on the relative qualities of programs but also on the implementation cost, which a consumer faces when installing and learning to use the program. The market outcome may be that the copyleft program is blockaded, deterred or accommodated in the market[11]. We analyse the most interesting outcome, i.e. when the copyleft program is accommodated in the market and we develop the optimal employment rule for the firm. Recent literature (Lerner and Tirole 2001, 2002, Kogut and Metiu 2001) has acknowledged the 'hidden' competition between copyright and copyleft programs and our essay formalizes this view. The essay introduces a model of the programmers' behaviour suggested by Lerner and Tirole and it develops the verbal ideas of Dasgupta and David (1987, 1994) concerning the different incentives for science and technology. Towse (2001) discussed the incentives of artists and Klamer and Van Dalen (2001) and Cowan and Jonard (2001) the incentives of scientists. Our model of copyleft programmers appears to be consistent with these views. The essay also contributes to the discussion on product differentiation. In our model, a single agent, the firm, determines by its actions the qualities of both programs in the market, since the copyleft community cannot be motivated by success in the consumer market.

[11] We borrow the terms used in the market entry literature (Tirole 1988).

The main results of the analysis concern the firm's employment decision, the firm's entry decision and the conditions for the presence of the copyleft program in the market. The larger the market is, the higher the consumers' valuation of quality is and the lower the programmers' complementary income is, the more the firm employs programmers. Interestingly, if the complementary income exceeds a certain threshold, the firm does not enter the industry and the copyleft program fully dominates the market. We show that if the size of the total programming population is large, the existence of a copyleft program in the market is more likely. An implication of the analysis is that consumer information about an existing substitute copyleft program can increase welfare[12]. Another observation concerns the impact of copyleft on the optimal level of copyright protection. The incentives of copyleft developers ultimately rely on copyright protection. Copyleft programming seems to be welfare increasing and this calls for a stronger copyright protection than current literature (i.e. Landes and Posner 1989, Koboldt 1995) suggests. This coincides with the results of Harbaugh and Khemka (2000) for conventional goods. They suggest that extending copyright enforcement in the market to cover low-value buyers can increase welfare.

Essay 2: Why do firms support the development of substitute copyleft programs?

In the first essay, the copyleft program was a pure rival to the firm's program. However, we see collaboration and firms supporting copyleft activities. There exists analysis to cover those cases where the copyright and copyleft programs are complements or there is a strategic motive of, for example, entry deterrence to support copyleft. Collaboration with copyleft communities by support may give the firm better access to scientific knowledge or to the labour market of programmers. The most intriguing scenario is the one where a firm supports a substitute copyleft program and in a sense destroys its own market. The second essay contributes by analysing the conditions for such behaviour. At the first stage the firm decides whether to support the copyleft development effort or not. At the second stage, consumers buy or acquire one of the programs. Now we assume for simplicity that the qualities of programs are exogenously determined ex ante and that there are no implementation costs. We assume that supporting copyleft development creates such

[12] Publication of product information has received attention in the literature. Lommerud and Sörgard (2002) found that publication of prices by authorities affects the telecommunications market entry.

compatibility between the copyright and copyleft program that is impossible to achieve through firm's own development effort. The copyleft community develops its program in a decentralized manner[13]. The firm cannot foresee the result. Yet, to be able to develop a compatible program, the firm would need specifications. By providing its own specifications to the copyleft community to work on, the firm accomplishes compatibility. We assume that programs exhibit network effects so that consumers value the network of a program in addition to its stand-alone value. Furthermore, the network of the copyright program consists only of consumers using it but the network of the copyleft program consists of the consumers using the copyleft program and the copyleft community. If programs are compatible, the network is common. As a main result, we show that there exists a threshold for the size of the copyleft community, which, if exceeded, creates an incentive for the firm to support the development of the substitute copyleft program. This threshold is increasing in the intensity of the network effect. If the firm chooses not to support copyleft programming and if the network effect is sufficiently strong the firm serves all consumers and the copyleft program exists only within the copyleft community. Using the terminology of Besen and Farrell (1994), if the firm decides to support the copyleft community and programs become compatible, the firm has higher profits by competing *within* the market than by competing *for* the market with an incompatible program.

Economides and Flyer (1998) and Woeckener (2001) found that firms competing in a market exhibiting network effects are likely to choose incompatibility when the effect is strong. Our results are parallel to theirs, since for a given copyleft community, the firm chooses incompatibility if the network effect is strong. In contrast, our result is just the opposite to the result of Economides (1996a). He found that under a strong network effect, a monopoly might invite the entry of firms and license its technology to them without charge to create a compatible network. Our result is driven by the fact that the firm's profit is increasing in the strength of the network effect under incompatibility, but constant under compatibility. The result of Economides is based on the idea that the additional profit from a large compatible network is greater than the reduction in profits caused by competition. We show that a standard imposed on

[13] Raymond (1998) described the method to be a 'bazaar' in contrast to conventional program development being like building a 'cathedral'.

the industry may be welfare reducing if the network effect is strong and the copyleft community is relatively small. One of the instruments of science policy seems to be to require the use of open copyleft program platforms for software applications in research to enable free exchange of ideas. Also in computer science research, copyleft platforms, such as Linux, are recommended or required. Inasmuch this increases the relative size of the copyleft community such a policy may be welfare reducing under certain industry conditions. Surprisingly, simultaneous standardization and science policy measures may increase welfare whereas each alone would reduce it.

Essay 3: Strategic R&D investment in future compatibility

The motivation of the third essay is the observation that the buyers of IT-products seem to follow the announced product development budgets closely. Suppliers commit themselves to R&D investments at the first stage and produce outputs at the second stage. We analyze the market outcome and various collusive scenarios between duopolists and compare them to the socially optimal solution. Buyers take into account the expected future compatibility of a product and the potentially high switching cost when vertical compatibility is low. The buyers regard the level of R&D spending to be informative about the future compatibility. In contrast to current literature (Shapiro and Varian 1999), we assume that rational buyers accept the prospect of lock-in to a product. Suppliers engage in a Cournot-game in outputs at the second stage. The suppliers have now a double motive to invest in R&D. It increases the buyers' willingness to pay and it acts as a strategic commitment device in the game between suppliers. A contribution of the essay is in the recognition and analysis of vertical compatibility between product vintages of one supplier. This is in contrast to horizontal compatibility between products of suppliers, which is assumed in the second essay. In the survey of Wiese (1997), such a phenomenon is mentioned and named "dynamic bundle compatibility" but his analysis is not developed further. In a related contribution, Wey (1999) explored an industry where the R&D effort of a supplier enhances the quality of own product but also the compatibility of the product of the competitor. In a related paper, Banker et al. (1998) discussed the impact of market structure and the intensity of competition to the quality of products.

The main result of the analysis is that the market outcome in such an industry results in underinvestment in R&D to develop vertical compatibility compared to the socially optimal level. Social optimum is the level of R&D investment that maximises welfare, that is, the sum of buyer surplus and supplier profits given the market structure. We analyse and compare the possibilities to correct for the market failure. As the R&D investments fall short of the social optimum, subsidies to R&D improve welfare. Comparison of modified market structures shows that if suppliers are allowed to collude in the determination of the R&D investments but have to compete at the output stage, welfare is greater than under market solution. For buyers, R&D collusion results in products that have low vertical compatibility, because suppliers choose low R&D investments. Moreover, extending the collusion to the output stage reduces welfare.

Essay 4: Signalling unobservable cost with investment in vertical compatibility

We extend the framework of the fourth essay to encompass incomplete information about the marginal cost level of the rival. The uncertainty leads firms to be engaged in a coordination game where the announced R&D budget to develop the future vertical compatibility of the product acts as signal of the marginal cost. Buyers and the rival can infer the R&D investment from the budget information. Now demand enhancement, strategic considerations and communication of private information motivate the R&D investment. The set-up of the game is asymmetric so that the informed firm knows the marginal costs of both firms and the uninformed firm knows besides its own cost only the distribution of its rival's cost. In ICT industries, this assumption of asymmetry seems reasonable since firms in the same market can have either integrated manufacturing with known costs or they rely on component suppliers. In separating equilibrium, the private information is revealed. The informed firm signals its, say, low marginal cost by a large investment in vertical compatibility development and the uninformed firm infers correctly the level of marginal cost of the informed firm before determining its own output. We show that the game has a unique separating equilibrium fulfilling the conditions of Mailath (1987). The contribution of our analysis is the characterization of separating equilibrium with regard to the marginal cost of the R&D investment. The informed firm derives a strategy function that maps its optimal R&D investment to its true marginal cost. If investing in R&D is costly, then the signalling motive dominates the R&D investment. Our model allows us to separate the motives and study the impact of industry environment changes in contrast to current literature (Andersen and Hviid 1999, Collie and Hviid 1993, Hindriks 1999) where the marginal cost of the signal is fixed. We provide conditions for the breadth of the cost distribution and the cost of R&D for separating equilibrium to be the likely outcome of the game. Our results differ from those of Dey (1996), who explored the use of export subsidies as a signal of discrete marginal costs. In a model that has technical similarities, he finds that with discrete costs (low, high), separating equilibrium cannot be supported whereas we show that with a continuum of cost, the unique separating equilibrium can be supported**.** Our choice of a continuous cost distribution seems relevant due to the complexity of ICT products and the component supply industry. Under private information, the informed firm invests more in R&D and receives lower profits than under full information. Aoki and Reitman (1992) analysed the use of a discrete decision of cost-reducing R&D as a signal of low marginal cost. They assumed that a low cost firm cannot reduce its cost further by R&D. Contrary to our results, they found that private information reduces the firms' R&D investments below the level that is optimal under full information. In our model, we consider vertical ex post differentiation of products. In the model of Boyer et al. (1995), the differentiation of products was assumed to be horizontal. They showed, as we do, that private information influences firm behaviour. Under asymmetric incomplete marginal cost information there exists a unique equilibrium and the location choices of firms depend on the cost difference in a way that is different from the full information choices**.** Elder and To (1999) analysed explicitly the stage following the output stage of our model with firms having asymmetric private information about the second period demand instead of costs. Consumers are 'locked in' to a product in the second period if they buy it in the first period. Firms set prices in the first period taking into account the signalling effect to competitor and the anticipation of demand. Like in our analysis, incomplete information results in lower profits than full information. We show that firms would prefer the credible revelation of cost information. This result coincides with that of Shapiro (1986).

4 Conclusion: the policy perspective

We point out some policy implications of our study that are relevant for technology policy, science policy and to some extent to competition policy, all within a (national) system of innovations[14]. Justman and Teubal (1986) classified technology policy to consist of tactical actions that directly affect the firms and of strategic actions to improve the infrastructure of the society. As the tactical and strategic levels have different scopes and time spans, technology policy has conflicting objectives: i) centralization and rationalization versus diversification, duplication and decentralization of R&D activities, ii) diffusion versus creation of knowledge, iii) static allocative efficiency versus dynamic structural change (Mowery 1995). Our research deals mainly with the tactical issues, but we provide some policy implications of intellectual property rights and knowledge creation. We present mechanisms in ICT industries that the policy-maker has to be aware of to be able to shape technology policy. Copyleft software may be a rival that changes the behaviour of a monopolist in the market. As we see in the analysis of the first essay, the implementation cost of programs determines whether the firm can act as an unconstrained monopoly or faces competition. This affects the incentives to innovate. Due to the decentralized organization of copyleft communities, data on copyleft community resources, objectives and programs may be difficult to acquire. In technology policy, there is a conflict of objectives concerning appropriability of research outcomes. As discussed, it is necessary for the incentives for research and development. On the other hand, diffusion of knowledge is reduced if appropriability is high. The literature on the economics of patents (see e.g Besen and Raskind 1991) essentially deals with this trade-off. Copyright protection is used in computer software mainly for historical reasons (Samuelson 1993). The results of the first essay suggest that strict copyright protection is likely to increase welfare by preserving the non-monetary incentives of developing copyleft programs. Subsidies to R&D are the traditional instrument for technology policy. In the third essay, we find that subsidizing the development of vertical compatibility can increase welfare in the static analysis. Research investments are then high and this is likely to contribute to

[14] "The set of institutions which…contribute to the development and diffusion of new technologies…" (Metcalfe 1995, p.462).

the growth of the economy. The alternative policy action is to allow or induce co-operation in R&D. As with subsidies, the results for welfare are positive but the firms choose small R&D investments. Compared to subsidies, the growth effects are likely to be weaker under co-operation.

In the grouping of Justman and Teubal (1986), science policy falls within infrastructure measures, enabling firm research. As Mowery (1995) and Salter and Martin (2001) pointed out, publicly funded basic research can contribute to innovation. It can create complementary knowledge inputs, provide education and training to employees and new instruments and techniques that make up the 'technology of scientific research'. In our analysis of copyleft, we take advantage of the discussion on the incentive structures of science and technology (Dasgupta and David 1987, 1994) and consider copyleft programming to have some characteristics of science. This implies that in markets where copyleft programs exist, support of science may have adverse effects beside the benefits stated above. This can be seen as follows. In the first essay we consider the employment decision of a software firm determining the qualities of programs in the market. The entry decision of the firm is dependent on the complementary income of copyleft programmers, an example of which could be the wages of university researchers. An increase in the support of science can lead to a collapse of the market, as the firm decides not to enter. In the second essay, an increase in the effective size of the copyleft community resulting from additional resources to scientific research may decrease welfare. For programs that are valuable to consumers, copyleft creates a direct confrontation of scientific and commercial output in the market and this should be taken into account in resource decisions in, for example, computer science and related fields.

Competition policy is also linked to the system of innovation (Mowery 1995). The actions to protect fair competition may affect the incentives for innovation. This has not been left unnoticed in the literature. The focus of competition policy is shifting away from protecting the consumers from the actions of large firms to ensuring that firms and their innovations can compete on a fair basis (Audretsch 1998, Hart 2001). The old paradigm was that firms increased their size by mergers and predation to acquire market power and reduced marginal costs. This implied that competition policy was aimed at constraining the actions of large firms to protect the consumers.

Static analysis of output to assess welfare and market structure provided data for the anti-trust policy actions, ‘bigger is worse’. The evolution of industries has shifted the focus from organizational and production efficiency to the creation of new knowledge as the primary source of welfare and growth. The creation of knowledge is likely to exhibit increasing returns to scale and appropriability is necessary for its incentives. This implies that competition is imperfect and even monopolies can be created. The focus is on the dynamic properties of markets and on inputs to production processes, ‘bigger is better’[15]. We try to bring out the dynamic aspects of innovation in our models by introducing two stages: R&D and output, but we abstract from the cumulative nature of knowledge creation. Copyleft software creates new challenges to competition authorities. First of all, the competitive pressure that it may exert on commercial programs as described in the first and second essay, is in a sense invisible. By definition, the programs are free and this means that the data on market shares measured in monetary terms is meaningless. It is difficult to acquire information on actual users of copyleft programs in term of data, which would reveal the market situation. There are several distribution channels for copyleft software and there is no obligation to track use. Industry data may tell that a market is ruled by a monopoly, yet it may be collapsing as we show in the first essay. Interestingly, the ‘crowding-out’ of a commercial program may take place because of a society’s action and fall within the category of unfair competition by public institutions. The analysis of the second essay reveals an interesting feature of monopoly: depending on industry circumstances, a monopoly may relinquish its position by inviting the entry of either a copyleft program or a copyright program. If we assume that the contribution of copyleft development to the knowledge base is independent of the market outcome, controlling for the competitive threat of the copyleft program to increase static welfare may imply small dynamic losses. Farrell and Katz (1998) discussed the effects of compatibility and standards to the incentives for innovation in markets with network effects. In an oligopoly, incompatibility may lead to higher welfare than compatibility between products. This coincides with our results in the second essay but for different reasons. The process by which consumers formed expectations of the network was the key to their results, but ours are driven by the intensity of network

[15] Sheremata (1998) and OECD (2000b) provided surveys of competition policy in the new economy. Foros, Kind and Sörgard (2002) showed that new phenomena, like the Internet, give rise to novel competition policy advice. Economides and White (1993) discussed the anti-trust implications of networks.

effect. One of their recommendations was that to ensure a beneficial process, competition authorities could inform consumers about the properties of products. We also assert in the first essay that informing consumers of a copyleft program increases welfare. If information dissemination is something that the competition authority finds worthwhile, informing about copyleft programs could be part of it. Standards are generally considered to be beneficial (Rubinfeld 1998**),** but Curran (1998) found standards to be mostly harmful to competition and welfare as they hinder the advance of new innovations. According to Tassey (2001) standards may have negative economic impacts due to lock-in to an inferior technology, poor quality of the standard or the high cost of implementing the standard. Our analysis points to similar results but for a different reason: a standard may increase competition by enabling the entry of a free copyleft program to a market ruled by a monopoly. However, welfare is decreased as firm profits decrease more than the consumer surplus increases, as we show in the second essay. Woeckener (2001) advised that the competition authorities should be more aware of compatibility arrangements than of the lack of standards.

The analysis of the third and fourth essay reveals the difference between a dynamic and a static approach in competition policy. In the third essay, the welfare level of the market outcome can be improved by allowing the firms to collude in research and development. However, this leads to a significantly lower effort in R&D. The static situation is improved but in a dynamic sense, the contribution to the knowledge base is reduced. Similarly, in the fourth essay, the rival's uncertainty about costs drives the firm to high R&D effort, perhaps over the level, which would be optimal for welfare. Firms would prefer credible exchange of information to resolve the uncertainty. Allowing such an action decreases the optimal R&D effort. This may increase welfare but, again, decreases the knowledge contribution.

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Forthcoming in Information Economics and Policy

Essay 1: Copyleft - the economics of Linux and other open source software

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An astonishing phenomenon is the rise of a large population of programmers who, seemingly against economic logic, develop and distribute software that is copylefted: freely available but licensed. Our paper suggests that the occupational choices of programmers based on reputation incentives determine the qualities of programs. A monopolist has to take into account the free software in the consumer market. When software implementation costs are low, the monopolist accepts the copyleft program in the market. We explain the simultaneous existence of commercial and copylefted programs, like Windows and Linux, and also why commercial alternatives to copyleft programs may not exist.

Keywords: Property rights; Copyleft; Linux; Open source software

JEL Classification: D23; L11; L15

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1 Introduction

Copyleft is a novel licensing scheme. It facilitates open and decentralized software development. Its key feature is that once a program is licensed by the inventor, the subsequent programs based on the original must also be licensed similarly. As investments in computer software are becoming quite large representing, for example, 11 percent of total national investments in Sweden in 1998 (Jagren and Morell, 2000), the incentives for software development work and the associated efficiency aspects are an increasingly important issue. In this paper we develop a positive economic model of software development in the presence of copyleft and analyze how it affects commercial software markets. For programmers, copyleft creates incentives alternative to employment allowing them to signal their abilities and receive complementary income.

We raise the question how the existence of a copyleft program affects the behavior of a monopoly firm with a copyright program who invests in the quality of its program at the development stage. It turns out that the firm can influence the occupational choices of programmers through the wage policy. The programmers choose whether to be employed by the copyright firm or to join the copyleft community developing a copyleft program and receive complementary income based on the acquired reputation. These choices in turn determine the qualities of the firm's copyright program and the copyleft program at the development stage. At the output stage, the firm supplies a program protected by copyright. It has a market of its own and there are no substitutes except the rival program eventually developed by the copyleft community. Consumers value quality and determine whether to buy the copyright program or acquire the copyleft program or not to buy any. This creates a trade-off, which the firm can try to exploit: it can pay a higher wage at the development stage increasing costs but also increasing revenue by improving the quality of the copyright program while reducing the quality of the competing copyleft program. We analyze the monopolist's profit-maximizing behavior when consumers face non-negative implementation costs, i.e. costs of installing and learning the program[1]. We characterize a monopolist entering the industry. We also analyze the welfare consequences of policy actions. The paper also has implications on the theory of vertical product differentiation. A novel industry structure arises: the decision of a single firm, the monopolist, determines the qualities of all (two) products in the market. To focus on the effects copyleft licensing has on labour and product markets, the model abstracts from network effects in consumer markets[2].

The main results are as follows. Program implementation cost is critical and determines whether the software firm has to take into account the existence of the copyleft program in the market. If the cost is low, there are consumers preferring the copyleft program, providing a constraint on profit maximization. There is an intermediate interval for implementation cost, at which the optimal price for the firm just deters the marginal consumer from acquiring the copyleft program. When the implementation cost is high, the firm is free to charge the optimal monopoly price. The larger the consumer market compared to the population of programmers is, the more the firm employs programmers and the smaller is the copyleft community. The firm employs many programmers if their complementary income from copyleft work is low or if the consumers' valuation of program quality is high. We show that there is a threshold market size below which the monopolist will not develop a copyright program. Casual empiricism suggests that the results coincide with the structures in software markets. The implementation costs of programs have no doubt decreased, resulting in greater use of free copyleft programs like Linux. On the other hand, there are applications, for example in networking, where consumers exclusively resort to copyleft programs[3].

Our analysis on copyleft licensing has policy implications. First, the incentives for copyleft programming are independent of the consumer market. Copyleft programmers do not pay attention to whether copyleft programs are used outside the copyleft community. It is possible that a copyleft program exists and consumers are

[1] The model is applicable in many markets but the reader may feel more familiar with it by imagining William Gates as the monopolist and his program as Windows. The copyleft community could then be the programmers working on the project initiated by Linus Torvalds and Linux the copyleft program.
[2] We plan to address this issue in the future.
[3] For example DNS and Sendmail have no commercial rivals, they are 'category killers' (Johnson 2001, Opensource.org 2002).

not aware of it. Informing consumers of such a program is likely to increase welfare with presumably low costs. Another policy implication concerns the enforcement of copyright. Paradoxically, copyright is vital to the incentives of copyleft programmers as the copyleft license is based on copyright. Securing copyright can be costly and the copyleft community may not have the resources to defend its copyright against firms. If society does not support a high level of copyright protection the copyleft communities are likely to restrict the distribution of programs to consumers because the risk of copyright violations increases. This in turn decreases welfare.

2 What is copyleft?

To copyleft a program, the programmer, besides copyrighting the program to himself, also signs a General Public License (GPL) (GNU Project 2000b) granting everyone the right to use, modify and distribute the program *on the condition that the licensee also grants similar rights over the modifications he has made*. Under this arrangement, everyone has to have free access to the program but it is protected from becoming someone's private intellectual property[4]. The strong implication is that this allows for decentralized program development. The enhancements and modifications accumulate to the basic program even if the programmers have no other affiliation with the project. There is another significant feature of copyleft. It is a device for linking the programmer and his contribution permanently together while the contribution is publicly observable. This creates an environment where talented programmers have an incentive to signal their abilities via the copyleft community.

Historically, copyleft licensing was created for ideological purposes by Richard Stallman and the Free Software Foundation (GNU Project 2000b). However, the functions and quality of some programs like Linux and Apache have reached and in some respects surpassed those of traditional copyright protected commercial programs. The population of programmers participating in the development work is today so large that ideological motivations are inadequate to explain the phenomenon.

[4] Lerner and Tirole (2000) and Johnson (2001) provide detailed descriptions of such licensing schemes (GPL, Open Source Software, Debian Social Contract) that create the copyleft environment. The Open Source Initiative (2000) contains the definition of open source software and the GNU Project (2000a) a classification of free and non-free programs. Browne (1999) provides a practitioner's view of copyleft licensing. Opensource.org (2002) provides license contents.

Copyleft programs have gained significant market shares in a short time. For example, in the year 2000, the web server program Apache was used in 63 percent of web sites, which translates to almost one hundred million sites ((Netcraft 2001). In the same year, the market share of Linux operating system in server use was 27 percent of 6.1 million shipments. The market share of Microsoft was 41 percent, but the increase from the previous year's shipments was largest for Linux, 25 percent, as Microsoft's shipments grew 20 percent. (Johnston 2001). In desktop use, the market share of Linux was 2 percent in 2000, but it has the highest growth rate. The co-existence of commercial copyright and non-commercial copyleft programs in the market is a reality. However, the low cost of copyleft programs means that the market shares for them in public market research reports are low even if the shares of users may be high. Deckmyn (2000c) reports that even though the number of users of Linux increases at twice the speed of Windows, the turnover from the Linux business is projected to be only a few percent of that of Windows in five years.

Even though signing the license agreement means that the creator, the programmer, cannot receive any rents from the sale of his creation, business activity based on copyleft programs is not absent. Varner (2000) categorizes the copyleft business actors into four groups: service sellers, loss leaders, widget frosting and accessorizing. A service seller provides installation and operation services for copyleft programs. Perhaps the best-known company that packages and supports Linux at the moment is Red Hat. Loss leaders distribute a copyleft program to create demand for some other copyright program, Netscape web browsers being an example. Widget frosting refers to hardware suppliers that may enhance their product with some copyleft program. Accessorizing is essentially selling complementary, but remote services or products. Recently, large computer companies (IBM, HP, SUN) have announced their support for some existing copyleft programs like Linux. SUN Microsystems has also developed programs (Staroffice) that are substitutes for existing office applications and copylefted them (see Deckmyn 2000b). Lerner and Tirole (2000) and Subramanian (2000) discuss the intriguing phenomenon of firms engaging in copyleft work.

The economics of information tell us that there is a fundamental trade-off between information as a public good and the incentives to create new information (Arrow

1962). Information, like a computer program, once it is created, is practically costless to reproduce. From society's point of view, it should be distributed freely. However, as incentives are then destroyed, there will be no creation of new information. Society's solution to the missing incentives has been to secure various intellectual property rights to originators. In the case of a new, novel and non-obvious invention, a patent gives the inventor a temporary monopoly over the invention. Copyright protects the rights of the originator of a unique expression, for example a work of art, for a fixed period.[5]

From the perspective of intellectual property rights, a computer program is a problematic object (Samuelson 1993, Dam 1995). It can be a unique expression as is a poem. Copyright would seem an appropriate method of protecting the rights of the originator. But a program, once it is running, also creates functions, like a machine. New and novel functions or uses for a function may seem to fulfill the requirements for a patent. Programming in a sense is creating and modifying algorithms. However, algorithms and 'mathematics' are not eligible for patenting. As a result of the first lawsuits over the property rights for software, copyright has generally become the method of securing property rights. Presumably the original motivation of the Free Software Foundation to introduce the copyleft licensing scheme was based on this development. Copyright entails a uniqueness requirement and the Free Software Foundation considered that the requirement restricted innovation in software. Recently, however, in the US patents have also been granted to programs and the EU considers a common policy on software patenting.

The rapid development of some originally copylefted programs (Linux, Apache, Mozilla, Sendmail, PERL) and the large number of participating programmers suggest that there must be powerful incentives to create and further develop copyleft programs. The licensing scheme rules out direct economic appropriation of rents based on property rights. One can see simultaneous software development, where the suppliers' incentives are secured by property rights and on the other hand copyleft software development where programmers give away their rights at the outset. Dasgupta and David (1987, 1994) present a framework of 'Science' and

[5] For a survey of the development of intellectual property rights, see David (1993).

‘Technology’, suggesting that new knowledge is created in society under two distinctly different incentive structures[6]. In ‘Science’, peer recognition and the resulting reputation lead to complementary benefits, such as grants, positions in academic organizations or highly compensated future positions in firms. The combination of these is the incentive. Scientific recognition is achieved by making one’s contribution public to peer review as quickly as possible and acquiring ***priority*** to the new knowledge. In ‘Technology’, the incentive structure is the traditional one: maximization of profit by securing property rights. By definition, latter rights keep the new knowledge private. Dasgupta and David, having studied several fields of research, conclude that these incentive structures in many cases appear simultaneously and that they both are present in the same research areas. Copyleft is a striking analog of the ‘Science’ while copyright belongs to the ‘Technology’. *The essential property of the copyleft licensing scheme is that it creates a particular incentive structure within the business environment. This structure has properties that are equivalent to the incentive structures of scientific communities.*

The framework of Dasgupta and David also captures a crucial element of the positive economic model of copyleft. They assert that the occupational choices of aspiring employees are the decisive factor in the relative shares of both incentive environments. Employees assess the benefits of the ‘Science’ and ‘Technology’ environments. For the same performance in the ‘Science’ environment, the expected monetary return is usually lower than in ‘Technology’ (see Stern 1999) but because of the complementary nature of income they may be linked to less interesting activities, like for example teaching or project management. The elasticity of the compensation with regard to the performance may be much higher in the 'Science’. An able scientist is almost certainly rewarded for his contributions because, according to the priority principle, they become public and receive the appreciation of peers. In the ‘Technology’, it is probable that the incentives in the firms do not take the contributions of individual employees fully into account, in tasks performed by groups maybe not at all. Furthermore, the secrecy inherent in private research inhibits also the accumulation of reputation to individual employees.

[6] Brooks (1994), Stephan (1996) and Stephan and Levin (1996) discuss similar issues.

Literature on copyleft or open source software is limited. Lerner and Tirole (2000), however, do provide an extensive survey of case studies of projects in which the development mode is decentralized and the licensing of the programs is based on copyleft. They analyze the motivation and incentives of the programmers engaged in copyleft activity, concluding that skill signaling is an essential incentive for copyleft work. Lerner and Tirole concentrate on the effectiveness, longevity and structure of decentralized open source software projects in comparison to the traditional hierarchical commercial projects. Johnson (2001) also focuses on the effects copyleft licensing has on program creation. He models copyleft activity as private provision of a public good: each programmer receives utility from the new code developed by each of them. A single programmer can either contribute to the project or 'free-ride', receiving utility from the work by others. He shows that free-riding becomes more common and ultimately a constraining factor in program development as the size of the project increases. He also analyzes and compares the welfare implications of both the copyleft device and the traditional software with copyright, finding that neither leads to the welfare optimum. Johnson acknowledges the signaling incentives in the copyleft work but regards the public good nature of copyleft as dominant. Dalle and Juillien (1999) view copyleft licensing as an ”anti-patent” system enhancing creativity in society. They acknowledge the skill-signalling incentive of copyleft programming but consider the expected profits from future programs created under copyright protection to be an important motive for programmers. They introduce an evolutionary adoption model to study the diffusion of a copyleft and a copyright program to users. However, none of these papers consider the implications the copyleft programs have on the markets for copyright programs. Their focus is on the implications of copyleft for labor markets and software creation.

As a method of securing intellectual property rights, copyright has received considerable attention in the literature. Landes and Posner (1989) provide a seminal model, where the level of copyright protection is endogenous. It is either a decision variable optimized by the social planner or is determined by decentralized markets. If protection is strong, the right owners face little competition from unauthorized copies in the market and profits are high. The trade-off is that a high level of copyright protection inhibits authors of new works from utilizing existing works and the costs of creating new works are higher. Koboldt (1995) develops these ideas further in a market where the original work is sold at a positive price and a substitute copy is sold at the cost of copying. These costs include the production cost and the cost of being caught violating the copyright. Takeyama (1994,1997) and Shy and Thisse (1999) analyze the incentives of protecting the copyright of programs with costly technical methods. Their models include both copyright programs and unauthorized cheap copies. They find, using different models and assumptions, that with programs exhibiting network externalities, the unauthorized copying may increase the profits of the copyright holders.

The structure of this paper is the following: in chapter three we first develop the cost function of the monopolist at the development stage based on the incentive structure when a copyleft community exists. We then analyze the market for programs and solve for the optimal behavior of the monopolist in the presence of a copyleft program. Based on the results we present some policy suggestions and finally conclude in chapter four.

3 The Model

3.1 Stages

There are two stages. At the first stage a monopoly firm and a copyleft community are engaged in programming projects. At the second stage the consumers value programs and the firm sets a profit maximizing price for its program. Consumers and the firm take the qualities of the competing programs as given. Programs are produced and consumers choose one of the programs or neither of them. The model is solved by backward induction. The time line is in figure 1.

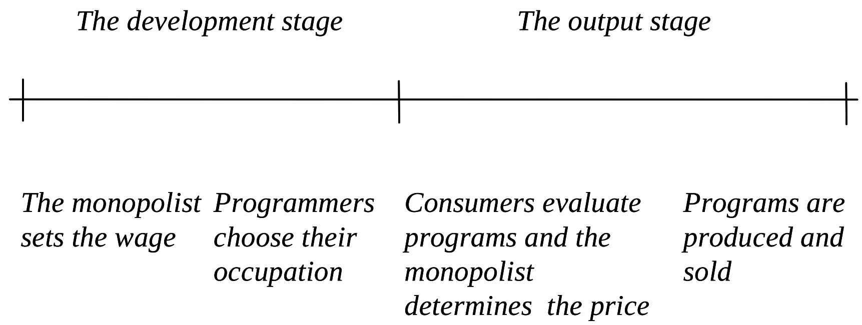

Figure 1: Order of events

The monopolist invests in the quality of his product, a program, at the development stage. The quality is dependent on the programming output. Programmers' ability is heterogeneous and unobservable to the monopolist. Copyleft licensing is an alternative for programmers who can be engaged in copyleft work and receive complementary income based on ability. To signal their skills, the programmers in the copyleft community develop a program that is a substitute for the monopolist's program. The monopolist faces convex costs of program development as a result of the existence of the copyleft community.

At the output stage, consumers buy the monopolist's program, acquire the copyleft program or no program. Consumers face implementation cost for the program. This cost includes the effort of acquiring the physical media, the effort of installing the program in the computer, conversion and rearrangement of data and learning the program[7].

Copyright protection ensures that the monopolist can price his product without the threat of illegal copies. Copyright protection, however, is also essential for the copyleft community. The copyleft license grants the copyright to the original programmer. The robustness of this property right is crucial to the incentives of programmers even though the copyleft license allows the free use and further

[7] While new programs have more complex properties, much of the programming effort is directed to enhancing 'ease-of-use'. A general trend in society is an increase in computer skills or 'literacy', both because of public education and user experience. This tends to decrease the implementation cost.

development of the program. Copyright protection in our model is perfect. We work with simple functional forms to obtain sharp results.

3.2 Programmers' occupational choice

A programmer has several career alternatives. He can be hired by a software firm, become an entrepreneur starting a business or become engaged in copyleft programming work. Based on Dasgupta and David (1987, 1994), we assume that career choices lead to different incentive structures. Employment in the firm is compensated by an equal wage for all programmers, as ability is unobservable[8]. This can be supported by casual empiricism of software development environments, which indicates that the process of creating a competitive program in a centralized development environment requires sophisticated teamwork and project management. It is difficult to assess the ability of a single programmer even if the productivity of programmers varies greatly. The public nature of a copyleft program encourages peer review. Able programmers can build a reputation that results in future complementary income, such as partnership in a software venture, grants or academic employment. Lerner and Tirole (2000) aggregate these career concern[9] and ego gratification incentives under a single heading: "signaling incentives". These incentives are the stronger the more visible the performance is, the more dependent it is on effort, and the more revealing it is about talent. The empirical analysis of Stern (1999) points to that the most able of the population tend to attach themselves to the 'Science' community, which corresponds to copyleft in our model.

To formalize, there are N programmers with industry-specific skills, N_R employed by the firm, N_L working in the copyleft community, $N = N_R + N_L$. Programmers' productivity a_i is evenly distributed on the unit interval $[0,1]$. We let P denote the subjectively expected complementary income of a programmer with the highest skill. The expected complementary income for a less able programmer i is then $a_i P$. The

[8] This simplifying assumption can be relaxed as long as the complementary income is more elastic than wage with regard to productivity.
[9] Rigorous analysis of career concerns can be found in Holmström (1999) and Dewatripont et al. (1999).

firm, not observing the individual skills, pays a uniform wage w to hired programmers regardless of their productivity. Programmer i is indifferent between employment and entering the copyleft community if $Pa_i = w$. Given w and P, the level of productivity of the marginal programmer is

$$a^* = \frac{w}{P} \ . \tag{1}$$

The number of copyleft programmers and firm programmers depends on the threshold productivity a^*. Programmers $N_L = (1 - a^*)N$ with productivity greater than the threshold value a^* join the copyleft community and those, whose productivity is below a^*, $N_R = a^* N$, are employed by the firm.[10] The complementary income P is assumed to be inversely related to the size of the copyleft community N_L. The members of the community value new contributions more the smaller the community is. This assumption is in accordance with Lerner and Tirole (2000) and Johnson (2001) on the inner dynamics of copyleft communities. Moreover, based on case studies, Lerner and Tirole assert that a copyleft community is prone to 'break' if its size increases. Johnson analyses the production process within the copyleft community and finds that as the size increases, free riding becomes a restrictive factor. We define the complementary income as a decreasing function of the proportion of programmers in the copyleft community. Several case studies of copyleft programming (Lerner and Tirole 2000) also indicate that some individuals stay in the copyleft community even if alternative monetary benefits are large. Our formulation also captures the view that some programmers have ideological reasons to be engaged and to stay in copyleft programming. The functional form chosen below conforms to this notion. We thus let the expected complementary income to the most able programmer, P, be a function of the threshold productivity a^* with the parameter $\beta > 0$ describing the level of complementary income (see figure 2)[11],

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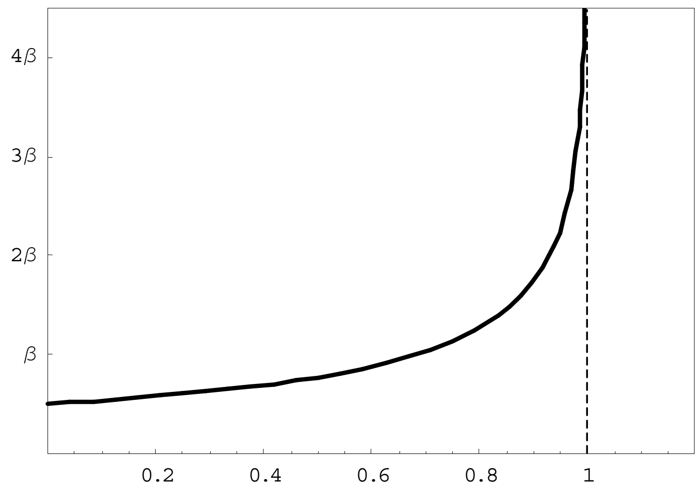
[10] Obviously there is an outside employment option, but we assume that the outside wage is below the wage levels present in this model.

[11] The parameterization looks complicated but satisfies $P(a^* \to 1) \to \infty, P(a^* \to 0) \to \frac{1}{2}\beta$ by L,Hopital's rule and $P' > 0$ when $0 < a^* < 1$. It has merits that become obvious when analyzing the monopolist's profit-maximization: the solution becomes algebraically easy and intuitive and yields

$$P\left(a^*\right) = \beta\left(\frac{-\ln\left(1-a^*\right)-a^*}{a^{*2}}\right). \tag{2}$$

Complementary income



Share of the copyright programmers a^*

Figure 2: Complementary income as a function of the relative share of copyright programmers

As the firm's wage is equal to the complementary income for the indifferent programmer, we have

$$w\left(a^*\right) = a^* P\left(a^*\right) = \beta\left(\frac{-\ln\left(1-a^*\right)}{a^*} - 1\right). \tag{3}$$

In (3), $w\left(a^*\right)$ is the wage rate the monopolist will offer to be able to hire $a^* N$ programmers. The offered wage has a direct effect on the marginal programmer and hence on the size of the copyleft community and the complementary income. The occupational choices determine the program development outputs. The

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simple subsequent results. Replacing (3) by a linear or exponential function for complementary income decreasing in the number of copyleft programmers does not affect the qualitative results.

complementary income specification implies that the monopolist cannot suppress the copyleft community completely by his own actions. The most able members always value copyleft work more than the wage offered by the firm. The number of programmers hired by the firm is $a^{*}N$ from and their average ability is $\frac{1}{2}a^{*}$, so the total development output of the firm is

$$X_R\left(a^{*}\right)=\frac{1}{2}a^{*2}N\ . \tag{4a}$$

Respectively, as the number of programmers in the copyleft community is $\left(1-a^{*}\right)N$ and their average ability is $\frac{1}{2}\left(1+a^{*}\right)$, the development output of the copyleft community is (see figure 3)

$$X_L\left(a^{*}\right)=\frac{1}{2}\left(1-a^{*2}\right)N\ . \tag{4b}$$

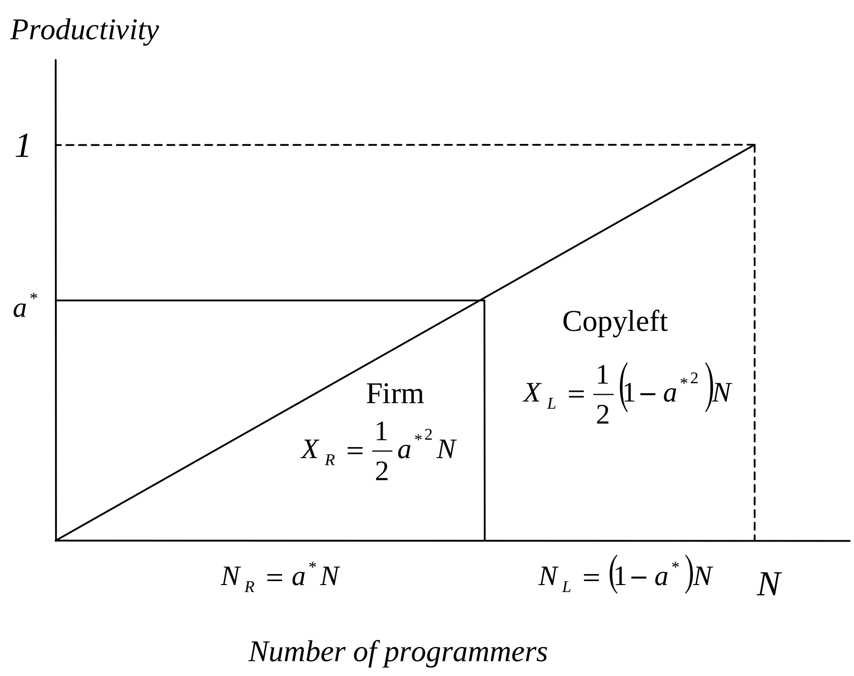

Figure 3: The total programming outputs of the firm and the copyleft community

The total development cost to the monopolist, C, is simply the wage cost in (3) multiplied by the number of programmers employed:

$$C\left(a^*\right) = w\left(a^*\right) N_R = w\left(a^*\right) a^* N = N\beta\left(-\ln\left(1-a^*\right) - a^*\right). \tag{5}$$

3.3 Market demand at the output stage

There is a consumer market supplied by a monopolist. We denote the copyright program by R and the eventual copyleft program by L. There are M consumers, who each buy at most one program. The valuation of the copyright program is evenly distributed on the interval $\left(0, V_R\right]$ and the valuation of the copyleft program on the interval $\left(0, V_L\right]$, respectively. The programs are substitutes and we assume that the ratio of the valuations is constant for all consumers:

$$\frac{V_{Lj}}{V_{Rj}} = \frac{V_L}{V_R}, \text{ for all consumers } j. \tag{6}$$

Let the price of the copyright program be p. Consumers face implementation costs for programs, $c_R \geq 0, c_L \geq 0$, respectively. We assume for the rest of the paper that the implementation costs are equal for both programs $c_R = c_L = c$. A consumer buys the copyright program if the surplus accruing to him from it is larger than that from the copyleft program and naturally at least zero. The marginal consumer, say j, is indifferent between the programs and the following condition holds:

$$V_{Rj} - p - c = V_{Lj} - c \tag{7}$$

Using (6) we can develop (7) into

$$V_{Rj} = \frac{p}{1 - \frac{V_L}{V_R}} \quad (> 0). \tag{8}$$

From (7) we can see that the existence of the copyleft program affects the monopolist's behavior. If the valuation of the copyleft program exceeds its implementation cost for some consumers, the monopolist has to take this into account when setting the profit-maximizing price. Consumers whose valuation is higher than that of the marginal consumer in (8) buy the copyright program. This is represented by distance OR in figure 4. If there exists a consumer k that receives a zero surplus from the copyright program, $V_{Rk} - p - c = 0$, but a positive surplus from the copyleft program, $V_{Lk} - c > 0$, the copyleft program will exist in the market. Recalling (6) we can develop the following condition for the existence of the copyleft program:

$$p > \left(\frac{V_R}{V_L} - 1\right)c \,. \tag{9}$$

Figure 4 illustrates this outcome. The distance $OL - OR = RL$ represents the number of consumers acquiring the copyleft program and the distance OR represents the number of consumers buying the copyright program. The other possibility is that the consumer having zero surplus from the copyright program does not have positive surplus from the copyleft program. In figure 4, this would mean that point L is to the left of point R. In that case, while there is a programming effort by the copyleft community, no consumers will use the developed program. The monopolist can control the demand for the copyleft program in the market. The price it sets determines whether consumers will acquire the copyleft program. Apart from that, and as noted earlier, the existence of the copyleft community and even the potential threat of a substitute program will have an impact on the monopolist's optimal price.

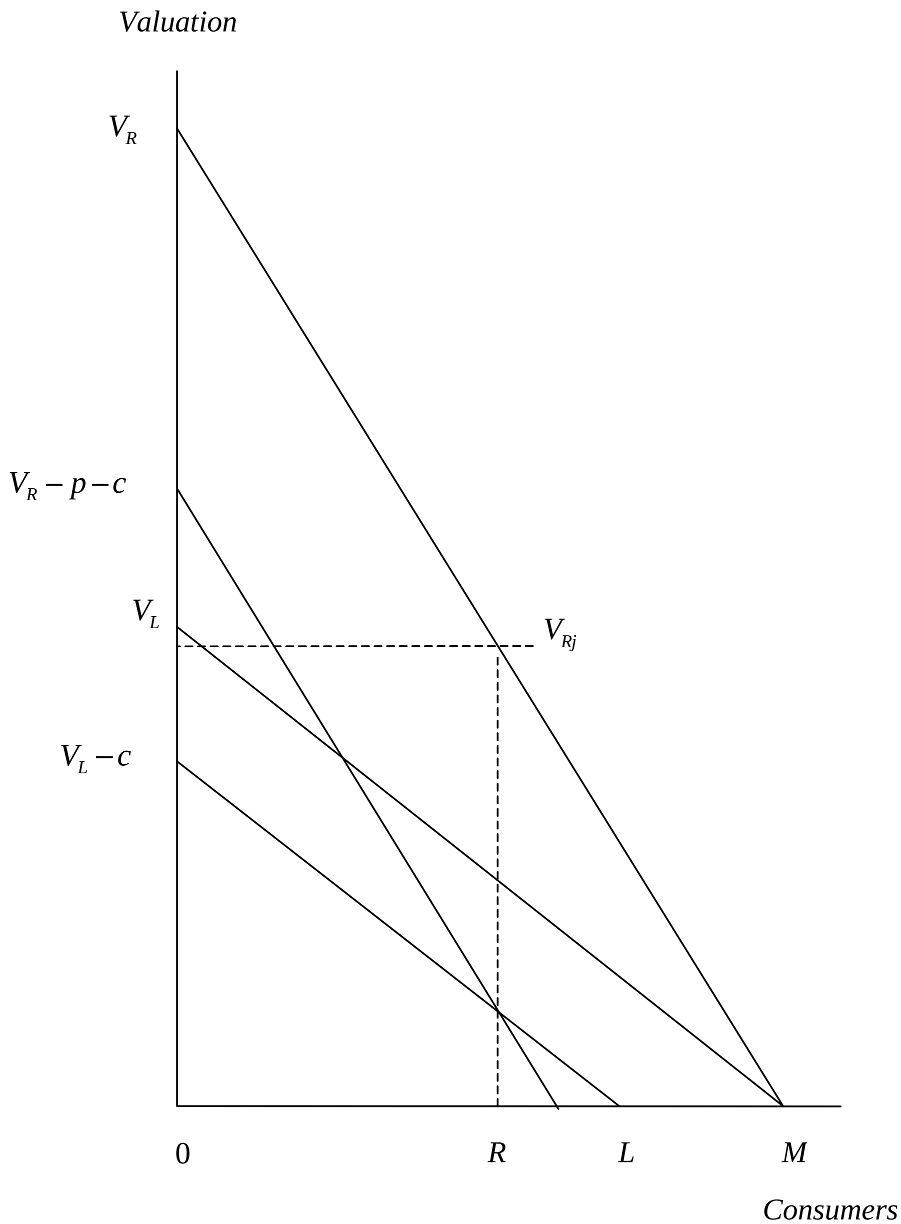

Figure 4: The market for copyright and copyleft programs

Because of the existence of the copyleft community, the demand function faced by the monopolist is a kinked one:

$$q = \frac{V_R - p - c}{V_R} M , \qquad \text{when } p \le \left(\frac{V_R}{V_L} - 1 \right) c , \tag{10a}$$

$$q = \frac{V_R - V_{Rj}}{V_R} M = \frac{V_R - \dfrac{p}{1 - \dfrac{V_L}{V_R}}}{V_R} M , \quad \text{when } p > \left(\frac{V_R}{V_L} - 1 \right) c . \tag{10b}$$

As the production costs are zero, the revenue function for the monopolist is

$$R = p \left(\frac{V_R - p - c}{V_R} \right) M , \quad \text{when } p \le \left(\frac{V_R}{V_L} - 1 \right) c , \tag{11a}$$

$$R = p \left(\frac{V_R - \dfrac{p}{1 - \dfrac{V_L}{V_R}}}{V_R} \right) M , \quad \text{when } p > \left(\frac{V_R}{V_L} - 1 \right) c . \tag{11b}$$

Consumers value the programs observing their properties. We assume that the value of properties is increasing in the program development output. Let the valuations V_R, V_L of the consumer with highest valuations be linear functions of the program development outputs

$$V_R = \mu X_R \left(a^* \right) = \mu \frac{1}{2} a^{*2} N , \ \mu > 0 , \tag{12a}$$

$$V_L = \mu X_L \left(a^* \right) = \mu \frac{1}{2} \left(1 - a^{*2} \right) N , \mu > 0 . \tag{12b}$$

We turn to reporting the main findings:

Proposition 1: The monopolist participating in the market will hire programmers with ability $\left[0, a^*\right]$. It must be the case that the productivity of the most able programmer hired, a^*, exceeds a threshold level given by $a^*_{\min} > \left(\sqrt{2}\right)^{-1}$. Moreover, the wage the monopoly pays must exceed a threshold, $w_{\min} = w\left(a^*_{\min}\right) > 0{,}52\beta$, to attract those programmers.

Proof: From (7), we note that to be present in the market the monopolist cannot allow the maximum valuation for the copyleft program to be higher than the maximum valuation for the copyright program. Otherwise, no consumers would have a positive surplus from buying the copyright program at a positive price, since they can acquire the copyleft program of the same or higher quality for free. The condition is satisfied if the total development output for the copyright program is larger than that for the copyleft program. The monopolist actions determine the outputs through the wage setting. Using (12a,b) and the inserting result to (4), the condition can be expressed as:

$$V_R > V_L \Rightarrow a^* > \left(\sqrt{2}\right)^{-1} = a^*_{\min} \Rightarrow w\left(a^*_{\min}\right) > 0{,}52\beta \qquad \text{Q.E.D.} \qquad (13)$$

Maximising the revenues in (11a,b) yields the optimal price with and without the copyleft product in the market. By inserting the valuations of (12a,b), we can express the prices as functions of the given productivity of the most able programmer hired by the monopolist, a^*. As the implementation cost is an interesting parameter in software markets, we solve for it from conditions of (11a,b). Inserting the respective optimal price and the valuations into the conditions in (11a,b) results in the following optimal prices for varying levels of c,

$$p = \frac{\mu N a^{*2} - 2c}{4} \qquad \text{if} \quad c > \frac{\mu N a^{*2}\left(1 - a^{*2}\right)}{6a^{*2} - 2} = \bar{c}\,, \qquad (14a)$$

$$p = \frac{2a^{*2} - 1}{a^{*2}}c \qquad \text{if} \quad \underline{c} < c < \bar{c}\,, \qquad (14b)$$

$$p=\frac{\mu N\left(2a^{*2}-1\right)}{4} \qquad \text{if} \quad c<\frac{\mu N\left(1-a^{*2}\right)}{4}=\underline{c}\ . \tag{14c}$$

We now prove:

Proposition 2: If the implementation cost is low, $c<\underline{c}$, the copyleft program will be acquired by some consumers.

Proof: Inserting the threshold values of the implementation cost and the optimal prices in (14a,b,c) into the condition for the copyleft program in (9) shows that the condition is satisfied for the price and the associated condition in (14c). Q.E.D.

If the implementation cost is high, no consumers with a positive surplus from the copyright program receive a positive surplus from the copyleft program. The monopolist can price his program as if there were no copyleft program available. If the distribution cost is between the two threshold values, the optimal price for the monopolist is the price that just deters the marginal consumer choosing the copyright program from receiving any positive surplus from the copyleft program. Ultimately, should the implementation cost be zero, all consumers use either the copyright or copyleft program.[12]

We solve the monopolist's profit-maximizing problem using backward induction. At the development stage, the monopolist anticipates that the program market behaves in a manner described above. It has to decide on the ability of the most able programmer it employs. This, in turn, determines the quality of its program and the quality of the program the copyleft community creates. Consumer decisions depend on the qualities of programs and implementation cost. The cost determines the market structure. In the analysis, which follows, we concentrate on the scenario in which the copyleft program exists in the market.[13] Profit is the revenue at the output stage, (11), minus the labor cost at the development stage, (5). The monopolist has no other costs and that there is

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[12] Using the terms of the literature on industry entry and exit (Tirole 1988, ch. 8), we could say that the copyleft program is blockaded (14a), deterred (14b) or accommodated (14c) in the market.

13 Profit functions of scenarios (14a) and (14b) are available upon request no discounting. Inserting in (11b) the optimal price in (14c) and the valuations of the programs in (12a,b) leads to the following profit function in terms of the decision variable a^*:

$$\pi(a^*) = R(a^*) - C(a^*) = M \frac{\mu N(2a^{*2} - 1)}{8} - N\beta(-\ln(1 - a^*) - a^*),$$

$$\text{when } c \le \frac{\mu N(1 - a^{*2})}{4} = \underline{c}. \tag{15}$$

We prove:

Proposition 3: When the implementation cost is sufficiently low $(c < \underline{c})$, the share of programmers hired by the monopolist is an increasing function of the size of the consumer market M and consumers' valuation of quality μ but decreasing in complementary income β.

Proof: Solving for the monopolist's profit maximization problem (15) yields the optimal productivity level of the most able programmer hired by the firm, a^{**}, which in turn determines the optimal number of employed programmers $N_R^{**} = a^{**}N$. The first-order condition for the monopolist's profit maximization is

$$\frac{d\pi}{da^*} = 1/2\, \mu NMa^* - \frac{N\beta a^*}{1 - a^*} = 0. \tag{16}$$

This yields two solutions for the optimal a^*, $a_1^{**} = 0$ and $a_2^{**} = 1 - \frac{2\beta}{M\mu}$, of which only a_2^{**} satisfies the second order condition[14] and the requirement of proposition 1 that the solution has to satisfy $a^{**} > (\sqrt{2})^{-1}$. We obtain:

$$a^{**} = 1 - \frac{2\beta}{M\mu}. \tag{17}$$

[14] The second order condition reads $\frac{d^2\pi}{da^{*2}} = 1/2\, \mu NM - N\beta\left(\frac{1}{((1 - a^*)^2}\right) < 0$.

Inspection of (17) proves the proposition. Q.E.D

We prove:

Proposition 4: When the implementation cost is sufficiently low, $(c < \underline{c})$, the profit-maximising wage the monopolist pays the programmers is increasing in the size of the consumer market M, consumers' valuation of quality μ and programmers' complementary income β.

Proof: Inserting the optimal productivity of the most able programmer employed, a^{**}, into the wage function (3) and differentiating yields the following comparative statics results:

$$\frac{dw(a^{**})}{dM} > 0, \ \frac{dw(a^{**})}{d\mu} > 0, \ \frac{dw(a^{**})}{d\beta} > 0. \qquad \text{Q.E.D.} \qquad (18)$$

We also show:

Corollary 1: When the implementation cost is sufficiently low $(c < \underline{c})$, a profit-maximising monopolist enters the industry if $\beta < 0{,}056M\mu$ and hires at least 89% of the programmers.

Proof: Inserting the optimal solution of the decision variable, a^{**}, into the profit function (15) and setting it equal to zero yields[15] the following condition for the model parameters:

$$\pi(a^{*} = a^{**}) > 0 \Rightarrow \beta < 0{,}056M\mu. \qquad (19)$$

The monopolist decides to enter the industry at the development stage if the condition in (19) is satisfied. Applying condition (19) to the optimal solution of the decision

[15] We use a numerical method to solve for the equation.

variable a^* in (17) allows us to characterize the employment decision of the monopolist as follows:

$$\beta < 0{,}056M\mu \Rightarrow a^{**} > a^*_{entry} \approx 0{,}89\,. \qquad (20)$$

If the monopolist enters the industry, it hires the profit-maximising number of programmers, $a^{**}N$. The condition in (19) determines a lower limit to the employment of programmers and it is 89 percent of all programmers. Q.E.D.

When the condition (19) is not satisfied we can interpret it as a scenario in which the level of complementary income in the software application area is large compared to the market. The approach taken by Johnson (2001), who analyses the copyleft activity as private provision of a public good, fits well to that situation. In his model, the programmers are also the only users of the software and the consumer market is not present.

We also find

Corollary 2: If the implementation cost, c, is lower than $\underline{c}_{\max} = 0{,}21\mu N$ or less than 13% of the highest valuation of the copyright program, V_R, both the copyright and copyleft program can co-exist in the market. The lower bound $\underline{c}_{\max}$ is half of the highest valuation of the copyleft program, V_L.

Proof: The requirements for the co-existence of the copyright and copyleft programs in the market are that the monopolist makes a positive profit and that the implementation cost is below the threshold value $\underline{c}$ defined in (15). It is decreasing in a^* and reaches its maximum at the lowest possible value of a^*. Inserting the condition for industry entry in (19) into the equation for the lower limit of the implementation cost in (15) yields the proposition:

$$\underline{c}_{\max} < \underline{c}\left(a^* = a^*_{entry}\right) \approx 0{,}21\mu N\,. \qquad (21)$$

To calculate the ratio of the threshold implementation cost $\underline{c}_{\max}$ to the maximum valuation of the monopolist's program V_R, we conclude that the lower limit in (15) is decreasing and the maximum valuation of the program in (12a) is increasing in the decision variable, a^*. The highest ratio obtains in the minimum value of the decision variable.

$$\frac{\underline{c}_{\max}}{V_R} < \frac{\underline{c}\left(a^* \approx 0{,}89\right)}{V_R\left(a^* \approx 0{,}89\right)} \approx 0{,}13. \qquad (22)$$

Comparing the equations for the lower limit of the implementation cost in (15) and for the maximum valuation of the copyleft product (12b), we note that their ratio is a constant and always $\frac{1}{2}$. Q.E.D.

If the implementation cost is higher than the value indicated in (21), the market is served either by the monopolist or by the copyleft community. In condition (21), we can see that the threshold value of the implementation cost is increasing in the total programming resource, N. Many determinants of the actual implementation cost are independent of the quality of the programs and more or less constant. This implies that consumers are more likely to use copyleft programs in software application areas where the programming resource is large.

4 Discussion

We turn to policy issues with the following suggestions. First, when implementation cost is low $(c < \underline{c})$, informing consumers about an unknown substitute copyleft program increases welfare[16]. To illustrate, let us assume two scenarios in the market. The first involves a monopolist supplying the market. There exists also a copyleft community of programmers. However, the consumers are not aware of the substitute copyleft program available at a low distribution cost. This assumption is realistic

[16] The Chinese and recently the German government are both promoting the use of Linux operating system. Their motives seem to coincide with the ones described here. (China joins the Linux bandwagon 2000, IBM signs Linux deal with Germany 2002)

since the copyleft programmers are indifferent as to whether the consumers use their program or not. The firm maximizes profits as if the scenario is the one defined in (14a) regardless of the implementation cost. The second scenario is the one defined by (15) and analyzed in the proof of proposition 3. In that scenario the consumers have full information on the substitute copyleft program. To make the analysis more tractable, we assume that the implementation cost is zero, $c = 0$.

Maximization of profit in both scenarios yields the following optimal productivities of the most able hired programmers (we denote the first scenario by M, the second by CL):

$$a_M^{**} = 1 - \frac{4\beta}{M\mu} \quad , \tag{23a}$$

$$a_{CL}^{**} = a^{**} = 1 - \frac{2\beta}{M\mu} \quad . \tag{23b}$$

Comparison of (23a) and (23b) shows that the monopolist will always hire less programmers and the quality of the copyright product will be lower when consumers are unaware of the copyleft substitute. When consumers are not aware of the potential copyleft program, welfare, that is, the sum of the firm's profit and consumer surplus from the copyright program is W_M. If consumers are aware of the copyleft product, some of them derive surplus from its use. The welfare measure is then W_{CL} [17]. Comparing welfare measures shows that that the inequality $W_{CL} > W_M$ holds when (we denote $Z = \frac{2\beta}{M\mu}$) $Z <\approx 1,53$. On the other hand, the profit in the monopoly scenario is higher, $\pi_M > \pi_{CL}$ when $Z < 2\ln 2 \approx 1.39$. According to proposition 1 and (17) the possible values of Z are $0 < Z < 1 - \left(\sqrt{2}\right)^{-1} \approx 0,297$. Welfare is thus always higher when consumers are aware of the existence of the copyleft program and the monopolist has no incentive to inform the consumers of the potential substitute copyleft program. An intriguing outcome is that the market may become unprofitable for the monopolist when consumers learn about the substitute copyleft program. The

[17] The welfare functions and calculations are available upon request.

market and cost parameters that result in profit when the monopolist is alone in the market may not fulfill the entry condition in corollary 1. This implies that when the monopolist anticipates a policy of informing consumers of copyleft programs the condition for commitment to the programming project at the development stage is the one in corollary 1.

Our second suggestion is that copyright enforcement is important for copyleft activity. Copyleft incentives rely on copyright enforcement. The literature on copyright (eg. Besen and Raskind 1991, Landes and Posner 1989) generally considers the enforcement of the copyright to fall on the responsibility of the author. Landes and Posner assume in their model that copyright is not perfect and that increasing the degree of protection is costly. This means that authors, usually firms, with considerable resources are able to defend their intellectual property. Copyleft programmers or communities, however, do not usually possess such resources. As we noted earlier, copyleft programmers are indifferent as to whether consumers use the copyleft programs or not. However, if the distribution of the copyleft program outside the copyleft community results in violations of the 'collective' copyright of the program they may prefer not to allow for it. The economics of copyright protection analyses the optimal level of copyright protection (Landes and Posner 1989, Koboldt 1995, Johnson 1985, Novos and Waldman 1984). There is a tradeoff between stronger incentives to create new works when copyright protection is high and the increased opportunity to create derivative works and lower control costs when protection is low. The existence of copyleft communities is an additional factor in this analysis. The incentives in copyleft activity are strengthened by strong institutional copyright protection. As the consumption of programs created by the copyleft community seems to increase welfare, this promotes stronger copyright protection. We considered copyleft activity analoguos to 'Science' in the introduction. It is interesting to note that scientific publications are an institution that largely protects the intellectual property rights (in the sense of *priority*) of the scientific community. Copyleft communities presently lack such institutions. The increased economic significance of copyleft software has already resulted in a discussion on the need for such institutions (see Deckmyn 2000a).

The novel contribution of this paper is the analysis of the impact of copyleft licensing on both the development environment and the consumer market for programs. The effect of copyleft on the incentives and conduct of programmers has not been left unnoticed in the literature. In our model, we extend the analysis by introducing a monopolist supplying a copyright protected program. Copyleft activity forces him to face constraints in the programmer labor market and competition from a substitute copyleft program in the consumer market. The role of the copyleft program is dependent on the level of consumer implementation cost for programs. When the cost is sufficiently low, some consumers choose to use the copyleft program and the monopolist has to take this into account in pricing his program. The presence of copyleft activity also creates a barrier to the market entry of the monopolist. The larger the consumer market is compared to the programming population, the larger is the share of the programmer population, which the monopolist hires and the smaller is the copyleft community. If the market size is small and consumer valuations are low, the monopolist may decide not to enter the market. Only the copyleft program is then available. This result coincides with some real-world phenomena. In certain markets, like those for some network utility programs, the supply consists entirely of copyleft programs. Our results imply that the monopolist may not be able to exercise full monopoly power in the market if a copyleft program exists. Schmalensee (2000) analyses the personal computer operating system market in the US and finds that the market leader, Microsoft, is in practice a monopoly, but does not use monopoly pricing. This deviation is a result of several factors but our analysis provides the explanation that the 'invisible' competition from Linux affects the pricing of Windows.

For programmers, copyleft licensing creates an alternative incentive structure reminiscent of scientific research. The assumptions of our model mean that the most able programmers join the copyleft community. There is parallel empirical evidence supporting this finding (see Stern 1999). Furthermore, even if case studies (Lerner and Tirole 2000) of copyleft program projects imply that some programmers choose to engage in copyleft programming instead of highly paid copyright programming, modeling of the complementary income needs further empirical study of the programmers' incentives. In our model, the consumer market is served by a monopolist. This is clearly a simplification. The program business is sequential in nature: first there is the development stage and then the output of the program. For the firms to recoup the programming investment in the market, imperfect competition of some degree is required. Relaxing the monopoly assumption and assuming an oligopoly does not change the qualitative results. In more general terms, the partial equilibrium nature of our model hides some important issues. Here we assume that the complementary income is an outside option. Looking at the whole economy in general equilibrium terms raises the question of the determination of the complementary income. A copyleft community may be present in each sub-industry and copyleft products may dominate some markets. In this environment we can ask who provides the income for the copyleft programmers and what consequences it may have. In taxing suppliers of copyright programs, society has to take into account the substitute nature of the copyleft programming, which it may support from public funds.

There are numerous avenues for future research concerning our topic. Our model does not address network effects for programs. These are an important property of programs and in the case of copyleft a new issue arises: the network for the copyright program is the number of consumers using it, while the network for the copyleft program is the number of consumers using it and the programmers in the copyleft community. This creates an environment in which a copyleft program may enter a market dominated by copyright programs more easily if it has a large number of developers. The incentive structure of copyleft programmers may also have other implications. In the standard literature on signaling models[18] where potential employees signal their ability with the level of education it is assumed that the amount of education acquired does not affect the employer's profit. Copyleft programming, if used as a signal of ability, may have a negative impact on the employer's profit. The copyleft community develops a substitute program in a decentralized manner and this affects the market for the program of the employer. He will take this into account and this may change the results of the signaling analysis.

[18] See for example chapter 11 of Hirschleifer and Riley (1992).

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Essay 2: Why do firms support the development of substitute copyleft programs? ♦

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Firms in the IT-industry use resources to initiate and support copyleft programmers' communities, which develop competing free programs. We introduce a model where programs exhibit network effects in the consumer market and where a firm selling a copyright program has an incentive to support the development of a free copyleft substitute program. The reason is that it creates compatibility between the programs that the firm cannot achieve by itself. The incentive arises under a weak network effect even when the network of copyleft programmers is small compared to consumer network. We report welfare results under different market outcomes and find surprisingly that policy actions, like standardization and increasing the size of the copyleft programmers' network, do not always increase welfare.

Keywords: Compatibility; Network effect; Copyleft; Open source software

JEL Classification: D23; L11; L15

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1 Introduction

Large firms in the IT industry, such as IBM, Nokia and Sun Microsystems support copyleft open source programming communities in several ways. They invest in program development and license the output for free. Firms also offer communication and project management facilities to communities. We explore the motives for such behaviour. Natural motives arise if the programs are complements or if supporting a copyleft program hurts competitors[1]. We show in a model of consumer markets with network effects that a firm may have an incentive to support the development of a zero-priced copyleft program even if it is a substitute. The network of the free good extends beyond the consumer market to its development community. The contribution of the paper is to analyse the behaviour of a profit-maximising firm facing competition from a zero-priced good and the welfare implications of policy actions.

Copyleft is a novel licensing scheme to advance open and decentralized computer program development (GNU Project 2000a). Licensing a program using the GPL (General Public License) agreement means that anyone can use, further develop and distribute the program code freely as long as he in turn applies the same agreement to his additions or enhancements to the original program[2]. This implies that there can be no rents for the creators of new program code, so the program has a zero price. It also implies that while consumers may use the free copyleft program, the copyleft community is not motivated by the actions of the consumers. The phenomenon of having parallel research paradigms, one based on the direct economic incentives, profits, and another based on scientific priority and complementary income from reputation, is recognized in the literature. Dasgupta and David (1987,1994) call these paradigms ‘technology’ and ‘science’, respectively. We call these paradigms copyright and copyleft in our analysis**.** Besides incentives, copyleft affects also the organization of programming. Copyleft communities are decentralized and self-managing like scientific communities (Raymond 1998). This implies that consumers cannot distinguish the anonymous members of the community from other consumers.

[1] We provide an overview of the literature on these scenarios in the appendix.

[2] There are other open source license agreements (see Lerner and Tirole 2002). The conditions of the agreements differ but most of them have the basic properties required in our model.

Copyleft programmers do not take responsibility of the copyleft program, but they are experts and may provide considerable support to consumers in order to signal their skills to peers[3]. In contrast, a firm has responsibility over its program and has an identity to consumers. We think that the software industry is an especially interesting environment for research on the incentives and structure of R&D. In software development, the R&D results are often directly available to consumers and copyleft programs, such as Linux and Apache, are widely used.

IBM copylefted the Eclipse software, a collection of programs designed to support the integration of programs from multiple vendors, also those developed by copyleft communities. Nokia copylefted the operating system (OST, Open Standard Terminal) of its Media Terminal device[4]. In both examples, firms cannot directly control the direction of the development work of the copyleft communities. With support, they try to achieve compatibility between their own programs and programs developed by other firms and copyleft communities[5]. The remarkable feature of these activities is that they seem to support the development of competing substitute copyleft programs.

A firm can support copyleft by providing program code and facilities for the development activities of the copyleft community. An important aspect of the firm actions seems to be the initiation of a copyleft community by providing a set of functions to start with and in the beginning also project management (Murray 1999, Lerner and Tirole 2002). We suggest that the purpose of these costly actions is to initiate and in the beginning lead the community to develop a program that is compatible with the copyright program. The firm cannot control the decentralized 'bazaar' of the copyleft community (Raymond 1998) or predict its development actions, so it cannot adapt to the properties of the copyleft program and create compatibility between the programs through own development work. There is a consumer market with a zero-price copyleft program developed by a copyleft

[3] See for example the recognition of programmers improving the PAM-Linux service (PAM-Linux 2002).
[4] "$40 million donation of software to open source community", see IBM News 2001. Another such example is The Classes of ISOCODE by IBM (Murray 1999).
[5] "By opening up the Eclipse source code, IBM is doing for software tools what Apache did for web application servers and what Linux did for operating systems" (Steve Mills, IBM, IBM News 2001). "Nokia aims at initiating the creation of an open standard for IP-based home entertainment. By making source code…available…we want to…stimulate widespread creation of applications" (R. Nelger, Nokia Home Communications, Collab.net 2001).

programming community and a commercial copyright program developed by the firm. The copyleft community has internal motives for development but consumers can use the program, which the community has developed. The programs are assumed to be imperfect substitutes and they exhibit positive network effects in the consumer market[6]. The network of the copyleft program consists of two groups, the consumers using it and the copyleft community developing it. The network of the copyright program is the just the consumers using it. At the first stage, the firm chooses between supporting the development of the rival copyleft program for it to turn out compatible and not supporting, in which case the programs become incompatible. At the second stage, consumers purchase the copyright program. The support choice is shown to depend crucially on two parameters, the strength of the network effect and the size of the copyleft community.

The results of the paper are the following. We prove that when the network effect is strong and the copyleft community is small, the firm chooses a price that deters the copyleft program from the consumer market and thus, being a monopoly, has no incentive to create compatibility through support. With a weak network effect and a small copyleft community, the firm accommodates the incompatible copyleft program in the market. When the size of the copyleft community is above a boundary value increasing in the strength of the network effect, the firm prefers compatibility and will support the community. The profit increase from increased willingness to pay for a larger network exceeds the loss from a smaller market share. We notice that there are no analogous results in the literature. Economides (1996b), for example, addressed the issue of whether a monopoly firm invites or supports the entry of rivals with compatible products to a market with network effects. However, the difference to our analysis is that under compatibility, the products are perfect substitutes and hence command the same price. In our model, compatibility does not create perfect substitutability and one good has a positive price while the other one is free. Consequently, our result is opposite to that of Economides, who finds that under a strong network effect, the firm prefers entry with compatible products because profits increase as the network effect raises the market price even if the firm's market share is reduced. Hence, and putting both results together, depending on the strength of the

[6] For a survey of network effects, see Economides (1996a).

network effect a firm may support either rival copyleft communities or rival copyright firms to create a compatible network. Thus a firm may give up its monopoly power in alternative ways depending on the network effect. For competition policy, it is of interest to notice that the firm chooses to stay as a monopoly under different conditions.

We assume that society can control the industry with two policy instruments. First, standardization makes programs compatible and the network becomes common. We show that standardization does not always increase welfare, which we measure as the sum of profits and consumer surplus[7]. The copyright program has a larger market share under incompatibility than under compatibility. The surplus from the basic valuations of the copyright program is higher than that of the copyleft program. The reduction in this surplus due to a reduced demand of copyright programs may be larger than the increased surplus from the common network. Secondly, science policy affects the consumer market by changing the size of copyleft programmers' community. We show that under incompatibility, an increase in the community's size is welfare reducing for a strong network effect, as the firm's profit reduction is larger than the increase in the surplus of consumers that use the copyleft program. Joint use of standardization and science policy may be welfare increasing when each used alone would not be**.**

Copyleft programming has not been left unnoticed in the current literature. Lerner and Tirole (2002) presented case studies and analysed programmers' motives, project organization and firm incentives for copyleft. Our paper is a formal extension of their ideas of a firm's incentives to support copyleft communities. Schiff (2002) provided a survey of the early literature on the economics of open source software. Weber (2000), Johnson (2001) and Kogut and Metiu (2001) concentrated on the development process of copyleft programs. We abstract in our paper of the development incentives but concentrate on the consumer market. For a model with endogenous development efforts for copyright and copyleft programs, see Mustonen (2002). The model includes a labor market for programmers and a consumer market for programs. Kuan

[7] As a parallel result in another setting, Woeckener (2001) found that under duopoly price competition, network effects and horizontal quality differentiation, enforcing compatibility between programs does not increase welfare.

(2001) discussed consumer markets for copyleft programs. She models some consumers as potential developers, who have incentives to develop the copyleft program for own use. In our model the consumer market is passive in development. This approach seems reasonable for programs that are widely used (Linux, Apache etc.). Harhoff, Henkel and Hippel (2000) discussed motives for users of a good to reveal voluntarily their innovations. In the case of copyleft software they acknowledge that the improvement of the properties of the good and reputation effects related to programming skills are the motivation for such behaviour. We claim that compatibility, a motive they find relevant in another context, is an important driver of costly revelation. Our specification of the consumer market with a free copyleft program draws on Koboldt (1995), who modelled competition between the original good and an imperfect copy of it. Takeyama (1994,1997) incorporated network effects into a game between firms where the copyright holders may not want to restrict the distribution of illegal copies in the market. In Gayer and Shy's (2001) approach, consumers differed in their ability to acquire the free good but the good with a price is equally accessible to all consumers. Furthermore, they assumed that only the free good exhibits network effects in the market. We make neither differentiating assumption.

In chapter 2 of the paper we develop the profit of the firm in different market outcomes. The outcomes follow from compatibility achieved by supporting copyleft or from incompatibility. In section 2.3 we compare profits and develop conditions for the firm to prefer any of the three outcomes. The welfare consequences of compatibility by standardization and of an increase in size of the copyleft community by science policy are analysed in chapter 3. Chapter 4 concludes.

2 The model

We introduce a two-staged model of a copyright firm facing competition in the consumer market from a zero-priced imperfect substitute. At the first stage, the firm decides whether to use resources with a fixed cost S to support the development of a compatible copyleft substitute program or not use resources and let the programs turn out incompatible[8]. At the second stage, consumers assess the programs and buy the copyright program or acquire the copyleft program. We distinguish three market outcomes: compatibility, incompatibility with both programs present and incompatibility with only the copyright program present in the market. By choosing compatibility, the firm competes *within* the market, whereas incompatibility implies competition *for* the market (Besen and Farrell 1994). There are many consumers with a mass of 1 that either buy one unit of the copyright program or acquire one unit of the copyleft program[9]. The fractions of consumers of the programs are M_R and M_L, $M_R + M_L = 1$. A consumer's valuation of a program consists of a basic valuation and a network valuation. As to the basic valuation, it is helpful to note that compatibility is a more narrow property than perfect substitutability. Two programs may be compatible but still imperfect substitutes. It follows from imperfect substitutability that consumers value programs differently. In our case, we assume that the valuation of the copyright program exceeds that of the copyleft program because the firm has an identity, which creates an explicit or implicit responsibility for the quality of the program that is valued by consumers[10]. As we confine our analysis to properties of a market where a copyright program with a positive price and a free copyleft program co-exist, it cannot be the case that consumers would value the copyright program less or equally compared to the copyleft program. The basic valuations of the copyright program, V_R, are evenly distributed on the interval $[0, 2]$ and of the copyleft program, V_L, on the interval $[0,1]$. We assume that the ratio of valuations of programs is a constant $1/2$ for all consumers except for the one with lowest valuation, implying vertical quality differentiation. We refer to the appendix for an alternative specification, where consumers' tastes differ.

The programs are network goods in the sense that a larger network of users of compatible programs increases the value of the program, as for example the exchange of data becomes easier and the quality of services improves. We assume a linear

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[8] We restrict $0 \le S < 1/4$ to secure positive profit under compatibility.

[9] Naturally all consumers may acquire the copyleft program, as it is free. Our focus is on the success of the copyright program. The 'dormant' copyleft programs that buyers of copyright programs may have do not affect the analysis.

[10] Such a difference in valuations arises most naturally for example in a model with quality uncertainty and risk-averse consumers. A smaller variance in quality implies a higher valuation.

representation of the network valuation with parameter $v \geq 0$, equal to all consumers. This is based on the observation that while the basic valuation of a program varies across consumers, they all seem to face similar challenges in the implementation and use of programs. We assume that consumers benefit from the existence of the copyleft community as they benefit from other consumers. The anonymous copyleft programmers are ‘super-consumers’ in the network providing, for example, rapid online advice, new functions and complementary software pieces. The firm may provide also some of such services, as in the model of Shy (2001, p.67), where a firm faces illegal copies of its program in the market. However, the firm services are more restricted than copyleft services, as much of firm support is conditional on the program license and thus consumers include it in the basic valuation. Because the firm’s contribution to the network is small we abstract from it and define the additional contribution of copyleft programmers to the size of the network as $\beta \geq 0$. It is likely to be much larger than the actual number of copyleft programmers as programmers can contribute more than consumers to the complementary services[11]. We assume that the number of programmers is small and exclude them from the market and welfare analysis. The copyleft programming community belongs to the network of users of programs that are compatible with the copyleft program.

We assume that consumers have perfect foresight and thus correctly anticipate the fraction of consumers buying the copyright program (see Shy 2001, p. 20). There exists a marginal consumer who is indifferent between the programs, given the price p and given the networks. All consumers with a higher basic valuation than that of the marginal consumer receive a larger surplus from the copyright program than from the copyleft program given the price and networks. The consumers anticipate that consumers with a higher valuation than that of the marginal consumer choose the copyright program. The marginal consumer m can thus be identified as the consumer that is indifferent between the programs. The identification of the marginal consumer determines the expectations of the consumers. The rest of the consumers acquire the

[11] To illustrate the specification, consider a consumer in need of advice. With a copyleft program, posting a question to a discussion group in the Internet results in answers from other consumers and programmers developing the code. In the case of a copyright program, other consumers provide answers but the firm supports only registered users that have paid for the program license. Copyright programmers may provide some answers but cannot divulge details or offer solutions that the firm provides only to license holders.

copyleft program and the size of the copyleft programmers' network becomes known. We assume that all consumers adopt these expectations. In the spirit of Katz and Shapiro (1985), we analyse only those outcomes where the network expectations of the consumers actually are fulfilled. To simplify the notation, we do not distinguish between expected and realized sizes of networks. Programs have zero production costs. In the following sections we determine the firm's profit, which depends on the intensity of the network effect v and the effective size of the copyleft programmers' network β under different market outcomes.

2.1 The firm supports copyleft

At the second stage, consumers assess the programs and their expected networks. When the firm supports copyleft programming at the first stage, programs turn out compatible and the network consists of all consumers and the copyleft community. Thus, the consumers' valuations of the network are equal for both programs. The incentive compatibility condition for consumer i to choose the copyright program with price p is

$$V_{Ri} - p + v(M_R + M_L + \beta) \geq V_{Li} + v(M_R + M_L + \beta). \qquad \text{(IC1)}$$

Noting that $V_{Ri} = 2V_{Li}$, the condition reads $V_{Ri} \geq 2p$. The individual rationality conditions require that for consumers j,k acquiring the respective programs, the net utilities must be non-negative,

$$V_{Rj} - p + v(M_R + M_L + \beta) \geq 0, \qquad \text{(IR1)}$$

$$V_{Lk} + v(M_R + M_L + \beta) \geq 0. \qquad \text{(IR2)}$$

We note that both individual rationality conditions are satisfied when the copyright firm has positive revenue. The condition for copyleft use (IR2) holds always and by the incentive compatibility condition (IC1), (IR1) then holds. The marginal consumer, for whom the incentive compatibility condition (IC1) is binding, will get positive surplus from the copyleft program, so there are consumers that acquire the copyleft product. The specified consumer valuation distributions and the fixed market size imply a downward-sloping demand schedule. The marginal consumer indifferent between the programs with a basic valuation V_{Rm} determines the fraction of buyers of the copyright program, $M_R(V_{Rm})$. Consumers that have a higher basic valuation than V_{Rm} buy the copyright program (see figure 1),

$$M_R(V_{Rm}) = \frac{2 - V_{Rm}}{2}. \quad (1)$$

The rest of the consumers use the copyleft program, $M_L = 1 - M_R(V_{Rm})$.

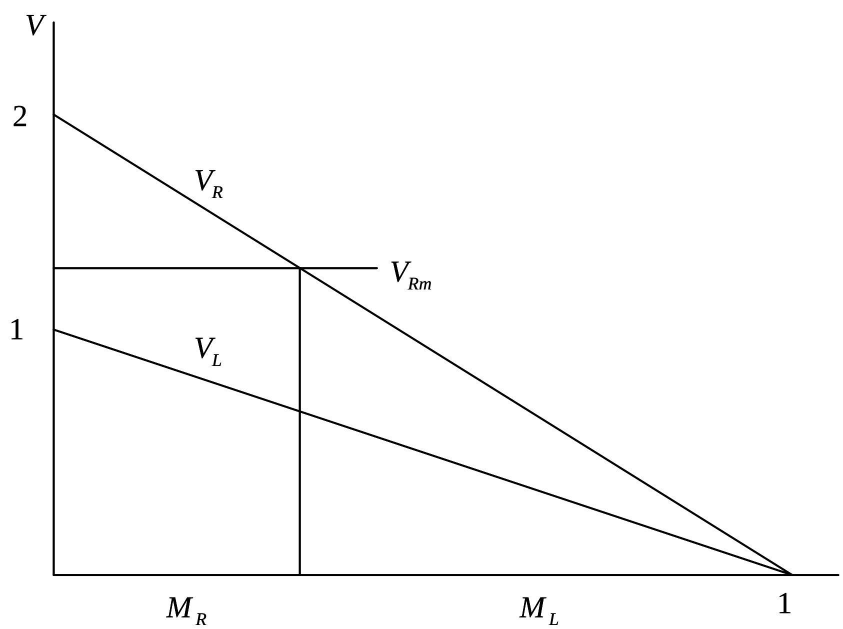

Figure 1: Determination of the number of buyers of the copyright program

Assuming the fulfilled expectations equilibrium, inserting the marginal consumer's valuation $V_{Rm} = 2p$ into (1) yields the demand of the copyright program, $M_R^c(p) = 1 - p$. The profit function of the copyright program reads

$$\pi = pM_R^c(p) - S = p(1-p) - S. \qquad (2)$$

With zero production costs, the profit maximising price is $p^c = \frac{1}{2}$ and the profit of the copyright firm is

$$\pi^c = \frac{1}{4} - S. \qquad (3)$$

We note that under compatibility, both the profit maximising price and the resulting profit are independent of the network effect v and the size of the copyleft programming community β. This proves to be important in the later comparison of scenarios. Even if the network is (very) valuable to consumers, the monopolist cannot take advantage of the surplus the network generates to consumers because the network of its rival - the copyleft program - is also valued equally. As a result of that, even a large network of copyleft programmers providing value to consumers does not benefit or harm the monopolist when it decides to compete *within* the market.

2.2 The firm does not support copyleft

When the firm does not support copyleft programming, the programs turn out incompatible. First, we analyse the case where some consumers choose the copyright program and the rest the copyleft one. The network of the copyright program consists of its users. The copyleft community extends the network of the users of the copyleft program. The incentive compatibility condition for consumer i to choose the copyright program is then:

$$V_{Ri} - p + vM_R \geq V_{Li} + v(M_L + \beta). \qquad \text{(IC2)}$$

Noting that $M_R + M_L = 1$ and $V_{Ri} = 2V_{Li}$, (IC2) is reduced to $V_{Ri} \geq 2\left(p + v\left(1 + \beta - 2M_R\right)\right)$. The individual rationality conditions of consumers of the respective programs are

$$V_{Rj} - p + vM_R \geq 0, \qquad \text{(IR3)}$$

$$V_{Lk} + v(M_L + \beta) \geq 0. \qquad \text{(IR4)}$$

The net surplus of the consumer with lowest valuation is positive so the condition (IR4) always holds. Again, we note that the condition (IR3) is not binding if the copyright firm has positive revenue in the market.

Inserting the valuation of the marginal consumer, $V_{Rm} = 2\left(p + v\left(1 + \beta - 2M_R\right)\right)$, into (1), we solve the demand of the copyright program: $M_R^{inc}(p) = \dfrac{1 - p - v(1+\beta)}{1 - 2v}$. The profit of the firm is

$$\pi^{inc} = pM_R^{inc}(p) = p\frac{1 - p - v(1+\beta)}{1 - 2v}. \qquad (4)$$

The profit maximizing price[12] is $p^{inc} = \dfrac{1 - v(1+\beta)}{2}$ and the resulting demand of the copyleft program is $M_R^{inc^*}(\beta, v) = \dfrac{1 - v(1+\beta)}{2(1 - 2v)}$. We note that the price of the copyright program is lower under incompatibility than under compatibility, $p^{inc} < p^c$. The price under incompatibility is decreasing in the size of the copyleft programming community. Lowering the price compared to the compatibility scenario increases the network of the copyright program. This effect on profit is stronger than price effect as it increases both the number of purchases and the valuation of the program through the network effect.

[12] The second order condition for an interior solution requires that $v < 1/2$.

Proposition 1: Under incompatibility, if the network effect satisfies $v < \min\left\{\frac{1}{3-\beta}, \frac{1}{1+\beta}\right\}$, both the copyright program and the copyleft program exist in the consumer market.

Proof: Both programs are in the market when the firm does not serve all consumers, $M_R^{inc*}(\beta, v) < 1$, which simplifies to $v < \frac{1}{3-\beta}$. Concurrently, the firm has to have positive demand, $p^{inc} > 0$. This inequality in turn simplifies to $v < \frac{1}{1+\beta}$. **Q.E.D.**

When the condition of proposition 1 holds, we can characterize the outcome as the accommodation of the copyleft program. Under accommodation the profit of the copyright firm is

$$\pi^{inc} = \frac{[1 - v(1+\beta)]^2}{4[1-2v]}. \tag{5}$$

The profit clearly depends on the network effect and the effective size of copyleft programming community, since $\frac{\partial \pi^{inc}}{\partial \beta} < 0$ and $\frac{\partial \pi^{inc}}{\partial v} > 0$ if $v > \frac{\beta}{1+3\beta}$. The firm competes for the market with an incompatible program by not carrying the cost of support S but accommodates the copyleft program.

Let us assume that the condition stated in proposition 1 does not hold for the industry. The firm wants to sell to all consumers. The mechanism of expectation formation described at the beginning of chapter 2 assumes that the marginal consumer is identified. In this case, that consumer must be the one with the lowest valuation, because he receives the smallest surplus from choosing the copyright program given the price and the networks. Identifying the marginal consumer determines the expectations, $M_R = 1, M_L = 0$. The copyleft program is deterred from entering the market. We name this outcome as copyright monopoly. Under monopoly, the incentive compatibility condition for the consumer with lowest (zero) valuations is

$$-p + vM_R \geq v(M_L + \beta). \qquad \text{(IC3)}$$

As $M_R = 1$, the price is $p^M = (1-\beta)v$. The individual rationality condition holds trivially. The consumer with lowest valuation determines the price of the copyright program. The surpluses for him are just the values of the networks of the programs[13] and he is willing to pay only for the difference in network valuations. When the copyleft program is deterred in such a manner, the profit of the copyright firm is

$$\pi^M = p^M 1 = (1-\beta)v. \qquad (6)$$

The profit is increasing in the network effect and decreasing in the size of the copyleft programming community. The firm competes for the market and covers it. Even if the firm controls the consumer market, it has to take into account the competitive threat of the copyleft network in pricing. In contrast to the case in section 2.1 where programs are compatible, the copyright firm has revenue only on a region of the (β, v)-space under incompatibility. From (6) we can see that under monopoly, the condition for positive revenue is $\beta < 1$. On the other hand, we can express the condition for positive revenue from proposition 1 as $\beta < \frac{1-v}{v}$. Taken together, the condition for positive profit under incompatibility is given by $\beta < \frac{1-v}{v}$ when $v < \frac{1}{2}$ and by $\beta < 1$ when $v \geq \frac{1}{2}$.

2.3 Comparing the profits under compatibility and incompatibility

If the profit of the firm is higher under compatibility than under incompatibility or monopoly at the second stage, it may be profitable for the firm to support the copyleft programming community at the first stage. We analyze the profits with respect to the interesting industry variables: the strength of the network effect, v, and the size of the

[13] An interpretation of this is that he wouldn't acquire either program without the network even for zero price.

copyleft programming network, β. The cost of compatibility is likely to be small compared to consumer market revenues, so we choose $S = 0$ to simplify the analysis.

We present the main result of the paper. The formal proposition is followed by an interpretation of the results utilizing a graphical representation in (β, v)-space.

Proposition 2: The firm chooses compatibility between the copyright and copyleft program and thus supports the copyleft community

- **under a weak network effect,** $v < 3/8$**, if the effective size of the network of copyleft programmers ,** β**, satisfies** $\beta > \frac{1}{v}\left(1 - v - \sqrt{1-2v}\right)$**.**
- **under a strong network effect,** $v \geq 3/8$**, if the effective size of the network of copyleft programmers,** β**, satisfies** $\beta > 1 - \frac{1}{4v}$**.**

The incentive to support copyleft is increasing in or independent of β.

Proof: Comparison of profits from compatibility (3) and incompatibility (5), $\pi^c > \pi^{inc}$, simplifies to $v\beta^2 + (2v-2)\beta + v < 0$. The inequality holds when

$$\frac{1}{v}\left(1 - v - \sqrt{1-2v}\right) < \beta < \frac{1}{v}\left(1 - v + \sqrt{1-2v}\right). \tag{7}$$

The condition of proposition 1 rules out values of β larger than the upper limit of (7), so only the first inequality of (7) is relevant. Both the first inequality in (7) and the condition for the incompatibility scenario in proposition 1 hold when $v < 3/8$.

Comparison of profits under compatibility (3) and monopoly (6) shows that $\pi^c > \pi^M$ implies $\beta > 1 - \frac{1}{4v}$. This condition holds and the condition of proposition 1 does not hold, which is the condition for the monopoly outcome, when $v \geq 3/8$.

The profit under compatibility is independent of β, $\frac{\partial \pi^c}{\partial \beta} = 0$, while the profit under incompatibility is decreasing in β, $\frac{\partial \pi^{inc}}{\partial \beta} < 0$ and $\frac{\partial \pi^M}{\partial \beta} < 0$. Thus the incentive for support increases in β if the firm's profit under incompatibility is positive. When $v < \frac{1}{2}$ and $\beta \geq \frac{1-v}{v}$ or when $v \geq \frac{1}{2}$ and $\beta \geq 1$ the profit under incompatibility is not positive and the incentive is independent of β. **Q.E.D.**

We note that $\pi^c > \pi^{inc}$ never holds when $\beta = 0$. If the copyleft programming community does not participate in the network of the copyleft program, the copyright supplier always prefers incompatibility. We illustrate the results of proposition 2 in figure 2. The (β, v)-space is split into various regions. The first part of proposition 2 is represented by the line denoted '$\pi^{inc} = \pi^c$' and the second part by the line '$\pi^M = \pi^c$'. The line '$\pi^M = \pi^{inc}$' shows the condition for the existence of the copyleft program under incompatibility in proposition 1. The profit of the firm is constant in the region denoted 'Compatibility', where profit is higher under compatibility than under incompatibility. In the regions 'Incompatibility' and 'Monopoly', profit turns out higher under incompatibility. We can use the figure to predict the market outcome given the industry properties, v and β. We note that for weak network effects even a small copyleft programmers' network creates an incentive to achieve compatibility. In addition to the regions that predict the firm's behaviour, the thin line shows the area of positive profit under monopoly and the dotted line shows the area for positive profit under incompatibility that are discussed in section 2.2.

If we relax the assumption $S = 0$ and allow for $0 < S < 1/4$, in figure 2 the qualitative effect is that the borders of the region 'Compatibility' move to right and the region where the firm chooses incompatibility is larger. We can interpret the relation between the model parameters as follows. For example, $v = 0.5$ implies that for the median consumer the value of the network if all consumers belong to it is one third of the total willingness to pay for the copyright program.

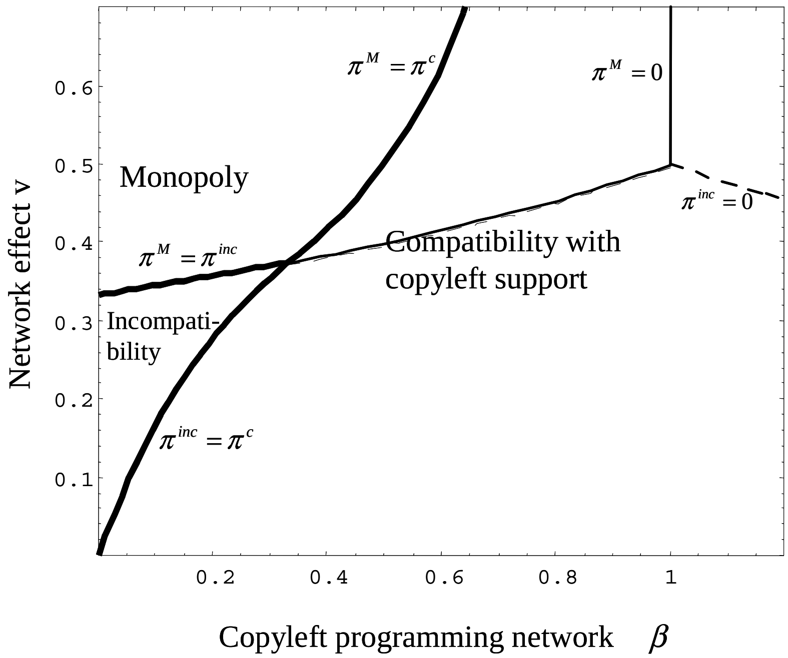

Figure 2: Regions of market outcomes

3 Welfare implications of standardization and science policy

In this section, we define the welfare measure and analyse how policy instruments affect welfare. We define the welfare measure to be the sum of firm profit and consumer surplus. We again choose $S = 0$. Furthermore, assuming that the actual number of copyleft programmers is small (even if the effective size of the copyleft network is large), we do not take into account their welfare. Then welfare when programs are compatible is

$$W^c = \pi^c + CS^c = \frac{7}{8} + (1 + \beta)v \,. \tag{8}$$

The common network including the copyleft programmers benefits all consumers. Welfare is increasing in the strength of the network effect and the size of the copyleft programmers' network. The welfare increments benefit only consumers, since the firm's profit is constant under compatibility.

When programs are incompatible and the firm does not sell to all consumers, welfare presented as a function of the fraction of consumers choosing the copyright program reads

$$W^{inc} = \pi^{inc} + CS^{inc} = \left(2v - \tfrac{1}{2}\right)\left[M_R^{inc^*}(\beta, v)\right]^2 + (1 - 2v - \beta v)M_R^{inc^*}(\beta, v) + \tfrac{1}{2} + v(1+\beta). \quad (9)$$

Under incompatibility, welfare is dependent of the industry parameters in a complicated way. The network of each program contributes to the surplus of the consumers using it. The firm's maximization of profit determines the fraction of consumers buying the copyright program dependent on the industry parameters v and β. This in turn determines the value of each network to the consumers belonging to it. Summing the firm's profit and the surpluses from basic valuations and networks of both consumer fractions yields the welfare measure.

In the case of monopoly, where the programs are incompatible and all consumers buy the copyright program, welfare is

$$W^M = \pi^M + CS^M = 1 + v. \quad (10)$$

Under monopoly, welfare is increasing in the strength of the network effect but it is independent of the effective size of copyleft programmers' network, since there are no consumers using a program compatible with the copyleft program. A change in the size of the copyleft programmers' network has only a distributive effect as it changes the firm's profit and the consumer surplus by an equal amount but in opposite directions. Note that in this scenario, the copyleft program exists only within the copyleft programmers' community.

Society has two potential instruments to influence the industry. It can create compatibility by standardization and it may increase the number of programmers in the copyleft network by directing resources to scientific activities. An industry standard can be created by subsidizing and supporting developers or by legal or administrative means. In the following we abstract from the method and its costs, assuming that they are low compared to welfare changes. We assume that the standardization decision is made before the firm decides whether to support the copyleft community. We ask: how does a standard affect welfare given the industry properties, that is, its location in (β, v)-space? First of all, if the industry is in a point where the firm would support copyleft to achieve compatibility (in the region 'Compatibility' in figure 2), standardization creates the compatibility that the firm is trying to achieve by support S and support is not needed. In the regions of 'Monopoly' and 'Incompatibility' defined in proposition 2, standardization implies that the level of welfare becomes equal to welfare under compatibility. Comparing welfare under compatibility, under monopoly and under incompatibility we find that there exist sub-regions within the 'Monopoly' and 'Incompatibility' where standardization decreases welfare. Again, we proceed by presenting the formal proposition of the welfare consequences of standardization and then discuss the results utilizing a graphical representation.

Proposition 3: Standardization affects welfare in the following way:

i. **Welfare is increased if the firm chooses incompatibility and if** $v < \dfrac{3\beta^2 + 10\beta + 3}{4\beta^2 + 16\beta + 12}$**.**

ii. **Welfare is decreased if the firm chooses incompatibility and if** $v > \dfrac{3\beta^2 + 10\beta + 3}{4\beta^2 + 16\beta + 12}$**.**

iii. **Welfare in increased if the firm chooses monopoly and if** $v > 1/(8\beta)$**.**

iv. **Welfare is decreased if the firm chooses monopoly and if** $v < 1/(8\beta)$**.**

Otherwise welfare is unaffected. With standardization, the firm never supports the copyleft community.

Proof: Under standardization, welfare is W^c from (8) regardless of industry properties. Comparing welfare in (8), (9) and (10) yields the results. The inequality $W^c < W^{inc}$ simplifies to the first result and the second result follows from the first. The inequality $W^c < W^M$ in turn simplifies to the third result and the fourth result follows from it. The aim of the support to the copyleft community is compatibility and when standardization creates the compatibility, the firm has no incentive for support. **Q.E.D**

In figure 3, we superimpose the results of proposition 3 to the regions of firm behaviour implied by proposition 2. The thin line that divides the region 'Incompatibility' denotes the first and second result and the thin line in the region 'Monopoly' denotes the third and fourth result. In figure 3, we see regions named '$W^M > W^c$' and '$W^{inc} > W^c$' where the conditions of the second and fourth result hold. There the introduction of a standard would actually decrease welfare because the decrease in the firm's profit is larger than the surplus increment to consumers from having one common network instead of two networks or one without the copyleft programmers' community.

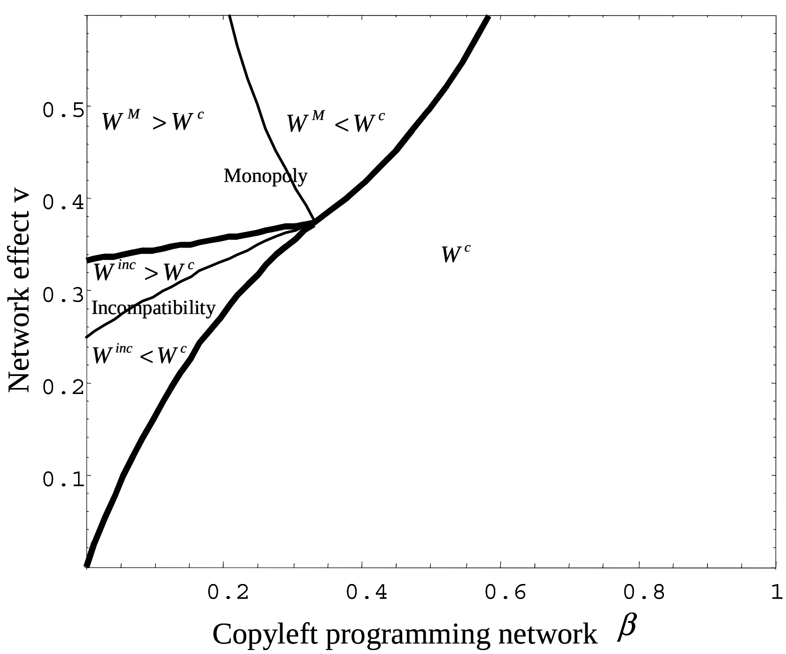

Figure 3: Welfare effects of standardization

Another policy action is to increase the size of the copyleft network by science policy measures. For example, resources for academic research on computer science could be conditional on the technical environment being a copyleft program, like Linux. This is probably done to ensure free exchange of scientific information, but the action affects the consumer market, inadvertently or by purpose because the size of the copyleft community increases. We assume that the decision is made prior to the support decision of the firm and we abstract from the costs of the resources. There is a direct effect of the copyleft programmers' network on welfare, determined by the sign of $dW/d\beta$. We next report the formal proposition and interpret it in the graphical representation.

Proposition 4: The size of the copyleft community, β, affects welfare in the following way:

i. **Welfare is increasing in β if the firm chooses compatibility by supporting copyleft.**

ii. **Welfare is increasing in β if the firm chooses incompatibility and if** $v > \frac{\left(7+3\sqrt{(-1{,}89+\beta)(-1+\beta)}-3\beta\right)}{16-8\beta}$.

iii. **Welfare is decreasing in β if the firm chooses incompatibility and if** $v < \frac{\left(7+3\sqrt{(-1{,}89+\beta)(-1+\beta)}-3\beta\right)}{16-8\beta}$.

iv. **Welfare is independent of β if the firm chooses monopoly.**

Proof: Calculating the respective partial derivatives of (8), (9) and (10). **Q.E.D**

In figure 4, we see the familiar regions of the firm's behaviour in (β, v)-space. The first result of proposition 4 is that welfare always increases in β under compatibility, '$\frac{dW^c}{d\beta} > 0$'**.** The thin line in the region of incompatibility (at the southwest corner of the figure) denotes the second and third result of proposition 4. Above this line but within the region, welfare is increasing in β, '$\frac{dW^{inc}}{d\beta} > 0$'. Below the line, it is decreasing in β, '$\frac{dW^{inc}}{d\beta} < 0$'**.** Under monopoly, welfare is unaffected, '$\frac{dW^M}{d\beta} = 0$'. Within the region of monopoly and in the sub-region '$\frac{dW^{inc}}{d\beta} < 0$'**,** a science policy action increasing the size of the copyleft programmers network is useless or even welfare reducing. An interesting indirect effect arises when the effective size of the copyleft network is increased by science policy. The industry properties change and the firm may now decide in favour of compatibility instead of incompatibility or monopoly. We can examine this effect with the help of figure 4. If the industry resides originally at point 'A', an increase in the copyleft programmers' network to 'B' reduces welfare, $W_B^{inc} < W_A^{inc}$, because the firm decides to have incompatibility in both points and welfare is decreasing in β. But if the increase is larger, up to point 'C', welfare may increase. The firm chooses now compatibility and if the increase in β is large enough, welfare is increased, $W_C^{inc} > W_A^{inc}$.

The simultaneous use of both policy instruments, standardization and science policy, can increase welfare when neither alone would. The dotted line in the region of monopoly in figure 4 denotes the third and fourth result of proposition 3. Welfare under standardization is lower than welfare under monopoly to the left of the line and higher to the right. Let us assume that the industry is at point 'D' in figure 4. By proposition 3, welfare is reduced if programs are standardized, $W_D^c < W_D^M$. Moreover, according to proposition 4, welfare remains constant if the size of the copyleft programmers' network, β, is increased to point 'E', $W_D^M = W_E^M$. The reason is that the firm still chooses monopoly and under monopoly welfare is independent of β. However, welfare increases when *both* actions are introduced. Because point 'E' is on the right side of the dotted line, welfare at that point is higher under standardization than under monopoly. A science policy action that moves the equilibrium from 'D' to 'E' together with standardization increases welfare to a level that is higher than that under monopoly at point 'D', $W_E^c > W_E^M = W_D^M$.

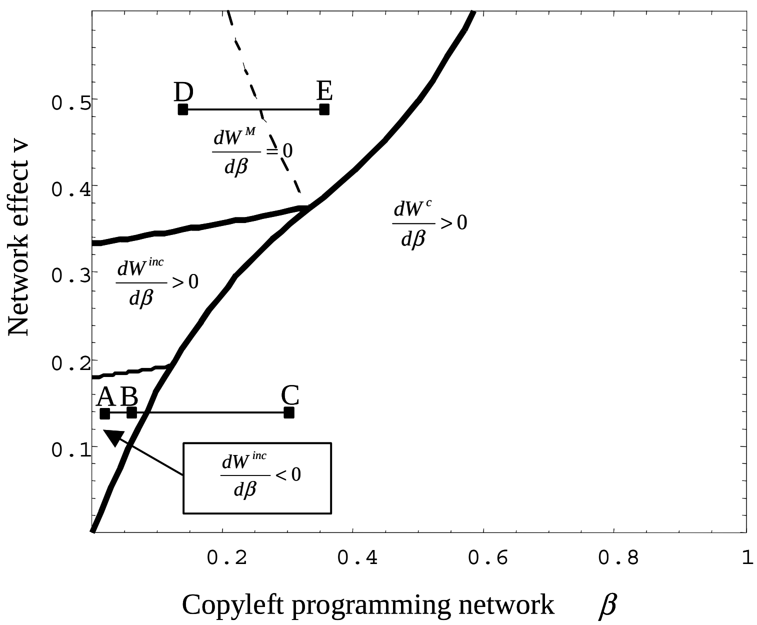

Figure 4: Welfare effects of science policy

4 Concluding remarks

A firm may be willing to expend substantial resources to support a copyleft community even if the copyleft program will compete with the firm's program. Intuitively, the crucial element is the copyleft community's contribution to the network. Support of copyleft development creates compatibility between the programs. Consumers' willingness to pay is increased with the introduction of a compatible network that includes the copyleft programmers' community. On the other hand, support is costly and more importantly, compatibility increases competition by reducing, in a sense, differentiation between programs. We determined the conditions for the firm to prefer support and thus compatibility as opposed to incompatibility. The welfare analysis showed that standardization or society's support of copyleft might have adverse welfare implications in contrast to received views.

Our analysis assumed that consumers have perfect foresight when they form their expectations. Our model facilitates the industry analysis also under alternative assumptions. In the appendix we analyse the firm's decision under stubborn expectations (Farrell and Katz 1998) i.e. where each consumer expects all other consumers to choose a certain program. The presented framework could be extended in several directions. Uncertainty in R&D and especially in the interaction between the firm and the copyleft community would raise some new questions. Programs could have implementation costs for consumers. Acknowledging them as in Mustonen (2002) would result in a richer set of outcomes because the market would not always be covered as in the present model. We assume that the copyright protection is perfect for the firm and the copyleft community[14]. Considering the degree of protection as variable would allow for a comparison to the existing copyright literature, including Landes and Posner (1989).

[14] Note that to be effective, the copyleft (GPL) license agreement requires that copyright be respected because it is based on granting the copyright to licensees.

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Appendix I: Motives of firms to support copyleft programming

Firms have several motives for interacting with and supporting copyleft communities (McMillan 2001). The co-operation may increase knowledge spillovers from the copyleft community, which often has scientific affiliations (Rosenberg 1990). The copyleft community may also act as a test environment for complex new algorithms. The incentives of copyleft programmers are directed towards signaling skills. Testing and subsequent corrections provide opportunities for skill signaling (Mustonen 2002). Parallel to co-operation with education institutions, firms also interact with copyleft communities to identify potential employees. These motives seem to coincide with the motives cited for firms engaging in basic research (Cassiman, Perez-Castrillo and Veugelers, 2002) [15].

With complementary programs, a motive for investing in a copyleft development project may arise. Though there can be no direct profit from the copyleft program to the copyright firm, its existence may directly or indirectly increase total profits. The direct effect means that when consumers acquire the free copyleft program it increases the demand for the proprietary copyright program. If the copyleft program changes the market structure of the complementary good market and thus increases consumer valuations in the market of the proprietary good, the effect is indirect. Openoffice is an open source software development project based on the office software package Staroffice developed by Sun Microsystems (Collab.net 2001). An important motive for Sun to invest in the project facilities and code development seems to be that this program is complementary to the main (and proprietary) programs and products of Sun Microsystems, namely hardware and system software (McMillan 2001). An example of indirect effect is the model of Parker and Van Alstyne (2000). They considered a firm acting on two markets. A firm sells a basic good at a consumer and a content-creator (like music) market. The use of the basic good by consumers requires that a complementary good provided by the content-creators is compatible with it. This happens when the content-creators consume the same basic good and use it in their production. The consumers' utility thus increases the more the basic good is consumed in another market. Parker and Van Alstyne called this a cross-market externality. They showed that when a good exhibits such externalities, it can be profitable for the firm to invest in its development and give it away for free, for example by copylefting, in either market. A strategic motive arises in the model of Kende (1998). He considered a monopolist selling a system good consisting of a main component and differentiated complement secondary components. He analyzed the conditions under which the monopolist finds it profitable to open the system. Opening implies that he provides the secondary good at zero-profit price and allows free entry to that market. Although Kende did not address copyleft activity explicitly, in the case of software this can be accomplished by copylefting the secondary good. Copylefting research and development results and/or program code can act as an entry deterrence device for an incumbent monopolist. Subramanian (2000) presented a model where the incumbent can copyleft code by licensing it for free. This induces further development activity, which in turn increases

[15] One element of the costs of support of copyleft activity is increased control cost in program development: Pieces of program code licensed with GPL 'contaminate' other parts of programs so the firm may lose the property rights to them. This 'contamination' may happen accidentally or by purpose (GNU 2000b).

the quality of the incumbent's program. The entrant can act in a similar way. The incumbent is assumed to have an installed base of users while the entrant's program does not have users. Subramanian showed that copylefting is an optimal strategy for the incumbent when entry is deterred or accommodated and the programs exhibit network effects. Microsoft's strategy of distributing its web browser, Internet Explorer, free of charge could be explained in these terms.

Appendix II: Demand for copyright and copyleft programs when consumers' tastes differ

In the paper we assume that the ratio of valuations of programs is equal to all consumers. An interpretation of this property is that both programs have similar functions but that the quality of all functions of the copyright program is higher or there is less uncertainty about the quality of the copyright program. This may be the case when all consumers have similar tasks to perform using the program, for example an office software package (A copyleft package like Openoffice versus a copyright package like Microsoft Office). However, another quality dimension of programs is their suitability to a certain task. One word processing program might perform well for text input, another well for creating output. This implies that consumers with different tasks to perform have different valuations of the programs. In the following we provide a sketch of modeling such a consumer market. Let us assume that consumers are evenly spread on the interval $[0,1]$. The consumer at 0 has basic valuation A of the copyright program R and the consumer at 1 values the copyleft program L to αA. Assuming linear taste, the consumer at x values R to $A - tx$ and L to $\alpha A - (1-x)t$. With this specification, assuming that the market is covered, the indifferent consumer at x determines the market outcome at price p. When programs are compatible, it holds for the indifferent consumer:

$$A - p - tx + v(1+\beta) = \alpha A - t(1-x) + v(1+\beta)$$

When programs are incompatible the indifference condition reads:

$$A - p - tx + vx = \alpha A - t(1-x) + v(1-x+\beta)$$

The conditions remind the indifference condition of the Hotelling model of horizontal differentiation. We can solve the profit of the firm in each case. Depending on the parameters, this specification allows for the maximum valuation of the copyleft program to be higher than that of the copyright program, that is, $\alpha > 1$. The specification has similarities with the model of Gayer and Shy (2001), where the consumers differ in another dimension.

Appendix III: Stubborn expectations

Instead of the assumption of perfect foresight we can make other assumptions concerning expectations. Farrell and Katz (1998) suggest that expectations can be stubborn. In our model, such expectations could prevail if each consumer expects all other consumers to choose the copyleft program regardless of industry properties. In the following, we outline the firm's decisions under stubborn expectations. Under compatibility, expectations on how consumers choose between programs do not affect the outcome. The firm's profit is the same as in section 2.1, $\pi^c = \frac{1}{4} - S$. Under incompatibility, we can apply the analysis in section 2.2. The marginal consumer m is indifferent between the copyright program without any expected network and the copyleft program with an expected network of all consumers and copyleft programmers, $V_{Rm} - p = V_{Lm} + v(1+\beta)$. Consumers that have a higher valuation than V_{Rm} buy the copyright program. We solve for the fraction of consumers buying the copyright program as a function of the price and maximize profits like in section 2.2. This yields the optimal price, which is the same as in the case of perfect foresight, $p^s = p^{inc} = \frac{1-v(1+\beta)}{2}$. The fraction of consumers buying the copyright program is, however, different, $M_R^{s*} = \frac{1-3v(1+\beta)}{2}$. The firm's profit is thus $\pi^s = \frac{(1-v(1+\beta))(1-3v(1+\beta))}{4}$. We can compare this profit to the profit under compatibility. In contrast to the results of section 2.3, the firm never chooses incompatibility if compatibility is free, $S = 0$, under stubborn expectations. For $0 < S < \frac{1}{4}$, if the cost of compatibility is high and the network effect is weak, incompatibility may yield a larger profit. An example: Let the support cost of achieving compatibility be $S = 0{,}08$ and the strength of the network effect $v = 0{,}1$. The profit under incompatibility is larger, $\pi^s > \pi^c$, when $\beta < 0{,}22$. In the case of perfect foresight in section 2.3, the profit under incompatibility is larger if $\beta < 2{,}4$ for these industry parameters. In this example, the firm finds it profitable to support a much smaller copyleft programmers' community to achieve compatibility under stubborn expectations than under perfect foresight.

EURAS Yearbook of Standardization, vol. 3, ed. by Manfred J. Holler and Esko Niskanen (Homo Oeconomicus XVII(3), Munich 2000), pp. 303-315.

Essay 3: Strategic R&D investment in future compatibility[♠]

Mikko Mustonen[*]

The future compatibility of a product can be important to a buyer. With IT products, switching costs may in the worst cases well exceed the purchasing price. We develop a model in which rational buyers value products by their expected levels of future compatibility, using suppliers' R&D budget levels as signals. Suppliers compete by investing in R&D to increase compatibility. In all the analysed market scenarios R&D investment levels fall short of the social optimum. Welfare closest to optimum is reached when suppliers collude in R&D but compete in product markets.

1 Introduction

Why did the sales volume of a computer family (such as DEC VAX, HP 3000) go down when the supplier announced 'stabilization' or 'refocusing' of its development effort? Even when prices were heavily cut?[1]

Products can have compatibility between each other ('horizontal') or within one supplier's product generations ('vertical'). In computer markets 'vertical' compatibility is present on hardware, middleware (support software) and application level. Conventional analysis of compatibility usually concentrates on the 'horizontal' (for a survey, see Perrot (1993)) but the latter, 'vertical' compatibility may be an important factor for buyers. An example of 'vertical' compatibility can be found in

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1 For market response to development effort changes on HP 3000 family, see Moad (1990).

core information systems of large organisations ('mainframes'). Buyers of system components consider the expected support to their present application software base. They also value the product for its future compatibility and have to take into account the possibility of non-compatibility.

Greenstein (1993) researched US government mainframe computer purchases. Government bidding rules mandate the assessment of conversion costs for new non-compatible systems. According to his empirical findings, such costs are a significant factor in system selection "to the extent that buyers are anticipating the problems associated with future purchases" (p.22 footnote). The Intel microprocessor is an example on the hardware level. To be competitive, the new generation of chips (like 486 after 386) also has to support the instruction set of the previous product because buyers are not willing to change their operating environment or applications simultaneously with a hardware upgrade. Buyers of components for networks (Internet, cellular networks) have to consider similar product aspects. On the software level, a simple example is spreadsheet applications. They contain user data and if there is no compatible future product, users have to do the conversion, even to the extent of retyping to insert the data into the new environment[2]. A common element in these examples is the differing length or timing of the life-spans of system components. In a mainframe environment, the typical life-time of a hardware component is 1-5 years, but application software is used for 5-30 years.

Buyers' expectations of future compatibility are formed on the markets. Traditional signals of this aspect of quality might include the price of the product, advertising and warranties (Tirole 1988, p.106-115). Let us assume here that the level of research and development a supplier undertakes is viewed as a signal of a product's future 'vertical' compatibility. Rational buyers base their assessment on suppliers' perceived business decisions. Casual empirism suggests that suppliers openly publicise, even promote the general levels and growth rates of their R&D budgets. As far as hardware and supporting software (middleware) are concerned, it is known that a major part of the development effort is directed towards maintaining compatibility of interfaces

[2] Shapiro and Varian (1999, chapter 5) provide an overview of various sources of switching costs in IT environment.

with other components while taking advantage of some new innovations in electronics.

The notion that suppliers use their R&D budgets to signal the quality of products has been noticed in the literature. Salonen (1989) used a signaling model to analyse a monopoly, which can influence the quality of the product by making R&D investments. He shows that making such investments common knowledge increases buyer utility and firm profits. There is also empirical evidence of firm R&D investment acting as a buyer signal: Lichtenberg (1988) studied US government procurements and found that firms used their private R&D spending as a signal of competitiveness which was actually taken into account when assessing their capabilities. These observations imply that R&D budgets serve multiple purposes. Traditionally, R&D investment is modelled to reduce unit costs of production. Our paper, like Salonen (1989), however departs from this traditional mechanism in that it does not analyse innovation from the perspective of cost-reducing instruments but rather focuses on the signalling role of R&D. Multiple roles of R&D investment suggest that buyers face a signal extraction problem i.e. seeing the R&D budget, they have to assess how it is divided between, for example, compatibility enhancement and unit cost reduction.

We develop a model where firms undertake R&D investments and buyers form expectations of future costs. The model of the paper is in terms of a sequential game played in two stages. In first stage, suppliers commit to R&D investments enhancing vertical compatibility in future knowing both the structure of the game in output stage and how buyers behave. Buyers form expectations about future switching costs. The known R&D investment costs are taken to be informative about future costs. In the second stage, buyers act to maximise their expected surplus and suppliers produce outputs maximising profits. The cost expectations of buyers are realized in the future.

The equilibrium of the game satisfies the condition of subgame perfection for suppliers and represents a rational expectation’s equilibrium for the buyers. We calculate optimal equilibrium values for R&D investment levels and produced quantities in three market scenarios: (i) Cournot equilibrium. Suppliers engage in a Cournot game both in setting R&D investment levels and in production; (ii) collusion in R&D and output. Suppliers act as a joint monopoly and (iii) an R&D cartel. Suppliers engage in the Cournot game in output stage but collude when setting R&D levels[3].

Models of vertical product differentiation with fixed costs of quality (eg. Motta 1993, Beath and Katsoulacos 1991 p. 113-) focus on similar issues, but buyer valuation is based on tastes. Swann (1986) researched 'quality innovation' which "can be analyzed within an existing space of qualities and characteristics" (p.2). He then analysed quality innovations in computer systems' (speed, power consumption, etc.). Here we assume that such properties are included in the buyer's basic willingness to pay. The quality aspect in our analysis is an external future cost. Wey (1999) analysed 'R&D output spillovers' resulting from R&D investment. In his model, R&D that was directed to developing the supplier's niche product also enhanced the competitor's mass-market product's compatibility and market position. Our analysis takes another approach: R&D investment is used in a strategic fashion and influences market conditions through rational buyer expectations.

The model is an extension of the analysis of product lock-in and switching costs related to compatibility. Contrary to the conventional approach[4], we assume that rational buyers accept the prospect of a lock-in because their system environment has other components with longer life spans. Theoretically, we extend the Brander-Spencer framework of strategic R&D investment (1983) by modelling the effect of R&D directly on the supplier output game. In the Brander-Spencer model, firms commit to R&D investments to reduce their own unit costs. We introduce a signalling mechanism, based on some empirical support, for buyers to form expectations on compatibility. We then analyse the welfare aspects of different market scenarios.

A comparison of market scenarios reveals that optimal levels of R&D investment are closest to the social optimum in a Cournot equilibrium scenario, followed by collusion in R&D and output, with the R&D cartel as the last. For produced quantities the order is: Cournot, the R&D cartel and collusion. As welfare measure we use total

[3] Suppliers compete in quantities, because the prime focus is on hardware products that exhibit rising marginal costs and component subcontracting, to which suppliers have to commit.
[4] See Shapiro and Varian (1999), chapters 5 and 6.

surplus, i.e., industry profits with consumer surplus added. The welfare level is highest with the R&D cartel, followed by Cournot and collusion scenarios.

Since all the scenarios fall short of social optimum, there are opportunities for policy action. R&D or production subsidies can be used to correct market failures. Allowing or encouraging co-operation between suppliers in setting R&D investments increases welfare while presumably incurring low costs. However, for buyers, co-operation results in a reduced level of future compatibility.

The structure of this paper is as follows: we present the model in chapter 2. In chapter 3 we solve it under competitive, collusion and R&D cartel market conditions. Welfare measures are developed in chapter 4. We compare optimal R&D investments, outputs and resulting welfare for market scenarios in chapter 5. Chapter 6 concludes the paper.

We believe our approach can be applied to products other than those related to information industry. For example, buyers of toxic products or complex systems (such as aeroplanes) could similarly take into account disposal and switching costs.

2 The model

We analyse future compatibility in a partial equilibrium industry setting with two suppliers and numerous identical buyers. The two goods are perfect substitutes so that the willingness to pay among the different buyers is equal ex ante. Since there are differences in expected net switching costs between current and future vintages of products, the market prices, of course, will be different. The equivalence of hedonic prices describes the market equilibrium. Although buyers are indifferent between products ex ante, after commitment to a product they face high costs ex post if they switch to a competing product. Products are not substitutable ex post.

Suppose supplier decides on R&D investment level x, incurring quadratic costs, $c = \frac{1}{2} v x^2$. This investment is used to develop better compatibility between current and following generations of his own product (for example in computers, how much of the present application software base will function in a future environment). Let market valuation of this investment cost as increased compatibility be $s(c)$, $s' > 0$.

Let the switching cost L (software conversion, education, etc) to a non-compatible system environment (from the same or another supplier) be constrained by $0 < L < 1$[5]. Buyers take this into account when valuing the product. They see R&D investment in compatibility as correcting this expected future cost. Subtracting the compatibility benefit from the maximum switching cost gives the buyer's expected net future cost D^e:

$$D^e = L - s(c) \tag{1}$$

All buyers form expectations prior to purchase since the levels of committed R&D budgets are public. The net cost may also be negative, implying that the R&D investment is expected to enlarge the product's compatibility. (For example it allows the use of some application software that was not previously possible).

Let us assume that all products have the same life-span and that all buyers have to purchase products of the following generation at the same time. This is consistent with many information technology products. (Supplier support and service for old products is limited, horizontal compatibility with complementary products decreases with time.) Following Katz and Shapiro (1985) we can now formulate the industry demand in the presence of expected externalities. We assume that buyers have a willingness to pay for the homogeneous products

$$r - D^e \tag{2}$$

[5] L could be larger than 1 (which in this model corresponds to market size), but this requires treatment of parameter restrictions and adds little to the analysis.

where r is evenly distributed on the interval $[0,1]$. Each buyer has the same expectation of maximum switching cost L and the same valuation of supplier i's R&D investment cost to reduce switching cost, $s(c_i)$. Buyers thus maximise their surplus

$$r - D^e - p \tag{3}$$

The hedonic price (price + expected costs) must be equal for all products ($i \neq j$) that enter the market. Let this common value be ϕ.

$$\phi = p_i + D_i^e = p_j + D_j^e \tag{4}$$

For a given value of ϕ, only those buyers whose $r \geq \phi$ buy the products. Each buyer buys one unit of the product and r is evenly distributed, so the total quantity sold is

$$Q = 1 - \phi = 1 - p - D^e \tag{5}$$

We assume, as Katz and Shapiro did, a fulfilled expectations equilibrium: these expectations are realized in the future.

Consider a duopoly (suppliers 1,2) producing homogeneous (besides expected future compatibility) products for this market. Then from (1) and (5) and noting that $Q = q_1 + q_2$, for supplier 1 (supplier 2 is symmetric):

$$p_1 = 1 - q_1 - q_2 - (L - s(c_1)) \tag{6}$$

In this simple(st) model we assume that the buyers' valuation of the R&D investment is rational and that its effect on compatibility is linear:

$$s(c_1) = s\sqrt{\frac{2}{v_1}c_1} = sx_1,\ s > 0 \tag{7}$$

To bring out the novel effect, we assume that the unit cost of production is zero for both suppliers and that R&D is completely directed to compatibility enhancement. The profit of supplier 1 (supplier 2 is identical) is then:

$$\pi_1 = \left(1 - q_1 - q_2 - \left(L - sx_1\right)\right)q_1 - \frac{v_1}{2}x_1^2 \quad (8)$$

R&D investment affects profits in three ways: (i) through outputs and a net switching cost that affect the price, (ii) through supplier's own output and (iii) through supplier's own compatibility costs.

3 Solving the model

Following Brander and Spencer (1983), we solve the game backwards, first the output stage and then the strategic R&D investment stage. The mathematical treatment of the model has similarities with the model of d'Aspremont and Jacquemin (1988).

3.1 Cournot equilibrium

Suppliers are competing in the output and R&D investment stages. We assume a symmetric setup: suppliers have identical cost structures $v_1 = v_2 = v$ for R&D investments. Suppliers' profit functions, conditional on R&D investments are given in (8). The corresponding symmetric Nash-Cournot equilibrium in the output phase is:

$$q_1^* = \frac{1 - L + 2sx_1 - sx_2}{3} \qquad \text{(similar for supplier 2)} \quad (9)$$

Inserting (9) into (8) we can now express supplier profit as a function of R&D investments:

$$\pi_1^* = \frac{1}{9}(1 - L + 2sx_1 - sx_2)^2 - \frac{v}{2}x_1^2 \qquad \text{(similar for supplier 2)} \tag{10}$$

In the R&D stage suppliers make decisions maximising (10) with respect to R&D investments. The symmetric Nash-Cournot equilibrium solution satisfying[6] maximization is:

$$x_1^* = \frac{4s(1-L)}{9v - 4s^2} \tag{11}$$

This level of R&D investment is the supplier 1's best response to the rival's equilibrium action x_2^*, both knowing the demand effect that R&D has on the output stage.

3.2 Collusion in R&D investment and output

We assume that suppliers can collude to set R&D investments and output levels as a joint monopoly, and that their commitment to collusion is credible. Assuming (as above) a symmetric solution, the joint profit function is

$$\Pi = 2(1 - 2q - (L - sx))q - vx^2 \tag{12}$$

Maximising profit with regard to output gives

$$q = \frac{1 - L + sx}{4} \tag{13}$$

inserting (13) to (12) yields the joint profit as a function of the collusive R&D investment:

[6] The stability and second order conditions in all scenarios except welfare with loss (WL) are satisfied with $v > \frac{8}{9}s^2$.

$$\Pi = \frac{1}{4}(1 - L + sx)^2 - vx^2 \tag{14}$$

maximising (14) for optimal R&D investment levels for colluding suppliers gives:

$$x^C = \frac{s(1-L)}{4v - s^2} \tag{15}$$

3.3 R&D cartel

We assume that suppliers compete on the product market but can or are allowed to decide jointly on R&D investments. Again, we assume that credible commitments exist with respect to R&D investments. In this model we assume that there is no R&D information exchange within the R&D cartel. We believe this assumption is consistent with information technology products. Products that appear similar to the buyer may internally be quite different and the development of own compatibility benefits little from the exchange of R&D information. Suppliers' joint profit as a function of R&D investments is from (10):

$$\Pi^{RDC} = 2\frac{1}{9}(1 - (L - sx))^2 - vx^2 \tag{16}$$

Maximising this gives

$$x^{RDC} = \frac{2s(1-L)}{9v - 2s^2} \tag{17}$$

4 Welfare maximisation

We define the welfare measure as the sum of supplier profits and buyers' surplus. With the linear inverse demand schedule, consumer surplus is

$$C = \frac{1}{2} 2q2q = 2q^2 \tag{18}$$

Adding this to profits (12) gives the following social welfare function:

$$W = 2(1 - q - (L - sx))q - vx^2 \tag{19}$$

Welfare-maximising output is then:

$$q^w = \frac{1 - (L - sx)}{2} \tag{20}$$

inserting this into (19) gives welfare as a function of R&D investments, the maximum of which is the socially optimal level of R&D investment:

$$x^W = \frac{s(1 - L)}{2v - s^2} \tag{21}$$

5 Analysis of scenario outcomes

Table 1 summarises the results we have derived so far.

	R&D investment	Quantity produced
Competitive '*'	$x_1^* = \frac{4s(1-L)}{9v-4s^2}$	$q_1^* = \frac{3v(1-L)}{9v-4s^2}$
Collusion 'C'	$x^C = \frac{s(1-L)}{4v-s^2}$	$q^C = \frac{v(1-L)}{4v-s^2}$
R&D cartel 'RDC'	$x^{RDC} = \frac{2s(1-L)}{9v-2s^2}$	$q^{RDC} = \frac{3v(1-L)}{9v-2s^2}$
Welfare optimum 'W'	$x^W = \frac{s(1-L)}{2v-s^2}$	$q^W = \frac{v(1-L)}{2v-s^2}$

Table 1: Optimal R&D investments and corresponding output quantities for market scenarios.

5.1 R&D investments and produced quantities

We compare the optimal values R&D investments and output quantities in each scenario.

Proposition A.1: Optimal R&D investment levels in each scenario satisfy the following condition:

$$x^W > x^* > x^C > x^{RDC}$$

Proof: comparing R&D investments in Table 1**.** Q.E.D.

In the Cournot equilibrium scenario, even if suppliers commit to large R&D investments for strategic reasons, the level falls short of welfare optimum. In the

R&D cartel scenario the R&D investment level is even lower than in the collusion in R&D and output scenario. The net switching cost loss to buyers is inversely related to R&D investment levels so it is lowest at the social optimum.

Proposition A.2: Optimal output quantities in each scenario satisfy the following condition:

$$q^W > q^* > q^{RDC} > q^C$$

Proof: again comparing quantities in table 1. Q.E.D.

The output in the Cournot equilibrium scenario is nearest to welfare optimum. As can be expected collusion in R&D and output results in the lowest output. In our model buyers' surplus is an increasing function of produced quantities (18). The order of the above condition also holds for surplus.

The intuition of propositions A.1 and A.2 is the following. Cartel in the R&D stage relieves the suppliers from competing in strategic fashion with R&D investments. The resulting optimal level of R&D investment is lower than in Cournot competition because in that suppliers over-invest in R&D for strategic reasons. However, the R&D cartel members engage in Cournot competition in the output stage. R&D investment in our model has a demand-shifting effect and in anticipation of Cournot competition the optimal R&D investment level for cartel is even lower than that for collusive suppliers. As a consequence of the Cournot competition the optimal produced quantities are higher for cartel members than for collusive suppliers.

5.2 Welfare analysis

Proposition B.1: Welfare measures (19) calculated with optimal R&D investment and output levels of each scenario satisfy the following ordering:

$$W^W > W^{RDC} > W^* > W^C$$

Proof: see Appendix.

The R&D cartel scenario comes closest to welfare optimum. Compared to the Cournot equilibrium scenario, joint decisions on R&D investments decrease buyers' surplus via lower output and increase net switching costs since the R&D investment level is lower. This is more than compensated by higher profits due to lesser duplication of R&D effort. Collusion in R&D and output results in the lowest welfare level.

5.3 Implications for policy

In all market scenarios R&D investment levels and produced quantities are lower than in the social optimum. This implies that there is room for correcting government action. Subsidies for either or both R&D investment and production, committed by a credible policymaker, can correct the market failure. The final benefit of the subsidies depends on their financing. The analysis of a technically similar model by Hinloopen (1997) suggests that R&D subsidies financed by taxing the industry suppliers at the output stage result in a net welfare increase. Welfare is highest in the R&D cartel scenario. The fact that suppliers' profits are higher than in Cournot competition is an incentive to form the cartel. The policymaker's action allowing or even encouraging co-operation in setting R&D investment levels increases welfare at presumably low costs. A potential negative effect of this action arises from the fact that suppliers have an incentive to extend this co-operation to other areas (Martin 1995), such as production, and this may be detrimental to welfare. In our model this incentive is present as profits are higher for collusive suppliers than for R&D cartel members.

Comparison of allowing an R&D cartel and subsidisation as policy options reveals a distinct difference: the R&D cartel results in higher net switching costs and as a consequence, there is more discontinuity in the buyer's environment (software conversion, education, etc.). If buyers have an influence on the policy setting or if the policy maker assesses discontinuity as unwanted 'lack of standardisation', there may be a bias towards subsidies.

6 Discussion

We have developed and analysed a partial equilibrium analysis model that seeks to explain issues concerning compatibility. Buyers form expectations about the future compatibility of products by assessing public information on the suppliers' R&D budgets. A buyer's willingness to pay for a product is adjusted taking into account expected future costs of imperfect compatibility.

The two suppliers compete on the product market knowing the effect their committed R&D investments have on buyers' willingness to pay and thus on market shares. When they commit to R&D budgets in order to enhance compatibility they take market responses into account. Optimal R&D investment levels and outputs are lower than social optimum regardless of market conditions. Even strategic (over) investment in R&D falls short of the social optimum. Welfare, measured as total surplus, is nearest to social optimum when suppliers, on one hand, collude in setting R&D investments and on the other hand compete in product markets.

There seem to be several interesting areas of further research. First, the concept of signalling begs further study. Future analysis will focus on existence and conditions for pooling and separating equilibria. Second, modelling expected future ('vertical') compatibility has a lot in common with network externalities (that can be described as 'horizontal' compatibility). This points to the value of analysing the interaction between them, perhaps in the form of optimal R&D budget allocation. Third, letting suppliers compete on prices and analysing incentives for product compatibility differentiation can be expected to reveal properties that correspond to software markets. Finally, cost and information asymmetries and asymmetric government action in a trade setting provide avenues for further research.

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Appendix

Proof of proposition B.1. Inserting respective values of R&D investment and output into welfare function (19) and subtracting yields:

$$W\left(x^{RDC}, q^{RDC}\right) - W\left(x^{*}, q^{*}\right) = \frac{\left(3v + 2s^2\right)\left(12(1-L)sv\right)^2}{\left(9v - 4s^2\right)^2\left(9v - 2s^2\right)^2} > 0$$

since all the terms are positive.

$$W\left(x^{*}, q^{*}\right) - W\left(x^{C}, q^{C}\right) = \frac{\left(90v^2 - 31vs^2 - 4s^4\right)\left((1-L)v\right)^2}{\left(9v - 4s^2\right)^2\left(4v - s^2\right)^2} > 0$$

The first nominator term is positive when $v > \frac{8}{9}s^2, v < -\frac{1}{5}s^2$. Our model restricts $v > \frac{8}{9}s^2$ so all the terms are positive.

Essay 4: Signalling unobservable cost with investment in vertical compatibility ♠

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When buyers value products in terms of the expected compatibility between the current and the new vintage, firms can invest strategically to control for the switching costs. Their open announcements of R&D budgets transmit information in two ways. First, the announcements determine the buyers' beliefs of the compatibility. Second, as only an efficient firm finds it optimal to have a large R&D-budget, a firm can signal its private information of its production cost to the uninformed rival. The paper proves that the likely outcome is a unique separating equilibrium if the R&D cost is low but the uncertainty of the rival's production cost large. With high R&D cost, the dominating motive for strategic announcements is to affect the rival's cost belief.

Keywords: *Vertical compatibility; R&D; Cost signalling*

JEL Classifications: *L15, D82, L13*

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1 Introduction

Looking back, IBM invested a great deal in the late 1960s to create the first computer architecture, called S/360, with vertical compatibility between product vintages and then to maintain that property. Vertical compatibility was non-existent in competitors' products and was expensive to develop[1]. In this paper, we suggest that a motive for announcing R&D budget plans is to influence the expectations of buyers and the beliefs of competitors. Buyers of information technology (IT) equipment are known to value the compatibility between product vintages to secure complementary investments in, for example, application software. We suggest that the level of R&D a firm undertakes is informative of the current product's future vertical compatibility and influences buyers' perceptions[2].

One of the characteristics of strategic behaviour of firms in the IT industry is the early announcement of product development projects. Firms communicate their R&D budgets to the market even if knowledge spillovers and the advantage of a surprise would suggest secrecy[3]. In an oligopolistic industry, firms can thus use R&D budgets as strategic instruments. In principle, products can have horizontal compatibility between each other[4] or vertical compatibility between one firm's product generations[5] (Wiese 1997). Core information systems of large organisations (mainframes) provide an example of the latter. What matters for the buyers of system components is the expected support of their current application software base. They also evaluate the products in terms of their expected future compatibility (Greenstein 1993). If the expected future compatibility is low, buyers expect high future switching costs when changing to the new vintage of the product. These costs can be significant. Greenstein (1997) found that the cost of switching the supplier of a mainframe system amounted up to 250 percent of system hardware price. The more efficient a firm is in

[1] For the history of System/360, see IBM 360/370/3090/390 (2002) and Pugh (1984).
[2] Moad (1990) provided a description of buyers' responses to Hewlett-Packard's reduced investment in the vertical compatibility of the HP 3000 system.
[3] See Bayus, Jain and Rao (2001) for examples of such behaviour and further references.
[4] See Perrot (1993) for a survey of horizontal compatibility analysis.
[5] In computer markets, for example, vertical compatibility can be found on the hardware, middleware (support software) or application level. See Mustonen (2000) for welfare aspects of vertical compatibility.

production, the larger is its optimal R&D budget[6]. The reason is that efficiency in output production allows the firm to take better advantage of the buyers' increased willingness to pay. Besides influencing buyers, the R&D budget in compatibility has a further role: since the firm's true efficiency and R&D budget are inversely correlated, the competitor considers the R&D budget as a useful signal when it infers the firm's efficiency in production. Thus, the R&D budget represents a credible, costly signal of private cost information.

In our model the informed firm, say *I*, has private information of its marginal cost. It uses the total cost of the R&D investment to signal its marginal cost to its uninformed competitor, firm *U*. Firms control the vertical compatibility between own product vintages through their R&D policy. In a separating equilibrium, firm *U* updates its belief of the production cost of firm *I* to match the true cost but in a pure pooling equilibrium, no information is revealed. We explore the impact of private information on the R&D plan and thus on the compatibility of product vintages. We develop conditions for information revealing behaviour in terms of the cost of an R&D plan. The model can be viewed as a two-player signalling game with continuum of types. The signalling game is nested in a game of strategic commitments to R&D investments. A contribution of the paper is the introduction of a signalling game with a continuum of types where the outcome of the game is fundamentally dependent on the cost of creating the signal. The cost of R&D can be high or low relative to its impact on revenue[7]. Firms commit themselves to R&D investments at the first stage, enhancing vertical compatibility between current and future vintages. They anticipate the behaviour of product markets. R&D investments become common knowledge at the end of first stage both to buyers and firms. Firm *I* with private information uses its R&D investment as a signal to influence the competitor's belief of his production

[6] Firms might differ also in their efficiency in R&D. Private information on R&D cost creates a signal extraction problem for buyers and the rival, as the observable R&D budget is then a product of the private information and the signal. An optimal strategy for a firm with private information might be not to announce the R&D budget and perhaps choose another signalling device. We abstract from such uncertainty and concentrate on interaction between signalling with announced R&D budgets and the cost of R&D.

[7] In Spence's (1974) original signalling model, an extension like ours would be analoguos to a scenario where the disutility of an education level, which is the signal of productivity, is small or large relative to the wage. In a labour market setting, such differences could arise from industry differences in revenue per labour input. This view would require relaxing Spence's assumption of perfect competition between firms. Aoki and Reitman (1992) analysed an R&D signalling game with discrete types of firms with a variable cost of creating the signal.

cost. At the second stage, buyers act so as to maximise their expected surplus and firms produce profit-maximising outputs. The buyers' expectations of the switching costs are realised. The equilibrium of the game is a perfect Bayesian equilibrium for firms and represents a rational expectations equilibrium for the buyers. Firm *I* has private information on its cost while the cost of firm *U* is public knowledge. In the industry of our interest, Information Technology, IT, this asymmetry often arises, as some firms have integrated supply chains with private price information while others in the same market rely on independent component producers that post prices[8]. Moreover, in an evolving industry firms may differ in their ability to analyse competitors[9].

We prove that the game satisfies Mailath's (1987) conditions for the existence of a unique separating signalling equilibrium, i.e. (i) type monotonicity, (ii) belief monotonicity and (iii) single crossing. We show that in separating equilibrium, due to the signalling incentive, the R&D investment is larger than under revealed information. For an R&D strategy that is linear in true cost, the relative role of signalling is increasing in the cost of R&D and for a high cost its role is dominating. We also show that when the cost of R&D investment is low or the support of the cost distribution is large, the separating equilibrium is the likely outcome. In particular, if firm *I* can credibly reveal its cost information, it prefers revelation at the R&D stage to revelation at the output stage.

We use our results to assess qualitatively the industry development in a dynamic setting. Suppose there is an exogenous reduction in the cost of R&D of developing vertical compatibility. Our results then indicate that firms may switch from a pooling strategy to a separating strategy. This results in shifts in market shares and also in increased vertical compatibility between the product vintages of firm *I*.

We focus on the product development role of R&D. According to Rosenkranz (1996), R&D is in practice split roughly 60/40 between process (cost-reducing) and product innovations. The distinction between the two can be blurred. In terms of the

[8] Choi (1998) makes a similar argument for asymmetric information.

[9] We assume that firms communicate their investments truthfully. Bayus et al. (2001) analysed a signalling game where firms may make intentional false announcements, called 'vaporware'.

definitions of Levin and Reiss (1988), the profit functions in the cases of process and product innovation are similar by structure in the absence of spillovers. In our analysis, the industry properties motivate the analysis of product innovation. First, the marginal cost of a final IT product depends largely on the marginal costs of components. An innovation in the component industries, whether public or secret, may or may not lead to a lower cost of the final product. This depends on, for example, the technology of the final product. Thus, there may be inter-firm differences in the marginal costs of firms and they can be private information. However, with R&D, firms can increase the quality, in our case compatibility, of their products. Second, signalling an already low cost with a large investment to lower it further is likely to be less efficient than signalling by increasing demand, so firms are more likely to choose product innovation as the signalling device. We extend the seminal framework of Brander and Spencer (1983) of strategic R&D investment by incorporating the effect of R&D on the buyers' valuation instead of cost reduction. Firms undertake R&D investments to enhance the vertical compatibility of their products and buyers form expectations about future switching costs. In IT industries, R&D is relevant information, as a major part of the development effort is directed towards maintaining the compatibility of interfaces to other system components so that firms can take advantage of available new innovations in electronics and underlying algorithms. From this perspective, our model is an extension to papers that analyse the product lock-in and switching costs related to compatibility. Shapiro and Varian (1999) discussed how buyers recognize and manage the lock-in. In their view, firms try to develop and market their products in such a manner that buyers find themselves to be locked-in. The idea of firms signalling their marginal cost dates back to the seminal paper by Milgrom and Roberts (1982), developed further by Srinivasan (1991). Our approach differs from those as we focus on a stable market structure instead of entry deterrence. In the industrial organization literature, the notion of an R&D investment as a signal has been analysed but from a different perspective. Yet, parallel to our analysis, Aoki and Reitman (1992) analysed signalling with R&D with the aim of influencing competitor's cost beliefs. In their model, the signals are, however, simultaneous discrete investment decisions on cost-reducing R&D. Like in our model, a firm can have a low or a high marginal cost and firms compete in Cournot-Nash fashion at the output stage. A substantial range of investment costs is irrelevant for the low-cost firm because it is assumed that the investment cannot reduce the low cost further and acts only as a signal of low cost. A high-cost firm can find it profitable to mimic the low-cost firm. Contrary to our results, firms in their model thus tend to invest less in R&D than under full information. The result that firms under-invest compared to the full information scenario is driven by the fact that R&D is directed to cost reduction, which the firm with a low cost cannot utilize. This implies that the nature of R&D affects the results. Salonen (1989) studied a monopoly that can influence the beliefs of buyers on product quality by undertaking and publishing its R&D investment. His analysis showed that making the quality investment public information increases welfare. Padmanabhan, Rajiv and Srinivasan (1997) analysed the optimal R&D investments aimed at increasing product quality in a two-period model. A monopolist, having superior knowledge of the demand potential arising from a network externality, tries to influence buyers' beliefs by announcing his R&D investment in each period. R&D investment may also act as a signal to investors. In the model of Bhattacharya and Ritter (1983), firms communicated information with R&D investment to potential investors in order to have better terms of financing. Lichtenberg (1988) provided empirical evidence of the role of R&D investments as signals. Collie and Hviid (1993) analysed a signalling game with continuum of cost types. The competitiveness of the firm in home country is private information and the government tries to influence the cost beliefs of the firm in the foreign country with a subsidy. In the separating equilibrium, the subsidy is higher than under full information. Andersen and Hviid (1999) analysed the pricing strategy of a Stackelberg leader with private information about demand. In the separating equilibrium, the leader signals high demand with a price, which is higher than the price under full information. Our paper extends those approaches by introducing a cost parameter for the signal, i.e. the R&D investment.

In chapter 2 of the paper, we develop first the market demand and the resulting profit functions for firms. Then we show in section 2.2 that there exists a unique separating equilibrium strategy function that maps the true production cost to the R&D investment revealing fully all private information. This is then compared to the pure pooling equilibrium in section 2.3. In chapter 3 we analyse the firms' incentives to reveal the private information. Chapter 4 concludes.

2 The model

There are a large number of buyers with a mass of 1 with basic willingness to pay r, distributed evenly on the interval $[0,1]$. In addition, buyers value the future compatibility of a product. The market is supplied by two firms, *I*(nformed) and *U*(ninformed). Their products are perfect substitutes so that the willingness to pay among buyers is equal *ex ante*. However, since there are differences in the expected switching costs between the current and the future vintages of products, the market prices will be different. Although buyers are indifferent between the products *ex ante*, after committing themselves to a product they expect to face high costs *ex post* if they switch to a competing product. The firms commit themselves to R&D investments, x, to control for the vertical compatibility between the current and the future vintages of their *own* products. Firms are assumed to be equally efficient in R&D. The cost of R&D investment is $\frac{1}{2}vx^2, v > 0$.[10]

Buyers assess the future switching costs. High vertical compatibility means low switching cost between vintages**.** Knowing the cost function of R&D, buyers and firms infer from the observed R&D budgets the resulting expected vertical compatibilities. We assume a zero discount factor. Like Katz and Shapiro (1985), we restrict the analysis to equilibria where the expectations are fulfilled i.e. we do not distinguish between expected and realized compatibilities. The cost of switching to a future vintage of the product from another firm and the maximum switching cost to the future vintage from the current firm is $L > 0$**.** With R&D investment x_j by firm j, the expected switching cost between the vintages of products of firm j is reduced to $L - x_j$ and does not affect the product of the rival[11]. Buyers maximise their surplus $r - (L - x_j)$. With both current products in the market, it holds for the marginal buyer: $r_m = (L - x_j) + p_j$, $j = I, U$. Buyers with willingness to pay exceeding $(L - x_j) + p_j$ buy the products. Thus, given p_j and x_j, the demand for the current products is $1 - r_m$. With firm outputs q_I, q_U and output equalling demand,

[10] It turns out that we must have $v > 4/3$ to secure interior solutions in all maximizations.

[11] We assume switching cost to the next vintage of the product is always positive, $L - x_j > 0, j = I, U$.

$$q_I + q_U = 1 - r_m = 1 - p_I - \left(L - x_I\right) = 1 - p_U - \left(L - x_U\right). \tag{1}$$

From (1), we can derive the inverse demand functions for the products:

$$p_I = 1 - q_I - q_U - \left(L - x_I\right), \tag{2a}$$

$$p_U = 1 - q_I - q_U - \left(L - x_U\right). \tag{2b}$$

Both firms face a constant marginal cost of production: $c_I > 0, c_U > 0$. The profit functions are[12]

$$\pi_I = \left(1 - q_I - q_U - \left(L - x_I\right)\right)q_I - c_I q_I - \tfrac{1}{2} v x_I^2, \tag{3a}$$

$$\pi_U = \left(1 - q_I - q_U - \left(L - x_U\right)\right)q_U - c_U q_U - \tfrac{1}{2} v x_U^2. \tag{3b}$$

2.1 Full information equilibrium

We model the imperfect competition resulting in strategic behaviour as a Cournot-Nash competition at the output stage. In IT-industry this seems an appropriate solution concept as it can be interpreted as a reduced form of price competition with capacity constraints (Tirole 1988, Kreps and Scheinkman 1983). We solve the game backwards, i.e. first the output stage and then the strategic R&D investment stage. For comparison to the incomplete information scenarios, we assume in this section that the marginal costs of production are common knowledge before firms commit themselves to R&D investments. Solving for the optimal quantities of the output game, $q_I^*\left(x_I, x_U\right) = \dfrac{1 - L + 2x_I - x_U - 2c_I + c_U}{3}, q_U^*\left(x_I, x_U\right) = \dfrac{1 - L + 2x_U - x_I - 2c_U + c_I}{3}$ and inserting into the profit functions (3a, 3b) allows us to express profits as functions of R&D investments:

[12] As discussed in the introduction, the functional forms of the profit functions (3a, 3b) are similar to those in the case of cost-reducing R&D (see for example d'Aspremont and Jacquemin 1988).

$$\pi_I^*(x_I, x_U) = \tfrac{1}{9}(1 - L + 2x_I - x_U - 2c_I + c_U)^2 - \tfrac{1}{2}vx_I^{\ 2},$$

$$\pi_U^*(x_I, x_U) = \tfrac{1}{9}(1 - L + 2x_U - x_I - 2c_U + c_I)^2 - \tfrac{1}{2}vx_U^{\ 2}.$$

Maximizing with respect to R&D investments yields the reaction functions. The optimal R&D investment for firm *I* in the Cournot-Nash equilibrium is:

$$x_I^*(c_I, c_U) = \frac{12}{(9v-4)(9v-12)}\left[(3v-4)(1-L) - (6v-4)c_I + 3vc_U\right]. \tag{4}$$

A similar expression holds for firm *U*. We note that a firm's optimal R&D investment is decreasing in own marginal cost, $\frac{\partial x_I^*}{\partial c_I} < 0$, but increasing in the competitor's cost, $\frac{\partial x_I^*}{\partial c_U} > 0$.

2.2 Separating signalling equilibrium

We next explore the R&D investment of firm *I* possessing private information on its production cost. The equilibrium concept of the R&D game is perfect Bayesian equilibrium. We require that the R&D investment strategy is optimal given the cost belief of the rival and that the cost belief is consistent with the equilibrium strategy. The sequence of events is given in table 1. We solve the game of strategic investments using backward induction as under full information. For the beliefs to be consistent with the strategy, we utilize forward induction for firm *U* to assess whether firm *I*'s past actions were rational when firm *U* updates its beliefs (cf. Gibbons 1992, p.239). We show that the game has a unique separating equilibrium with all cost information revealed. The game also has pooling equilibria where private information is not revealed. The technical analysis is analogous to that of Collie and Hviid (1993).

1. The distribution of the private cost information of firm *I* and the true production cost of firm *U* are common knowledge.
2. Nature draws the production cost of firm *I* from this distribution.
3. The R&D stage: Firms commit themselves to R&D investments to control the vertical compatibility of their products.
4. Observing the R&D budgets, buyers value the current products.
5. Observing the budget of firm *I*, firm *U* updates its belief of firm *I*'s production cost
6. The output stage: Firms choose outputs and current products are sold.

Table 1: Sequence of events with private information

We introduce an assumption:

Assumption 1: Firms have constant marginal costs of production, c_I *and* c_U*. Before the R&D stage takes place, Nature draws* c_I *from a symmetric distribution on the interval* $\left[\bar{c}_I - \Delta, \bar{c}_I + \Delta\right]$ *with a mean* $\bar{c}_I$, $\bar{c}_I > \Delta$. *Firm I knows its cost, but firm U knows only the mean and interval of the distribution.* c_U *is common knowledge.*

At the output stage, firm *U* has determined its cost belief. In the following, we show that the optimal outputs of both firms depend on firm *U*'s belief of the true production cost of firm *I*. Assuming a signalling mechanism where firm *U* considers the R&D investment of firm *I* as a credible signal of its production cost, we define the cost belief of firm *U* conditional on the R&D investment of firm *I*, $\tilde{c}_I(x_I)$. Given the R&D investments and denoting the outputs under private information by $\tilde{q}_I, \tilde{q}_U$, the profits of the firms read now as:

$$\pi_I = \left(1 - \tilde{q}_I - \tilde{q}_U - \left(L - x_I\right)\right)\tilde{q}_I - c_I \tilde{q}_I - \tfrac{1}{2} v x_I^2 \quad (5a)$$

$$\pi_U = \left(1 - \tilde{q}_I - \tilde{q}_U - \left(L - x_U\right)\right)\tilde{q}_U - c_U \tilde{q}_U - \tfrac{1}{2} v x_U^2 \quad . \quad (5b)$$

The first-order conditions are:

$$\frac{\partial \pi_I}{\partial \tilde{q}_I} = 1 - 2\tilde{q}_I - \tilde{q}_U - (L - x_I) - c_I = 0 \quad (6a)$$

$$\frac{\partial \pi_U}{\partial \tilde{q}_U} = 1 - 2\tilde{q}_U - \tilde{q}_I - (L - x_U) - c_U = 0 \,. \quad (6b)$$

When firm *U* determines its output it does not know the true cost of the rival, c_I, and has to replace it with its belief of the cost, $\tilde{c}_I(x_I)$. Firm *U* infers that when firm *I*'s cost is the one it believes, the optimal output of firm *I* in the Nash-Cournot equilibrium is:

$$\tilde{q}_I = \frac{1 - 2\tilde{c}_I(x_I) + c_U - 2(L - x_I) + (L - x_U)}{3} \,. \quad (7)$$

Both firms know that firm *U* uses its inference of the output of firm *I* in (7) to choose its own output at the Cournot-Nash equilibrium. Inserting (7) into (6a, 6b) and solving the best-response functions in (6a, 6b) gives the Cournot-Nash equilibrium in outputs:

$$\tilde{q}_I^* = \frac{2 - 3c_I - \tilde{c}_I(x_I) + 2c_U - 4(L - x_I) + 2(L - x_U)}{6} \quad (8a)$$

$$\tilde{q}_U^* = \frac{2 - 4c_U + 2\tilde{c}_I(x_I) - 4(L - x_U) + 2(L - x_I)}{6} \,. \quad (8b)$$

At the R&D stage, firm *U* is uncertain of the true marginal cost of firm *I*, c_I. This means that it uses the best statistic, the prior expectation of the cost, $\bar{c}_I$. We assume that firm *U* chooses the R&D investment that is optimal under full information if firm *I*'s cost is the mean cost: $\bar{x}_U = x_U^*(\bar{c}_I, c_U)$. Firm *I* can regard this as a constant when determining its strategy. Note that under uncertainty, for firm *I*, the R&D game differs from the game under full information. Firm *I* can choose its R&D investment knowing that firm *U* does not respond. We define the following variables to simplify the notation.

$$\tilde{A}(c_I, \tilde{c}_I) = 2(1 - L) - 3c_I - \tilde{c}_I(x_I) + 2c_U - 2\bar{x}_U \,,$$

$A(c_I) = 2(1-L) - 4c_I + 2c_U - 2\bar{x}_U$,

$\bar{A} = 2(1-L) - 4\bar{c}_I + 2c_U - 2\bar{x}_U$,

where $\tilde{A}, A, \bar{A} \geq 0$.

The output, profit margin and profit for firm *I* can be expressed now as functions of the R&D investment, the cost belief and the true cost:

$$\tilde{q}_I^* = \frac{\tilde{A}(c_I, \tilde{c}_I) + 4x_I}{6}, \; p_I - c_I = \frac{\tilde{A}(c_I, \tilde{c}_I) + 4x_I}{6},$$

$$\pi_I = \pi_I(x_I, \tilde{c}_I(x_I), c_I) = \frac{\left(\tilde{A}(c_I, \tilde{c}_I(x_I)) + 4x_I\right)^2}{36} - \frac{vx_I^2}{2}. \quad (9)$$

Expression (9) is informative of the motivation for signalling: the profit of firm *I* is decreasing in the cost belief of firm *U*, $\frac{\partial \pi_I}{\partial \tilde{c}_I} < 0$. Under full information, a high level of R&D investment is a result of low own marginal cost. Under cost uncertainty, firm *U* regards a high level of firm *I*'s R&D investment as a credible costly signal of firm *I's* cost efficiency when it updates its prior belief of *I*'s marginal cost. We can also see in profit function (9) the dual role of the R&D investment. The R&D investment increases revenue by influencing both the cost belief of firm *U* and the buyers' perceptions of the vertical compatibility.

Proposition 1: There exists a unique separating signalling equilibrium in the game.

Proof: Building on Mailath (1987), we show that there exists a unique separating signalling equilibrium. The profit function of firm *I* (9) must satisfy the conditions for incentive compatibility: belief monotonicity, type monotonicity and single crossing. We assume that the individual rationality condition in terms of positive profit is satisfied. A further requirement is that there is a one-to-one strategy function from the true cost to the signal. In our model, all these conditions are satisfied and the proposition holds for any arbitrary density of cost distribution.

Belief monotonicity requires that the profit of firm *I* changes monotonically in firm *U*'s cost belief. This holds since

$$\frac{\partial \pi_I}{\partial \tilde{c}_I} = -\frac{4}{9(9v-8)}(\tilde{A}(c_I, \tilde{c}_I) + 4x_I) < 0\,. \tag{10}$$

The type monotonicity condition states that the signal, the R&D investment, has to change monotonically in the true marginal cost. Differentiating the profit function shows that this condition holds,

$$\frac{\partial^2 \pi_I}{\partial c_I \partial x_I} = -\frac{16}{3(9v-8)} < 0\,. \tag{11}$$

We define the isoprofit curve of firm *I* with true cost c_I as the set of signal, belief pairs $(x_I, \tilde{c}_I)$ with equal profit. The interpretation of the single crossing condition is that the isoprofit curves of different true costs may cross only once. This is to ensure incentive compatibility so that imitating another cost is not profitable with any true cost. We require that a change in the slope of the isoprofit curve Ψ must be monotonic in the true cost for any positive level of the signal. This condition is satisfied, as

$$\Psi = \frac{\frac{\partial \pi_I}{\partial x_I}}{\frac{\partial \pi_I}{\partial \tilde{c}_I}} = (9v-8)\left\{-2 + \frac{9vx_I}{\left(\tilde{A}(c_I, \tilde{c}_I) + 4x_I\right)}\right\},\ \frac{\partial \Psi}{\partial c_I} = -\frac{54v\tilde{A}(c_I, \tilde{c}_I)}{(\tilde{A}(c_I, \tilde{c}_I) + 4x_I)^2} < 0\,. \tag{12}$$

Q.E.D.

To determine the unique signalling equilibrium, we define a strategy function for firm *I* as the optimal R&D investment in terms of its true cost, $x_I^s = \sigma_I(c_I)$. The strategy function represents a perfect Bayesian equilibrium where private information is fully revealed. At the output stage, firm *U* updates its belief of firm *I*'s marginal cost: $\tilde{c}_I(x_I) = \sigma_I^{-1}(x_I)$. Firm *I* takes into account the effect that its R&D investment has on firm U's belief. Firm I's profit is a function of its own R&D investment and the cost belief of firm U, $\pi_I = \pi_I\left(x_I^s, \tilde{c}_I\left(x_I^s\right), c_I\right)$. Differentiating yields the first order condition[13]

$$\frac{d\pi_I}{dx_I^s} = \frac{\partial \pi_I}{\partial x_I^s} + \frac{\partial \pi_I}{\partial \tilde{c}_I}\frac{d\tilde{c}_I}{dx_I^s} = 0. \tag{13}$$

The first term is the direct effect of the R&D investment on profits. Costly R&D increases demand as buyers assess the positive impact on compatibility and thus on market share in the Cournot-competition at the production stage. The second term is the signalling effect: the R&D investment changes beliefs that have an impact on profits by belief monotonicity in (10). In the perfect Bayesian equilibrium, firm U updates firm I's marginal cost correctly, $\tilde{A}(c_I, \tilde{c}_I) = A(c_I)$. Since the derivative of an inverse single-variable function is the inverse of the original function, the first-order condition (13) can be expressed as

$$\frac{d\sigma_I}{dc_I} = -\frac{\dfrac{\partial \pi_I}{\partial \tilde{c}_I}}{\dfrac{\partial \pi_I}{\partial x_I}} = \frac{A(c_I) + 4\sigma_I}{4A(c_I) - 2(9v-8)\sigma_I} \quad . \tag{14}$$

The optimal strategy function of firm I satisfies this differential equation. To find the initial condition of the strategy function, we consider a scenario where private information is revealed after the R&D stage and firm U voluntarily updates its belief to correspond with the true marginal cost of firm I. In anticipation of this, firm I chooses the optimal R&D investment by maximising profits in (9) taking $\bar{x}_U$ and a belief update $\tilde{c}_I = c_I$ as given, yielding[14]

$$x_I^r(c_I) = \frac{2}{(9v-8)}A(c_I). \tag{15}$$

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[13] We show in the appendix that the second order condition is satisfied.

[14] Comparing this to the full information R&D investment in (4) shows that for the mean cost $x_I^*(\bar{c}_I) = x_I^r(\bar{c}_I)$ and that $\frac{\partial x_I^*}{\partial c_I} < \frac{\partial x_I^r}{\partial c_I}$ for all c_I.

The initial value condition follows from the fact that firm *I* with highest cost knows that firm *U* updates its belief to the correct one when observing the R&D investment that is optimal for the highest cost with information revelation after the R&D stage (see appendix),

$$\sigma_I(\bar{c}_I + \Delta) = x_I^r(\bar{c}_I + \Delta). \tag{16}$$

The strategy function $\sigma_I(c_I)$ can be interpreted as having a counterpart in reality: it is a result of the firm's business strategy process. A firm could develop a strategy guideline by meticulous analysis and simulation of the competitive situation for each potential production cost prior to knowing own and competitor's costs. The decisions determined by following this strategy when learning costs are characterised by the strategy function.

To compare the R&D investments under signalling and under revelation after the R&D stage in a simple manner, we express the optimal signalling behaviour as a function μ of the compound variable $A(c_I)$: $x_I^s = \sigma_I(c_I) = \mu(A(c_I))$. Then $\frac{d\sigma_1}{dc_1} = -4\frac{d\mu}{dA(c_I)}$ and we can transform (14) into

$$\frac{d\mu}{dA(c_I)} = -\frac{A(c_I) + 4\mu}{16A(c_I) - 8(9v - 8)\mu}. \tag{17}$$

The strategy function μ is a first-order homogeneous differential equation and we could solve it by transforming it into a separable differential equation. However, the result is complex and not instructive. Instead, for the following proposition, we assume that firm *I* considers only a linear strategy function, $x_I^s = ZA(c_I)$[15]. Solving (17) with this assumption (see appendix) yields a solution $Z_1 = \left(5 + 3\sqrt{1 + 2v}\right)/4(9v - 8)$. With a linear solution, the initial

[15] Defining the linear strategy function in terms of $A(c_I)$ instead of the true cost c_I allows for a comparison of the R&D investments.

condition $Z_1 A(\bar{c}_I + \Delta) = x_I^r(\bar{c}_I + \Delta)$ is satisfied only when $A(\bar{c}_I + \Delta) = 0$. The variable A includes other parameters besides c_I, so this is a special case.

Proposition 2: With a linear separating strategy function, the ratio between the optimal R&D investments of the informed firm *I* under private and under revealed information is increasing in the cost of R&D, v. The investment under private information is at least 35 percent higher.

Proof: When information is revealed after the R&D stage, firm *I* sets its R&D investment according to (15). The ratio of the R&D investments under private and revealed information is $\frac{Z_1 A(c_I)}{x_I^r(c_I)} = \frac{5 + 3\sqrt{1+2v}}{8}$. The ratio is increasing in the cost of R&D, v. By assumption $v > 4/3$, which implies that the ratio is larger than $1{,}35$. **Q.E.D.**

Our result shows that in the separating equilibrium with high R&D cost, the R&D investment is almost completely motivated by the signalling motive as the firm would invest much less under information revelation, $x_I^r(c_I) << x_I^s(c_I)$. With low R&D cost, the R&D investment under private information is also larger than under revelation but the difference is small. Thus the dominating motive now is the effect on buyers' perceptions. We can also interpret the larger investment in R&D under private information than under revelation as the value of information. With signalling, firm *I* spends more on R&D than would be optimal if information is revealed.

2.3 Pooling equilibrium

The described game with incomplete information has pooling and semi-pooling equilibria besides the unique separating equilibrium. Coordination of firms to pooling strategy requires a focal point for the R&D stage. A reasonable candidate for the focal point is the R&D investment which the expected mean type of firm *I* would undertake under full information, $x_I^p = x_I^*(\bar{c}_I, c_U)$. As firm *U* knows only the distribution of the true cost of firm *I*, it cannot prefer any other value to the mean. Such a pure strategy in pooling means that firm U learns nothing from the signal, say x_I^p, and retains the prior cost belief. In the following, we analyse the existence of the pure pooling equilibrium and develop conditions for it to be supported[16]. We compare the pure pooling equilibrium to the unique separating equilibrium. We apply two refinements for the selection of equilibrium by assuming responses to out-of-equilibrium R&D investments (Kreps and Wilson, 1982). First, if all types of firm I have a higher profit in pure pooling equilibrium compared to separating equilibrium, the pooling equilibrium is the more likely outcome. Second, if no type of firm I profits by deviating from the pooling behaviour given the out-of-equilibrium beliefs, the pure pooling behaviour is supported as an equilibrium.

Assumption 2: In a pooling equilibrium, if firm U encounters an out-of-equilibrium R&D investment, it updates the marginal cost belief to be the highest: $\tilde{c}_I = \bar{c}_I + \Delta$.

Given this assumption we can predict the game outcome:

Proposition 3: For low cost of R&D, $v \le 8/3$**, it is the separating equilibrium which is the likely outcome. If R&D is more costly,** $v > 8/3$**, the separating equilibrium is also the likely game outcome if the support for firm *I*'s cost type is sufficiently large,** $\Delta > \frac{v(18v-48)}{63v^2-16v-64}\bar{A}$ **, i.e. if cost uncertainty is great.**

Proof: Profit of firm I from pooling is equal to the profit under information revelation for the mean cost. Furthermore, the profit function with pooling is less convex in true cost type than the profit function under revelation[17]. The initial condition implies that the R&D investment and therefore profit are equal under signalling and under information revelation for the highest cost, $\pi_I^s(\bar{c}_I+\Delta) = \pi_I^r(\bar{c}_I+\Delta)$ and $\pi_I^s < \pi_I^r$ for any other cost. If the firm with highest cost

[16] Note that now we do not need to assume any functional form for the strategy function. We exclude the semi-pooling equilibria from the analysis as it does not seem to provide focal points for coordination to pooling only for some types.

[17] The second derivatives of profit functions are $\frac{\partial^2 \pi_I^p}{\partial c_I^2} = \frac{1}{2} < \frac{\partial^2 \pi_I^r}{\partial c_I^2} = \frac{16}{9}$

has a lower profit from pooling than from information revelation, this is a sufficient condition for pooling not to dominate. The inequality $\pi_I\left(x_I^p, \bar{c}_I, \bar{c}_I\right) < \pi_I\left(x_I^r\left(\bar{c}_I + \Delta\right), \bar{c}_I + \Delta, \bar{c}_I + \Delta\right)$ holds when $v \leq 8/3$ and $\Delta > \dfrac{v(18v-48)}{63v^2 - 16v - 64}\bar{A}$ (see appendix).

Firm I is most likely to deviate from pooling when its true cost is the lowest or the highest. When deviating, firm I chooses the optimal R&D investment given the true type and the out-of-equilibrium beliefs instead of the pooling R&D investment. For the lowest cost, pooling is always supported when $v > 16/9$. (See appendix). For the highest cost, deviation coincides with the separating behaviour since the out-of-equilibrium belief encountered is the true type. The conditions for pooling not to be supported are the same as for the pooling profit dominance above, $v \leq 8/3$ and $\Delta > \dfrac{v(18v-48)}{63v^2 - 16v - 64}\bar{A}$. The proposition follows from satisfying all these conditions. **Q.E.D**.

We can interpret the result of proposition 3 from two directions. The effect of the R&D investment to profits is decreasing in the cost of R&D, $\dfrac{\partial^2 \pi_I}{\partial x_I \partial v} < 0$. This means that the signalling mechanism is more important for the firms when R&D costs are low. In addition to that, a broad support of the true cost implies that the benefit of exploiting the private information is large. Separating is then a likely outcome for low cost of R&D and broad support of true cost.

3 Cost Revelation

We can ask whether firm I would voluntarily reveal the private information and firm U would believe the announcement. As shown by Shapiro (1986), a credible outside authority is necessary for successful cost revelation between oligopolists in Cournot-Nash competition. They have an incentive to report low costs. Assuming the existence of a credible procedure for information exchange we can state the following proposition:

Proposition 4: ***Ex ante,*** **both firms prefer credible revelation of the private information both to the separating and to the pooling equilibrium. Revelation before the R&D stage is preferred to revelation after the R&D stage.**

Proof: Revelation before the R&D stage corresponds to the full information scenario. The optimal R&D investments and thus profits are equal for firm *I* with mean cost under full information and under revelation after the R&D stage. The profit functions are convex (quadratic) in true type. In the appendix we show that the profit function under full information is more convex than the one under revelation, $\frac{\partial^2 \pi_I^*}{\partial {c_I}^2} > \frac{\partial^2 \pi_I^r}{\partial {c_I}^2}$ and we showed earlier that the profit function with revelation is more convex than with pooling. From the convexities[18], noting that profits are equal for the mean cost in all cases, we can conclude that *ex ante,* $E\pi_I^* > E\pi_I^r > E\pi_I^p$. Under full information, firm *U* can adjust its R&D investment to the true cost of firm *I* and receive the maximum profit corresponding to the true cost, which is always higher or equal than the profit under revelation after the R&D stage. For firm *U,* pooling implies fixed R&D investments with no adjustment to true cost and thus lower profits than under revelation after the R&D stage. The signalling R&D investment of firm *I* is always larger than or equal to the optimal R&D investment under revelation after the R&D stage, $x_I^s \geq x_I^r$. The profit of firm *I* is lower with signalling since it could increase profit by reducing the R&D investment closer to optimum. firm *U's* profit is also lower because its profit decreases in firm *I*'s R&D investment. **Q.E.D**.

If the source of private information is vertical integration of the supply of components and raw materials, our result suggests that integration must yield other benefits to the firm that offset the negative impact of private information. In IT-industries, the reliability and predictability of integrated component supply is the likely reason for owning the downstream production capacity. Our results coincide with the analysis of

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[18] For a random variable c and $p(c) = ac^2 + bc + dc$ it holds $Ep(c) = aVar(c) + p(Ec)$ and $\frac{d^2 p(c)}{c^2} = 2a$.

Choi (1998) of a duopoly game with private information. There vertical disintegration is a dominating strategy for both firms when they engage in Cournot-competition at the output stage.

4 Conclusion

In order to explain the eagerness of the firms in IT-industry to publish their R&D investment budgets, the paper developed an industry equilibrium model that shows that firms have multiple motives for making their R&D investments public. If firms coordinate to separating equilibrium under asymmetric private information, the resulting level of vertical compatibility at the market is higher than if the private cost information is revealed. Low cost of R&D to enhance compatibility or broad support of true cost predicts that firms coordinate to separating behaviour. The relative share of compatibility investment attributed to the signalling motive is increasing in the cost of R&D. Extending this analysis to symmetric private information would require that we introduce a third component in each firm's profit maximisation since the R&D investments are strategic substitutes. This suggests that with symmetric private information, the committed R&D investments have an impact on the game at the output stage (Mailath 1988). Analysis of such a scenario is more complicated and not addressed in this paper. Interpreting the results of Collie and Hviid (1993) in another context would suggest that for the symmetric separating signalling equilibrium, the optimal R&D investments are higher than under revealed information but lower than the R&D investment of the informed firm in our model.

The results described are somewhat sensitive to the underlying assumptions of the model. We have assumed that firms engage in capacity commitments and price competition at the production stage. This implies that the more efficient the informed firm *I* is, the larger is its optimal R&D investment. Introducing instead Bertrand-competition with differentiated products would reverse this logic. A smaller investment would be indicative of greater efficiency. The effect of signalling behaviour would then also be reversed. Such an approach could actually be appropriate for pure software products, with no output capacity constraints. Another extension of the model would be an introduction of two-audience signalling (see Bhattacharya and Ritter (1983) and Gertner, Gibbons and Scharfstein (1988). The firm with private information signals, in addition to the uninformed competitor, also to the uninformed buyers.

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Appendix

The second order condition for the profit-maximization (13)

Following Mailath (1987), the second order condition can be expressed as:

$\frac{d^2\pi_I}{dx_I^2} = -\left(\frac{d\sigma_I^{-1}}{dx_I}\right)^2 \left(\frac{d\sigma_I}{dc_I}\frac{\partial^2\pi_I}{\partial c_I \partial x_I} + \frac{\partial^2\pi_I}{\partial c_I \partial \tilde{c}_I}\right) \leq 0$. For the condition to hold, we require that the last term in parenthesis is positive. The first element of the term is clearly negative: the optimal R&D investment is higher the lower is the true type. The second element is the type monotonicity and it is negative in our model. Taking a partial derivative of (10) with regard to c_I shows that the third element is positive. We can conclude that the condition holds.

The initial condition (16)

The sequential structure of the game leads to the following reasoning:
a) Suppose a strategy function σ_I^A so that $\sigma_I^A(\bar{c}+\Delta) = x_I^A < x_I^r(\bar{c}+\Delta)$. In equilibrium, the uninformed firm *U* infers the upper limit $\tilde{c}_I^A(x_I^A) = \bar{c}+\Delta$ but the optimum for firm *I* is $x_I^r(\bar{c}+\Delta)$ when both the true cost and belief of the cost are the highest, $c_1 = \tilde{c}_1 = \bar{c}+\Delta$. A deviation to increase the R&D investment to $x_I^r(\bar{c}+\Delta)$ is profitable.
b) Suppose another strategy function σ_I^B so that $\sigma_I^B(\bar{c}+\Delta) = x_I^B > x_I^r(\bar{c}+\Delta)$. In equilibrium, firm *U* infers $\tilde{c}_I^B(x_I^B) = \bar{c}+\Delta$, but should it observe $x_I^r(\bar{c}+\Delta)$, the belief cannot be updated further upwards. Thus the deviation to decrease the R&D investment to $x_I^r(\bar{c}+\Delta)$ decreases firm *I*'s costs and does not change the competitor's behaviour. It is profitable and cannot be punished. So the optimal behaviour is always to set the R&D investment to $x_I^r(\bar{c}+\Delta)$ when the true type is $\bar{c}+\Delta$.

The characteristic equation of the differential equation (17)

Solving (17) with a linear function $x_I = ZA(c_I)$ leads to a quadratic characteristic equation $8(9v-8)Z^2 - 20Z - 1 = 0$, the solution of which is $Z = \frac{20 \pm \sqrt{400 + 32(9v-8)}}{16(9v-8)}$. Since we assume that the term $(9v-8)$ is positive, clearly $Z_1 = \frac{5 + 3\sqrt{1+2v}}{4(9v-8)} > 0$ and $Z_2 < 0$. In the analysis of the second order condition, we concluded that $\frac{\partial \sigma_I}{\partial c_I} \leq 0$, implying $\frac{\partial \mu}{\partial A(c_I)} \geq 0$. This holds with a linear solution only with $Z_1 > 0$.

Conditions for pooling (proposition 3)

Pooling does not dominate if firm I with highest cost $c_I = \bar{c}_I + \Delta$ receives a higher profit in separating equilibrium than in pooling equilibrium. If $\pi_I^{sw} = \pi_I\left(x_I^s(\bar{c}_I + \Delta), \tilde{c}_I = \bar{c}_I + \Delta, c_I = \bar{c}_I + \Delta\right) > \pi_I^{pw} = \pi_I\left(x_I^p, \tilde{c}_I = \bar{c}_I, c_I = \bar{c}_I + \Delta\right)$ holds, pooling does not dominate. We note that $x_I^p = \frac{2}{9v-8}\bar{A}$ and that for the highest cost, the R&D investment is equal in the separating equilibrium and under revelation after the R&D stage according to (16): $x_I^s(\bar{c}_I + \Delta) = x_I^r(\bar{c}_I + \Delta) = \frac{2}{9v-8}\left(\bar{A} - 4\Delta\right)$. The profits are

$$\pi_I^{pw} = \frac{\left(\bar{A} - 3\Delta + 4x_I^p\right)^2}{36} - \frac{v x_I^{p\,2}}{2},$$

$$\pi_I^{rw} = \frac{\left(\bar{A} - 4\Delta + 4\left(x_I^p - 4\frac{2}{9v-8}\Delta\right)\right)^2}{36} - \frac{v\left(x_I^p - 4\frac{2}{9v-8}\Delta\right)^2}{2}.$$

The inequality develops to $\Delta\left\{\Delta\left(-63v^2 - 16v + 64\right) + v(18v - 48)\bar{A}\right\} < 0$. The first term is always negative with the allowed values of v. When $v \le \frac{8}{3}$ the second term is non-positive and the inequality holds for any Δ. For $v > \frac{8}{3}$, the inequality holds when $\Delta > \frac{v(18v-48)}{63v^2 - 16v - 64}\bar{A}$.

Firm I with lowest true cost, $c_I = \bar{c}_I - \Delta$ has no incentive to deviate from pooling if the inequality $\pi_I^{pb} = \pi_I\left(x_I^p, \tilde{c}_I = \bar{c}_I, c_I = \bar{c}_I - \Delta\right) > \pi_I^{db} = \pi_I\left(x_I^d, \tilde{c}_I = \bar{c}_I + \Delta, c_I = \bar{c}_I - \Delta\right)$ holds. We note that $x_I^p = \frac{2}{9v-8}\bar{A}$. If firm I deviates, it will choose $x_I^d = \frac{2}{9v-8}\tilde{A}(\bar{c}_I - \Delta, \bar{c}_I + \Delta) = \frac{2}{9v-8}\left(\bar{A} + 2\Delta\right)$. The profits read then

$$\pi_I^{pb} = \frac{\left(\bar{A} + 3\Delta + 4x_I^p\right)^2}{36} - \frac{v x_I^{p\,2}}{2},$$

$$\pi_I^{db} = \frac{\left(\bar{A} + 2\Delta + 4\left(x_I^p + 2\frac{2}{9v-8}\Delta\right)\right)^2}{36} - \frac{v\left(x_I^p + 2\frac{2}{9v-8}\Delta\right)^2}{2}.$$

The inequality reduces to $\Delta\left\{\Delta\left(45v^2 - 112v + 64\right) + v(18v - 32)\bar{A}\right\} > 0$. We note that when $v \le \frac{14}{9}$ both terms are non-positive and the inequality does not hold for any Δ. For $\frac{14}{9} < v < \frac{16}{9}$, the first term is positive and the second one negative. The inequality holds when $\Delta > \Delta^D = \frac{-v(18v-32)}{45v^2 - 112v + 64}\bar{A}$. For $v \geq \frac{16}{9}$, both terms are non-negative and the inequality holds always.

Voluntary cost information revelation: convexity of the profit functions in cost type (proposition 4)

Differentiating the full information profit function $\pi_I^* = \pi_I^*\left(c_I, x_I^*(c_I), x_U^*(c_I)\right)$ shows that its second derivative with respect to true cost is positive, $\frac{d^2\pi_I^*}{dc_I^{\,2}} = \frac{\partial^2\pi_I^*}{\partial c_I^{\,2}} + \frac{\partial^2\pi_I^*}{\partial x_I^{*2}}\frac{dx_I^*}{dc_I} + \frac{\partial^2\pi_I}{\partial x_U^{*\,2}}\frac{dx_U^*}{dc_I} > 0$, since $\frac{\partial^2\pi_I^*}{\partial x_I^{*2}} < 0, \frac{\partial^2\pi_I^*}{\partial x_U^{*\,2}} > 0$ due to the second-order condition and symmetry in the model. From (4) we can see that $\frac{dx_I^*}{dc_I} < 0, \frac{dx_U^*}{dc_I} > 0$ and from (3a) that $\frac{\partial^2\pi_I^*}{\partial c_I^{\,2}} > 0$. In a similar fashion, we can show that for the profit function with revelation after the R&D stage, $\pi_I^r = \pi_I\left(x_I^r(c_I), \tilde{c}_I = c_I, c_I\right)$, the second derivative is positive: $\frac{d^2\pi_I^r}{dc_I^{\,2}} = \frac{\partial^2\pi_I^r}{\partial c_I^{\,2}} + \frac{\partial^2\pi_I^r}{\partial x_I^{r\,2}}\frac{dx_I^r}{dc_I} > 0$. To prove that the profit function is under full information more convex than under revelation, it is sufficient to show that $\frac{\partial^2\pi_I^*}{\partial x_I^{*2}}\frac{dx_I^*}{dc_I} > \frac{\partial^2\pi_I^r}{\partial x_I^{r\,2}}\frac{dx_I^r}{dc_I}$, since in our model $\frac{\partial^2\pi_I^*}{\partial c_I^{\,2}} = \frac{\partial^2\pi_I^r}{\partial c_1^{\,2}}$ and $\frac{\partial^2\pi_I^*}{\partial x_U^{*\,2}}\frac{dx_U^*}{dc_I} > 0$. The inequality yields: $\frac{\partial^2\pi_I^*}{\partial x_I^{*2}}\frac{dx_I^*}{dc_I} > \frac{\partial^2\pi_I^r}{\partial x_I^{r\,2}}\frac{dx_I^r}{dc_I} \Rightarrow v > 0$. This always holds.

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