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International Conference on Information Systems (ICIS)

2008

Voluntary Open-Source - The Effect Appropriability, Externality, and Uncertainty

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VOLUNTARY OPEN-SOURCE – THE EFFECT OF APPROPRIABILITY, EXTERNALITY, AND UNCERTAINTY

Open source volontaire – les effets de l'appropriabilité, de l'externalité et de l'incertitude

Completed Research Paper

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Abstract

Over the past decade, many profit-seeking technology firms voluntarily made their proprietary software open-source. In this paper, we study firm's motivation of such voluntary open-source and its implications. Through analyzing the tradeoff between supply-side externality and demand-side appropriability, we identify the conditions under which firms will voluntarily open source. Our result highlights the importance of supply-side benefit in open-source decisions. We also find that though open-source increases product quality, it may surprisingly reduce social welfare because of over-investment in product quality. The role of loss of quality control is also investigated, where we show that cost concern may limit a firm's incentive to open source. Finally, different firms' incentives to open source in competition are contrasted. We find that one firm's open-source encourages the other to follow, yet both firms could make lower profit in equilibrium. Our work deepens our understanding of this nascent phenomenon and offers advices to practitioners.

Keywords: Open-source, supply-side externality, appropriability, quality, uncertainty, competition

Résumé

De nombreuses sociétés privées ont choisi d'ouvrir leurs logiciels propriétaires. Nous étudions la motivation des entreprises de pour une telle décision. En identifiant les conditions de l'open source volontaire, nous soulignons l'importance des bénéfices du côté de l'offreur. Nous constatons que l'open source accentue la qualité du produit mais peut étonnant réduire le bien-être social en raison d'un surinvestissement en qualité. Les incitations au choix de l'open source en situation de concurrence sont également étudiées.

Introduction

The success of open-source has gone beyond Linux and Apache. Over the past decade, open-source has been rapidly gaining momentum in the business arena. Many technology firms now invest heavily in open-source initiatives. One noticeable pattern of their participation is that, instead of leveraging existing open-source products such as Linux, these firms voluntarily made their products which used to be closed-source, or proprietary, open-source. Examples abound, from IBM's creation of Websphere Community Edition, to Apple Inc's open-source of Darwin, and most recently, Sun Microsystem's announcement of its OpenJDK initiative (Table 1). These examples of software made open-source by their commercial owners indicate that this phenomenon is both new and gaining momentum.

Table 1: Software Made Open-Source Voluntarily by Owners

Company	Software	Date Open-Sourced
Apple	Darwin (core of OS X)	March, 1999
MySQL	MySQL Database	June, 2005
IBM	Eclipse	November, 2001
	Websphere	October, 2005
BEA Systems	Open JPA (BEA Kodo)	February, 2006
Sun Microsystems	Open Office	July, 2000
	Open Solaris	June, 2005
	Open JDK	May, 2007
Adobe	Flex	April, 2007
Microsoft	Silverlight	April, 2007

Academic research on open-source bears fruit in several key areas, including the motivation for developers to participate in open-source initiatives (e.g. Roberts et al. 2006), the governance of open-source projects (e.g. Baldwin and Clark 2006), and the competitive dynamics of open-source (e.g. Lerner and Tirole 2002). However, the voluntary open-source by profit-seeking firms poses new research challenges. Existing literature outlines open-source business strategies such as loss-leader, service-seller, widget-frosting and accessorizing (Mustonen 2003, Varner 2000), all of which call for making profit from open-source software by selling other related products or services. Discussions of these strategies are mostly qualitative – using examples or case studies to demonstrate the strategies' viability, and treat open-source as exogenous – demonstrating how business strategies can be built around an existing open-source product. However, they fail to justify the decision of open-source of an existing closed-source product or one that could alternatively be produced in closed-source manner. For a profit-seeking firm, open-source must be superior to the corresponding closed-source strategy in order to justify the decision of open-source. Existing literature presents at best a necessary but not sufficient condition. To our best knowledge, in-depth study of the endogenous open-source decision from firm's perspective is non-existent, and its implications on quality and welfare are not well understood. This is the motivation of our study, in which the first question we ask is when a firm, as a monopolist or in competition, will find it profit-enhancing to make its software product open-source.

Endogenous open-source decisions are determined by key supply- and demand-side factors. Since open-source product is available to consumers for free (technically a firm can charge for open-source software, but the freeredistribution clause in most open-source licenses effectively makes this not viable), the firm faces a demand-side *appropriability* issue. Multiple technology products are often used together as a system, where the value of one product is higher when used together with other products. This complementarity presents firms the opportunity to appropriate the return through related products after a product is made open-source. In the presence of cross-product network effects, an open-source product can lead to increased user base, which in turn leads to wider adoption and higher willingness to pay of the complementary product. (The indirect network effect, however, does not explain why firm will open source rather than just offer the product for free) On the supply-side, open-source software brings benefits to the firm. Open-source software is often developed with the help of external developer communities. These communities have been the focus of studies on the motivation of participation and the governance of open-source projects (e.g. Roberts et al. 2006), but their implications to firms have not been analyzed in extant literature. From the firm's perspective, these communities can offload a significant portion of software development cost. For example, Red Hat Linux version 7.1 has over 30 million lines of source code, which would have cost more than $1 billion to develop (Wheeler 2002), yet the company spent much less than that on R&D during its development. This cost reduction of open-source is referred to in our study as *supply-side externality*. Firm's open-source decision is thus essentially a tradeoff between the benefit from supply-side externality and the appropriability concern from demand-side. Furthermore, competition in industry may also encourage firms to seek alternative strategies such as open-source.

Open-source has significant product quality and social welfare implications. A debate is ongoing in industry on whether open-source or closed-source can produce higher quality products. From firm's perspective, though, we should note that quality is a strategic decision, as higher quality comes at higher cost. Rather than ask whether a firm *can* produce higher quality under open-source, we study whether the firm will *strategically choose* higher or lower quality. Open-source is usually perceived to be beneficial to the society, as it diminishes the market power of proprietary software firms and reduces distortion imposed by these firms. However, when a firm voluntarily opens source, the situation may not be so straightforward, because a profit-seeking firm will only open source if doing so increases its profit. In addition, when external communities shoulder part of the development cost, it is unclear whether firm will choose quality levels that are socially efficient.

Our work contributes to the existing literature by investigating the tradeoffs faced by profit-seeking firms on making open-source decisions. First, we highlight the importance of supply-side externality as a necessary condition for a firm to voluntarily open source. Second, we elaborate on the implication of open-source decision on product quality. We show that open-source induces the firm to increase the quality of the open-source software product, but the quality of the complementary product may be decreased. Somewhat surprisingly, we show that voluntary open-source increases social welfare when quality is exogenous, but may decrease social welfare when quality is chosen strategically, since the firm may choose a quality level that is too costly from the society's perspective. Furthermore, we show that in competition, low quality firm has higher incentive than high quality firm to open source when their qualities do not differ significantly, that one firm's open-source encourages the competitor to do the same, and that both firms may open source in equilibrium even when doing so reduces both firms' profit. Finally, we show that with quality uncertainty, firm may have to reduce the amount of work offloaded to external developer communities. Our work deepens understanding of open-source business strategies and provides guidance to industry practitioners.

The rest of this paper is organized as follows: section 2 reviews the prior research on open-source and related topics. In section 3, we study a monopolist's decision to make its product open-source. Section 4 compares and contrasts firms' open-source decisions in competition. Finally, we discuss and conclude in section 6.

Literature Review and Background

Existing research on open-source is classified into three categories: motivation for contributions, governance of open-source initiatives, and competitive dynamics (von Krogh and von Hippel 2006). The first stream of work (e.g. Roberts et al. 2006, Shah 2006) studies people's incentive to contribute to open-source projects. The organization of open-source developer community, which is different than that of a traditional project team internal to a company, poses unique challenges on effective governance of open-source initiatives, which inspires the second stream of research (e.g., Baldwin and Clark 2006, MacCormack et al. 2006). Our work contributes to the last steam – the competitive dynamics, where open-source related business strategies and their implications are studied.

Early studies on open-source competitive dynamics (e.g. Lerner and Tirole 2002, Bonaccorsi and Rossi 2003) give high level overviews on the drivers of open-source development, business opportunities which leverage open source, and the environmental factors which influence the success of open-source initiatives. West (2003) has a detailed case study of the open-source involvement of several prominent firms. Other study also looks at the determinants of the type of open-source licenses (Lerner and Tirole 2005). These works mostly discuss open-source qualitatively.

Economic modeling has also been used to analyze the competitive dynamics of open-source. Economides and Katsamakas (2006) constrast open-source and proprietary platforms. By analyzing firm profits in situations such as vertical integration, separate firms, and competition, the study finds that in most cases open-source results in lower firm profit and is dominated in competition against proprietary platforms. Casadesus-Masanell and Ghemawat (2006) analyzes the competition between Linux and Windows using a dynamic mixed duopoly model, and shows that with a forward-looking pricing strategy, a profit-maximizing firm can coexist with a competitor priced at zero in a market with network effects. Other studies analyze different pricing schemes under open-source (Kim et al. 2006), the tradeoff between self-development and free-ride (Johnson 2001), and programmers' occupational choice and its impact on firm strategy (Mustonen 2003). All these studies treat open-source as exogenous.

Firms can profit from open-source products through complementary products. An extreme form of complementarity requires all products to be used together, i.e., one product is useless without others. A rich literature (e.g. Spence 1976, Matutes and Regibeau 1988, Economides and Salop 1992, Economides 1996) shed light on complementarity as well as related issues such as network effects and compatibility. Of particular interest in this stream of work is the network effect in two-sided markets studied in Parker and Van Alstyne (2005), hereafter referred to as PVA. A two-sided market consists of two separate product markets connected by intermediary firms (a.k.a. platforms, as studied in Rochet and Tirole 2003). PVA shows that, if the demand of one product is strongly influenced by that of the other, then a monopolist firm selling both products may give out one product for free. Though not focusing on open-source, this insight potentially provides a demand-side justification for open-source.

The indirect network effect, however, holds only a partial explanation to voluntary open-source. Even a strong indirect network effect cannot explain why the firm would bother to open source rather than just give the product out for free. The key difference between open-source and a free product is the external developer community. Clearly, there is supply-side consideration at work. Furthermore, indirect network effect encourages firms to penetrate market with very low price to establish user acceptance. In many cases of the voluntary open-source, however, the products already established user acceptance before they were made open-source (e.g. Solaris operating system, and Websphere application server). This again points to factors outside indirect network effect.

Quality is an important consideration for software. A rich literature exists on this topic. Software quality has multiple dimensions with different implications to users and developers (e.g, Garvin 1987, Kekre et al. 1995). Different management and governance practices lead to different qualities and costs (Krishnan et al. 2000, Slaughter et al. 1998). Open-source literature has also studied the quality implication of the unique governance structure of open-source (Raymond 2001, Raghunathan et al. 2005). However, the strategic aspect of quality from firm's perspective has not been fully explored. And our study contributes to existing literature by filling this gap.

Monopoly

In this section, we study the open-source decision of a monopoly firm, where we focus on the tradeoff between supply- and demand-side factors as well as the concern of quality uncertainty. Studying monopoly situation can both reveal key insight without the complication of competition and offer practical guidance to firms which function as local monopolists in highly segmented markets.

Model Setup

We study a firm's voluntary open-source decision of an existing or new product: a firm may decide to open an existing product which is closed-source, or to develop a new product with open source. Our model extends the standard vertical differentiation model to account for product complementarity. A monopoly firm produces two complementary software products. Each product i is characterized by quality q_i. The quality can be considered as a "weighted-average" measure of multiple attributes (Garvin 1984). There is a heterogeneous group of consumers indexed by $\theta \in [0,1]$, which represents consumer's willingness-to-pay for quality. Consumers are uniformly distributed over this interval. Each consumer will purchase at most one unit of each product.

The two products can be used either together or separately. Let $\theta V_s(q_i)$ and $\theta V_c(q_1, q_2)$ be the value which consumer θ derives from using one product alone and using both products together, respectively. Both $V_s(.)$ and $V_c(.)$ are differentiable, and $\partial V_k / \partial q_i > 0, k \in \{s,c\}, i \in \{1,2\}$. We assume $V_c(q_1,q_2) - (V_s(q_1) + V_s(q_2)) \geq 0$, i.e. the sum of values derived from using either product separately is no more than the value derived from using both together (the larger this difference, the higher the degree of complementarity). We also assume that complementarity is at the product level, but not at the quality level, i.e. one product is more valuable when it is used together with the other product; however, its value is not necessarily higher when the other product has higher quality.

Consumers maximize their net utility – the difference between product value and price. The firm sells both products together at price p. Consumers who buy derive net utility $U_c(\theta, q_1, q_2, p) = \theta V_c(q_1, q_2) - p$. When the products are closed-source, consumers who don't buy derive net utility 0. But if one product is made open-source, it is available to consumers for free. Consumers who do not buy can still derive positive utility $U_s(\theta, q_i) = \theta V_s(q_i)$ from using the open-source product alone. Without loss of generality, we consider only the open-source of the second product (A firm will not make both products open-source as it cannot generate revenue).

The fixed cost of developing the products of qualities q_1 and q_2 is denoted as $C(q_1, q_2)$, while the marginal cost is zero. Following existing literature (Gal-Or 1987, Barua et al. 1991, Telang et al. 2004), we let the cost function be quadratic: $C(q_1,q_2) = c_1 q_1^2 + c_2 q_2^2 + d q_1 q_2$. The first two terms represent the cost of developing each product itself, while the last term represents the cost of integrating the two products. This cost function suggests that developing higher quality entails higher cost at increasing rate. Moreover, integrating the software also entails cost that goes up with the quality of both software – higher quality means there are more features to integrate (more coding work to provide the interface between the products, and more testing of all the features).

When the second product is made open-source, the firm can form a community of external developers to help develop the product. Their participation reduces the firm's own cost by a factor of $1-\beta$, transforming its cost function to $C^o(q_1,q_2) = c_1 q_1^2 + \beta c_2 q_2^2 + d q_1 q_2$. The lower the value of $\beta, \beta \in (0,1]$, the higher the degree of supply-side benefit. We assume $d < 2Min\{c_1, \beta c_2\}$, meaning the integration cost is lower than the development cost. This is consistent with the experience in industry, and is made to avoid uninteresting corner solutions.

Exogenous Quality

The monopoly firm makes decision in two stages. In the first stage, the firm decides whether to make the software open-source and then chooses product quality. In the second stage, the software is developed and the firm chooses the price at which to sell the products. Our discussion begins with the second stage, where quality is already exogenously given. The discussion of endogenous quality follows in the next section.

With exogenous quality, we compare the case of open-source with that of closed-source. It is easy to show that when the firm keeps the products closed-source, the optimal price of the product bundle is $p^* = V_c(q_1,q_2)/2$, and the maximum profit the firm makes is $\Pi^* = V_c(q_1,q_2)/4 - C(q_1,q_2)$. The top half of consumers in the market will buy. When it makes the second product open-source, the optimal price is $p_1^{o*} = (V_c(q_1,q_2) - V_s(q_2))/2 \geq V_s(q_1)/2$ and the maximum profit $\Pi^{o*} = (V_c(q_1,q_2) - V_s(q_2))/4 - C^o(q_1,q_2)$. Half of the consumers will buy the closed-source product, and all consumers, including those who do not buy, will also use the open-source product.

When making the second product open-source, the firm can appropriate return through the product which remains closed-source, as we show above that the price of the closed-source product is higher than the firm would charge were it the only product in the market. However, this profit is still lower than the monopoly profit when both products are kept closed-source, unless the cost is reduced sufficiently under open-source. This comparison holds for any quality level, including the profit-maximizing quality under open-source. This leads to our first proposition:

> *Proposition 1a: Absent supply-side externality, it is NOT optimal for a monopolist firm to voluntarily make its product open-source.*

This finding, though easy to derive, has non-trivial implications. It shows that the supply-side externality is necessary for a firm to justify its open-source decision. Discussions in industry on open-source strategies, however, often ignore this key factor. Note that this result does not conflict with that of PVA, which focuses on indirect network effect, while our result here focuses on supply-side factors. PVA shows that strong cross-product network effect is needed to justify the "give out for free" when supply-side benefit is not considered. Our analysis adds to their study by showing that the network effect arising solely from complementarity will not be strong enough to justify open-source (complementarity is cited as an important source of indirect network effect).

Comparing profits under open-source and closed-source, we can see that the firm would open source if $\beta \leq 1 - V_s(q_2)/4c_2q_2^{\ 2}$. This leads to the following comparative statics:

> *Proposition 1b: With exogenous quality, the higher the degree of supply-side externality and the higher the degree of complementarity between the two products, the higher is the firm's incentive to open source.*

To understand the welfare implications of open-source, we make the following assumptions regarding the development of open-source product. The first is on the motivation of external developers. Studies have found various factors that motivate developer participation, such as signaling (Lerner and Tirole 2002, Roberts et al. 2006) and ego gratification (Raymond 1999). We assume that developers contribute solely for the purpose of signaling to potential employers in labor market. This signaling effort is *costly* from the perspective of labor market and does not increase overall welfare, even though it may benefit the individual developers who exert the effort. Second, the external developers may very well also be the users, but we treat them as separate entities without loss of generality: since a developer can use the open-source product even if she does not contribute, her contribution must be tied to any benefit *in addition to* the value derived from using the product, thus making the two effects separable. Finally, since no consensus exists on whether open-source or closed-source is the more cost effective way of developing software, our study does not favor either form ex-ante and therefore, we assume the total cost incurred in developing the products does not change from the society's point of view when products are made open-source. Under these assumptions, we make the following observation about consumer surplus and social welfare:

> *Proposition 2: With exogenous quality, both consumer surplus and social welfare are higher under open-source than under closed-source. In addition, consumer surplus and social welfare under open-source decrease with the degree of complementarity.*

The finding on social welfare to a certain extent confirms the conventional wisdom that open-source is good. Both social welfare and consumer surplus are unambiguously higher under open-source. Under open-source, more consumers can use the product than if the product is kept closed-source and sold only to those who are willing to pay. The firm, meanwhile, is better off as it offloads development cost. This makes open-source a more Pareto efficient arrangement than the corresponding closed-source one when product qualities are the same.

Endogenous Quality

We now study firm's endogenous quality decision, where the firm first decides whether to open source, then chooses the quality of each product, and finally sets product price.

An assumption made here is that the firm still controls product quality under open-source. Though a simplification, this assumption is not unreasonable. The external developer communities sponsored by firms are usually controlled by those same firms. For example, the Fedora project, sponsored by Red Hat Inc, has a board of directors of nine members, five of which are employees of Red Hat. By "donating" employees to the developer community, the firm retains control over the open-source product. The quality control assumption will be relaxed later.

To proceed with finding the profit-maximizing quality, we specify the functional forms of value functions as follows: $V_c(q_1, q_2) = q_1 + q_2$ and $V_s(q_i) = \alpha q_i$, where $\alpha \in [0,1]$ represents the degree of the complementarity – the higher α , the lower the degree of complementarity (when $\alpha = 0$, one product is of no use without the other; while when $\alpha = 1$, consumer derive the full value of one product regardless of whether it is used together with the other). We first present the result of the benchmark closed-source case:

Lemma 1a: When the firm does not open source, the profit-maximizing qualities of the two products are $q_1^* = \frac{(2c_2 - d)}{4(4c_1c_2 - d^2)}$ *and* $q_2^* = \frac{(2c_1 - d)}{4(4c_1c_2 - d^2)}$.

When the firm makes the second product open-source, the development cost of the product is reduced. At the same time, however, the product will also be available for free and the firm can partially appropriate return only through the complementary product. Open-source thus shifts both revenue and cost functions. The result of the new optimization problem is stated below:

Lemma 1b: When the firm makes the second product open-source, the profit-maximizing qualities of the two products are $q_1^{o*} = \frac{2\beta c_2 - (1-\alpha)d}{4(4\beta c_1c_2 - d^2)}$ *and* $q_2^{o*} = \frac{2(1-\alpha)c_1 - d}{4(4\beta c_1c_2 - d^2)}$. *(We assume* $2(1-\alpha)c_1 - d > 0$ *to avoid uninteresting corner solutions)*

Comparing the optimal qualities under open-source and that under closed-source:

$$q_1^{o*} - q_1^* = \frac{d(\alpha(4c_1c_2 - d^2) - 2(1-\beta)c_2(2c_1 - d))}{4(4\beta c_1c_2 - d^2)(4c_1c_2 - d^2)}, \quad q_2^{o*} - q_2^* = \frac{2c_1(-\alpha(4c_1c_2 - d^2) + 2(1-\beta)c_2(2c_1 - d))}{4(4\beta c_1c_2 - d^2)(4c_1c_2 - d^2)}$$

We find that the firm may increase the quality of either the first product or the second product under open-source compared to the qualities if they were close-source. Interestingly, we find that the firm will always increase quality of one product while reduce quality of the other.

Proposition 3: When one product is made open-source, when product complementarity is low ($\alpha > \frac{2(1-\beta)c_2(2c_1 - d)}{4c_1c_2 - d^2}$*), the firm will increase quality for the closed-source product and decrease quality for the open-source one compared to the qualities they would choose when both are made close-source. . When product complementarity is high (*$\alpha < \frac{2(1-\beta)c_2(2c_1 - d)}{4c_1c_2 - d^2}$*), the firm will decrease quality for the closed-source product while increase quality for the open-source one.*

The comparative statics are stated in the following corollary.

Corollary 1: Firm's profit under open-source is increasing in the degree of product complementarity and supply-side externality. When the firm makes one product open source, the quality of the open-source product is increasing in complementarity and supply-side externality, while the quality of the product that remains closed-source is decreasing in complementarity and supply-side externality.

Proposition 3 shows that open-source may induce the firm to choose higher product quality in certain situations and lower quality in others. However, a profit-seeking firm will open source only if its profit is higher under open-source than under closed-source. This could narrow the quality implication of voluntary open-source. For example, if the situations which induce higher quality also lead to lower profit, then the firm will not open source in those cases at all. Indeed, the following proposition confirms this.

Proposition 4: When the firm voluntarily makes one product open-source, that is, when open-source increases firm profit, the firm will increase the quality for the open-source product and decrease the quality for the complementary closed-source product compared to their respective quality if both are kept closed-source.[1]

This result highlights the tradeoff between demand-side appropriability and supply-side externality. Supply-side benefit encourages the firm to increase the quality of the open-source product, because the development cost to the firm is lowered. Meanwhile, however, the appropriability concern discourages the firm to increase that quality, because the firm cannot fully appropriate the return. Since the appropriability effect works against the firm, the situations which lead to lower quality of the open-source product also lead to lower profit for the firm under open-source, thus the firm will not open source in those situations. It is a bit surprising to see that the firm will reduce the

[1] Technical proof of the proposition is available from authors upon request.

quality of the closed-source product while it increases that of the open-source one. The key factor leading to this conclusion is that complementarity is only at product level but not quality level. In the case when complementarity is at both product level and quality level, open-source may increase the qualities of both products together.

Proposition 2 states that open-source always leads to higher welfare when quality is exogenous. This naturally tempts us to state the same when quality is endogenous. However, a deeper look suggests this may not be true. It is the firm that chooses product quality, and it does so strategically to maximize its own profit. When product is closed-source and development cost is borne entirely by the firm, it has the incentive to make cost-effective quality decision. Under open-source, however, a potentially significant portion of the cost is shouldered by the external community, thus the firm may have an incentive to choose a quality level that is too costly from society's point of view. This inefficiency caused by supply-side externality may more than offset the market expansion effect of open-source and make the society collectively worse off. Figure 1 illustrates this effect: though for any fixed quality, welfare is high under open-source, the firm under open-source chooses a highly costly quality to maximize its own profit, while doing so results in lower social welfare compared with the case when products are kept closed-source, when the firm would choose lower quality. This effect, stated in the proposition below, cautions consumers and policy makers against prematurely welcoming firm's open-source decision before in-depth evaluation.

Proposition 5: When the firm voluntarily makes product open-source and can influence the quality of the open source product, the social welfare may be lower than under closed-source.

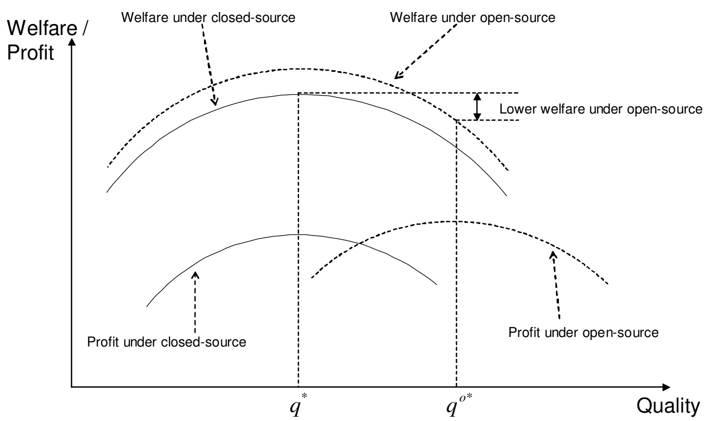

Figure 1: Social Welfare May Be Lower Under Open-Source

Quality Uncertainty

Though offloading work to external developer community reduces the firm's cost, it may also reduce firm's control on quality. To see this, consider the case where the firm assigns a task to a volunteer developer. If the developer is a highly-skilled one who contributes to signal her ability, the task can be completed with high quality. If the developer turns out to be a junior one who needs to improve her programming skills, the task runs a risk of not being completed successfully. If the firm does not know the developer's type, or if it does but does not fully control the assignment of tasks to developers (many developer communities, for example, allow developers themselves to decide what tasks to work on), then the firm will not fully control the realized product quality. We study in this section the effect of such uncertainty. The firm is assumed to be risk-neutral and maximize the expected profit.

The Impact of Uncertainty

Suppose that when the firm makes the second product open-source, it can dictate the expected product quality to be q_{2e}. But the realized quality, q_2, is determined by q_{2e} and a stochastic factor x, $q_2 = xq_{2e}$, where x has density function $f(x \mid \beta, \rho)$ with support on positive real line, and has expectation $E[x \mid \beta, \rho] = 1$. Recall that β is the measure of supply-side externality, while the parameter ρ is an index of the complexity or volatility of the product. We assume that for any two degrees of externality β_1 and β_2 where $\beta_1 > \beta_2$, $f(x \mid \beta_1, \rho)$ second-order stochastically dominates $f(x \mid \beta_2, \rho)$. This assumption means that the more work offloaded to the external community, the lower control the firm would retain, and the higher volatility the realized quality would have. Similarly for the parameter ρ, which represents the intrinsic volatility as determined by the type of product (for example, a standard GUI component is less risky to develop than a sophisticated business intelligence engine), we assume that for any two ρ_1 and ρ_2 with $\rho_1 < \rho_2$, $f(x \mid \beta, \rho_1)$ second-order stochastically dominates $f(x \mid \beta, \rho_2)$ – the smaller the value, the less risky the project is.

Consumer's willingness-to-pay is determined by the realized quality. Firm's development cost, however, can be determined by either the expected quality or the realized quality: if the firm mainly handles planning or design tasks in the early phases of projects, then its cost would be determined by the expected quality. If, however, the firm is involved in the development or the testing phase, then cost would be influenced by the realized quality.

If firm's cost is determined by expected quality, then the quality uncertainty has impact on only revenue but not cost. With expected quality q_{2e} and realized quality q_2, the firm's profit function under open-source is:

$$\Pi^o = \frac{1}{4}(q_1 + (1-\alpha)q_2) - (c_1 q_1^2 + \beta c_2 q_{2e}^2 + d q_1 q_{2e})$$

Thus the firm's expected profit is

$$E[\Pi^o] = \int (\frac{1}{4}(q_1 + (1-\alpha)x q_{2e}) - (c_1 q_1^2 + \beta c_2 q_{2e}^2 + d q_1 q_{2e})) f(x \mid \beta, \rho) dx$$
$$= \frac{1}{4}(q_1 + (1-\alpha)q_{2e}) - (c_1 q_1^2 + \beta c_2 q_{2e}^2 + d q_1 q_{2e})$$

This shows that when cost is determined by expected quality, uncertainty has no impact on expected firm profit; therefore, the firm will make decision on open-source and the expected quality as if no uncertainty is involved.

If the uncertainty influences not only realized quality but also firm's actual cost, the situation is more complex. In this case, with expected quality q_{2e} and realized quality q_2, the firm's profit function under open-source is:

$$\Pi^o = \frac{1}{4}(q_1 + (1-\alpha)q_2) - (c_1 q_1^2 + \beta c_2 q_2^2 + d q_1 q_2)$$

Thus the expected profit is

$$E[\Pi^o] = \int (\frac{1}{4}(q_1 + (1-\alpha)x q_{2e}) - (c_1 q_1^2 + \beta c_2 (x q_{2e})^2 + d q_1 x q_{2e})) f(x \mid \beta, \rho) dx$$
$$= \frac{1}{4}(q_1 + (1-\alpha)q_{2e}) - (c_1 q_1^2 + \beta c_2 {q_{2e}}^2 \int x^2 f(x \mid \beta, \rho) dx + d q_1 q_{2e})$$

Let $\beta' = \beta \int x^2 f(x \mid \beta, \rho) dx$. We can see from above that this decision problem under uncertainty is the same as the decision problem when no uncertainty exists and the externality parameter is β'. Apparently $\beta' > \beta$. As shown before, the lower β, the higher the firm's profit under open-source. Therefore, uncertainty reduces the firm's incentive to open source when cost is determined by realized quality. Furthermore, for any two ρ_1 and ρ_2 with $\rho_1 < \rho_2$, we can see that $\int x^2 f(x \mid \beta, \rho_1) dx < \int x^2 f(x \mid \beta, \rho_2) dx$. As a result, higher intrinsic uncertainty of the development task also reduces the firm's incentive to open source further.

> *Proposition 6a: When facing quality uncertainty, if the firm's cost is determined by the expected quality, the firm's incentive to open source and quality decision are the same as when no quality uncertainty exists. If the cost is determined by realized quality, then uncertainty reduces the incentive to open source. The riskier the development task is, the lower the incentive to open source.*

Endogenous Externality Decision

Quality uncertainty is determined by both the intrinsic risk of the development task and the degree of externality. If the firm can choose the degree of supply-side externality (e.g. choose how many employees to assign to the open-source projects), should it still offload as much work as possible, as it will do when no uncertainty exists? To answer this question, in this section we make β endogenous to the firm. Let $\beta \in [\underline{\beta},1]$, where $\underline{\beta} > 0$ is a positive lower bound which represents the maximum degree of externality that is achievable; this positive lower bound suggests that the firm can not offload all its development costs.

We have shown that when cost is determined by expected quality, the firm's decision problem is the same as when no uncertainty exists. Thus the answer follows trivially that the firm should offload as much work as possible, i.e. choose $\beta = \underline{\beta}$. When cost is determined by realized quality, however, the firm's problem can be expressed as

$$\max_{\beta\in[\underline{\beta},1]}\{E[\Pi^o]\} = \max_{\beta\in[\underline{\beta},1]}\{\frac{1}{4}(q_1+(1-\alpha)q_{2e})-(c_1q_1^2+\beta c_2 q_{2e}{}^2\int x^2 f(x\mid\beta,\rho)dx + dq_1q_{2e})\}$$

From the discussion in the previous section, this problem is the same as choosing β to minimize the parameter $\beta' = \beta\int x^2 f(x\mid\beta,\rho)dx$. Depending on the intrinsic risk, it may or may not be optimal to choose $\beta = \underline{\beta}$.

Consider the following example. Suppose the realized quality follows a simple two-point distribution: the realized quality is $q_2 = q_{2H} = (1+\rho(1-\beta))q_{2e}$ with probability 0.5 and $q_2 = q_{2L} = (1-\rho(1-\beta))q_{2e}$ with probability 0.5. The firm's problem is then to minimize $\beta' = \beta(1+\rho^2(1+\beta)^2)$. We can show that if $\rho^2 \le 3$, the firm should choose $\beta = \underline{\beta}$. But if $\rho^2 > 3$, then firm could choose either $\beta = \underline{\beta}$ or $\beta = 2/3+\sqrt{1-3/\rho^2}/3$. This shows that with low intrinsic uncertainty, the benefit outweighs the drawback of losing control of quality, so the firm should offload as much as possible. When the intrinsic uncertainty is high, however, losing control of quality may be too expensive, so the firm needs to balance the two effects, and settle with a degree of externality in the middle.

Interestingly, it is the *higher* quality that causes the problem in this case, because the firm needs to incur its share of the higher cost since its cost is dependent on the *realized* quality. Observations in real world confirm this: firms in industry often put fairly tight control on what features to be included in open-source products. It could be perplexing why firms would refuse to include features already developed by volunteers; our analysis illustrates the cost implication of such phenomenon.

> *Proposition 6b: When the degree of externality is endogenous decision, if cost is determined by expected quality, the firm should choose highest degree of externality possible, $\beta = \underline{\beta}$. If the cost is determined by realized quality, the firm may choose a lower degree of externality to control the uncertainty.*

Duopoly

In this section, we study firm's incentive to open source under competition. We are interested in the following questions: Would competition make a firm more or less likely to open source? Would the decision to open source depend on the relative quality of the firm in the market? Would one firm's open source decision influence another firm's?

To address these questions, consider a stylized model, where there are two firms in a vertically differentiated market, each producing two complementary products. Each firm sells its products in a bundle, thus the competition is at the "system" level. To focus our attention on the competition and the impact of appropriability and externality (component complementarity is discussed in detail in the monopoly section), we adopt a model setup that is similar to the case of monopoly but abstracts away complementarity by characterizing the value (or quality) that consumers can get at the system level: the system product produced by firm *i* is characterized by its value q_i and price p_i .[2] Both firms are ex-ante identical with the same quadratic cost function $C_i(q_i) = cq_i^2$. Without loss of generality, let firm 1 be the high quality firm: $q_1 > q_2$ (we ignore the case where both have the same quality, as it results in uninteresting Bertrand competition). Each firm has the option to make part of its product (one component) open-source. When doing so, its cost function becomes $C_i^o(q_i) = \tilde{\beta} cq_i^2$, where $\tilde{\beta} \in (0,1]$. Meanwhile, open-source brings to consumers a free product of the two products that make up the "system", which provides value $\tilde{\alpha} q_i$, where $\tilde{\alpha} \in [0,1)$ (use the open-source component alone). The parameters $\tilde{\alpha}$ and $\tilde{\beta}$ capture the degree of demand-side appropriability and supply-side externality similar to parameters α and β in monopoly, with the difference that they represent the degree at the system instead of component level: if $q_i = q_{i1} + q_{i2}$ where q_{i1} and q_{i2} are the two components of the product, and when the second product is open-source users can derive utility $\theta \alpha q_{i2}$ as discussed in monopoly section, then $\tilde{\alpha} = \alpha q_{i2} / q_i$. Similar connection can be drawn between $\tilde{\beta}$ and β in monopoly.

Note that open-source brings with it a free version with lower value makes this setup resemble that of versioning from demand side. However, we should point out an important difference: from the firm's perspective, this version is imposed *exogenously*. Extant research approaches versioning as a product design problem, where firms decide to create multiple versions catering to different clientele. In that setup, firms have full control over the quality and price of each version and use them to the firms' advantage. In open-source, however, the firm controls neither the quality nor the price of the lower value version – the quality is determined by the high value version and the degree of appropriability, while the price is fixed at zero. This additional version is a liability rather than an asset to the firm, which the firm has to weigh against supply-side benefit.

Consider the case where qualities are exogenously determined. When there is no open-source, it is a routine exercise to solve the price game of the standard vertical differentiation model: the optimal prices are $p_1^* = \frac{2q_1(q_1 - q_2)}{(4q_1 - q_2)}$ and $p_2^* = \frac{q_2(q_1 - q_2)}{(4q_1 - q_2)}$, and optimal profits are $\Pi_1^* = \frac{4q_1^2(q_1 - q_2)}{(4q_1 - q_2)^2} - cq_1^2$ and $\Pi_2^* = \frac{q_1 q_2 (q_1 - q_2)}{(4q_1 - q_2)^2} - cq_2^2$.

We first analyze the demand side assuming there is no supply-side benefit of open-source. When firm 1 opens source, a free version is available with value $\tilde{\alpha} q_1$. If $\tilde{\alpha} q_1 \geq q_2$, firm 2 will be driven out of market and firm 1 competes against its own free version only. In this case, compared with the closed-source duopoly, firm 1 competes against a higher value product of lower price, and is expected to charge lower price and make lower profit. If $\tilde{\alpha} q_1 < q_2$, the free product will occupy the lower portion of the consumer segment. Firm 2, facing the new competition from below, is expected to reduce its price, which in turn forces firm 1 to also reduce price. Thus both firms are expected to have lower price and profit than under closed-source. If firm 2, the low quality vendor, opens source, it creates a free version to compete against itself from below. Thus it is also forced to lower price and make lower profit. This leads to the following result:

> *Proposition 7: In a vertically differentiated duopoly where quality is exogenous, absent supply-side externality, neither the high quality nor the low quality firm finds it optimal to open source.*

This result generalizes the finding of proposition 1 to the case of competition. It shows that even under competition, the supply side externality is required to justify firm's decision to open source.

Does the high quality firm or the low quality firm have higher incentive to open source? For firm 1, the difference between profits under open-source and under closed-source is:

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[2] Assuming that the value is a linear function of quality, e.g., the value function adopted in the section of "Endogenous Quality". Since they have a 1-1 mapping, we use the term value and quality interchangeably here.

$$\Delta\Pi_1 = \Pi_1^{o*} - \Pi_1^* = \frac{4(1-\tilde{\alpha})^2 q_1^2 (q_1 - q_2)}{(4q_1 - q_2 - 3\tilde{\alpha}q_1)^2} - \frac{4q_1^2(q_1 - q_2)}{(4q_1 - q_2)^2} + (1-\tilde{\beta})cq_1^2 \quad \text{(D.1)}$$

While for firm 2, that difference is:

$$\Delta\Pi_2 = \Pi_2^{o*} - \Pi_2^* = \frac{(q_1 - \tilde{\alpha}q_2)(1-\tilde{\alpha})q_2(q_1 - q_2)}{(4q_1 - q_2 - 3\tilde{\alpha}q_2)^2} - \frac{q_1 q_2 (q_1 - q_2)}{(4q_1 - q_2)^2} + (1-\tilde{\beta})cq_2^2 \quad \text{(D.2)}$$

For both firms, open-source is better than closed-source only if the supply-side benefit outweighs the reduction in revenue from demand side. For this to be the case for firm 1, the externality parameter $\tilde{\beta}$ must satisfy:

$$1-\tilde{\beta} \geq 1-\hat{\beta}_1^C = \frac{1}{c}\left(\frac{4(q_1 - q_2)}{(4q_1 - q_2)^2} - \frac{4(1-\tilde{\alpha})^2(q_1 - q_2)}{(4q_1 - q_2 - 3\tilde{\alpha}q_1)^2}\right) \quad \text{(D.3)}$$

While for open-source to be profit-increasing for firm 2, the externality parameter must satisfy:

$$1-\tilde{\beta} \geq 1-\hat{\beta}_2^C = \frac{1}{c}\left(\frac{q_1(q_1 - q_2)}{q_2(4q_1 - q_2)^2} - \frac{(q_1 - \tilde{\alpha}q_2)(1-\tilde{\alpha})(q_1 - q_2)}{q_2(4q_1 - q_2 - 3\tilde{\alpha}q_2)^2}\right) \quad \text{(D.4)}$$

If the threshold degree of externality $\hat{\beta}_1^C$ is higher than $\hat{\beta}_2^C$, we would say the high quality firm has higher incentive to open source, ceteris paribas (keep in mind the two firms have the same cost functions), and vice versa. Intuitively, high quality firm enjoys higher supply-side benefit through open-source but also risks losing more revenue, while low quality firm has the opposite effect. It is therefore not clear which firm has higher incentive. Comparing the two threshold value shows that whether firm 1 or firm 2 has higher incentive depends on the quality and the appropriability degree $\tilde{\alpha}$. The situation is easier to characterize when $\tilde{\alpha}$ is small, as shown below:

> *Proposition 8: When $\tilde{\alpha}$ is small, if firm 1 has a significant quality advantage over firm 2 ($q_1 \geq 7q_2/4$), then firm 1 has higher incentive to open source than firm 2; otherwise ($q_2 < q_1 < 7q_2/4$) firm 2 has higher incentive to open source.*

This result suggests that when the two firms differ much by quality, the high quality firm can derive higher supply-side benefit relative to the revenue it forfeits through open-source than the low quality firm. While when the two firms' quality levels are close, the low quality firm experiences revenue squeeze in competition anyway, and finds the supply-side benefit more attractive.

Open-Source Equilibrium

How does one firm's open-source decision interact with that of the other firm? We analyze this using a game theoretic approach. In this game, both firms simultaneously decide whether to open source, and then engage in price competition. We use $\Pi_i(S1, S2)$ to represent firm *i*'s profit when firm 1 chooses strategy $S1$ and firm 2 chooses $S2$, where $S1, S2 \in \{C, O\}$ with C representing closed-source and O open-source. Table 2 summarizes the firms' profit (payoff) corresponding to each strategy profile. We focus on the case where both firms will remain in the market (the case of entry-blocking is quite straightforward).

Table 2: Firm Profit under Different Strategy Profiles

	Firm 2	
	C	O

Firm 1	C	$\Pi_1 = \frac{4q_1^2(q_1-q_2)}{(4q_1-q_2)^2} - cq_1^2$ $\Pi_2 = \frac{q_1q_2(q_1-q_2)}{(4q_1-q_2)^2} - cq_2^2$	$\Pi_1 = \frac{4(q_1-\tilde{\alpha}q_2)^2(q_1-q_2)}{(4q_1-q_2-3\tilde{\alpha}q_2)^2} - cq_1^2$ $\Pi_2 = \frac{(q_1-\tilde{\alpha}q_2)(1-\tilde{\alpha})q_2(q_1-q_2)}{(4q_1-q_2-3\tilde{\alpha}q_2)^2} - \tilde{\beta}cq_2^2$
	O	$\Pi_1 = \frac{4(1-\tilde{\alpha})^2 q_1^2(q_1-q_2)}{(4q_1-q_2-3\tilde{\alpha}q_1)^2} - \tilde{\beta}cq_1^2$ $\Pi_2 = \frac{(1-\tilde{\alpha})q_1(q_2-\tilde{\alpha}q_1)(q_1-q_2)}{(4q_1-q_2-3\tilde{\alpha}q_1)^2} - cq_2^2$	$\Pi_1 = \frac{4(1-\tilde{\alpha})^2 q_1^2(q_1-q_2)}{(4q_1-q_2-3\tilde{\alpha}q_1)^2} - \tilde{\beta}cq_1^2$ $\Pi_2 = \frac{(1-\tilde{\alpha})q_1(q_2-\tilde{\alpha}q_1)(q_1-q_2)}{(4q_1-q_2-3\tilde{\alpha}q_1)^2} - \tilde{\beta}cq_2^2$

To proceed, we first define a few threshold values of $\tilde{\beta}$, whose meanings and values are listed in Table 3. These threshold values are calculated based on the profit functions listed in Table 2. Recall that for both firms, the lower the value of $\tilde{\beta}$, the higher the firm's profit under open-source.

Table 3: Threshold Values of $\tilde{\beta}$

Symbol	Description	Value
$\hat{\beta}_1^C$	The threshold value below which $\Pi_1(O,C) \geq \Pi_1(C,C)$	$1-\hat{\beta}_1^C = \frac{1}{c}\left(\frac{4(q_1-q_2)}{(4q_1-q_2)^2} - \frac{4(1-\tilde{\alpha})^2(q_1-q_2)}{(4q_1-q_2-3\tilde{\alpha}q_1)^2}\right)$
$\hat{\beta}_1^O$	The threshold value below which $\Pi_1(O,O) \geq \Pi_1(C,O)$	$1-\hat{\beta}_1^O = \frac{1}{c}\left(\frac{4(q_1-\tilde{\alpha}q_2)^2(q_1-q_2)}{(4q_1-q_2-3\tilde{\alpha}q_2)^2 q_1^2} - \frac{4(1-\tilde{\alpha})^2(q_1-q_2)}{(4q_1-q_2-3\tilde{\alpha}q_1)^2}\right)$
$\hat{\beta}_2^C$	The threshold value below which $\Pi_2(C,O) \geq \Pi_2(C,C)$	$1-\hat{\beta}_2^C = \frac{1}{c}\left(\frac{q_1(q_1-q_2)}{q_2(4q_1-q_2)^2} - \frac{(q_1-\tilde{\alpha}q_2)(1-\tilde{\alpha})(q_1-q_2)}{q_2(4q_1-q_2-3\tilde{\alpha}q_2)^2}\right)$
$\hat{\beta}_2^{CO}$	The threshold value below which $\Pi_2(O,O) \geq \Pi_2(C,C)$	$1-\hat{\beta}_2^{CO} = \frac{1}{c}\left(\frac{q_1(q_1-q_2)}{q_2(4q_1-q_2)^2} - \frac{(1-\tilde{\alpha})q_1(q_2-\tilde{\alpha}q_1)(q_1-q_2)}{q_2^2(4q_1-q_2-3\tilde{\alpha}q_1)^2}\right)$

First, it is easy to see from Table 2 that, as long as $\tilde{\beta} < 1$: $\Pi_2(O,C) < \Pi_2(O,O)$. This means that (O, C) can never be an equilibrium. The intuition is clear: if firm 1, the high quality firm, opens source, then there is already a free version in the market with value higher than firm 2 would bring to the market with open-source. Thus firm 2 can enjoy supply-side benefit through open-source at no additional cost from the demand side.

We next compare $\hat{\beta}_1^C$, below which $\Pi_1(O,C) \geq \Pi_1(C,C)$, and $\hat{\beta}_1^O$, below which $\Pi_1(O,O) \geq \Pi_1(C,O)$. From Table 3:

$$\hat{\beta}_1^C - \hat{\beta}_1^O = \frac{1}{c}\left(\frac{4(q_1-\tilde{\alpha}q_2)^2(q_1-q_2)}{(4q_1-q_2-3\tilde{\alpha}q_2)^2 q_1^2} - \frac{4(q_1-q_2)}{(4q_1-q_2)^2}\right) \quad \text{(D.5)}$$

It can be shown algebraically that this expression is negative, i.e. $\hat{\beta}_1^C < \hat{\beta}_1^O$. The intuition is that open-source costs firm on the demand side with the free version that comes with it. The higher this cost, the higher supply-side benefit the firm needs to justify it. When firm 2 opens source, it brings a free version to the market, which reduces the additional demand side cost of firm 1 when it opens source as well. This effect lowers the supply-side requirement and makes firm 1, other things equal, more likely to open source.

We now characterize the equilibria of this game. As we show above, (O, C) can never be an equilibrium. Would (C, O) be an equilibrium? To see this, we compare $\hat{\beta}_1^O$, below which $\Pi_1(O,O) \geq \Pi_1(C,O)$, with $\hat{\beta}_2^C$:

$$\hat{\beta}_1^O - \hat{\beta}_2^C = \frac{1}{c}\left(\frac{q_1(q_1-q_2)}{q_2(4q_1-q_2)} - \frac{(q_1-\tilde{\alpha}q_2)(1-\tilde{\alpha})(q_1-q_2)}{q_2(4q_1-q_2-3\tilde{\alpha}q_2)} - \frac{4(q_1-\tilde{\alpha}q_2)^2(q_1-q_2)}{(4q_1-q_2-3\tilde{\alpha}q_2)q_1^{\,2}} + \frac{4(1-\tilde{\alpha})^2(q_1-q_2)}{(4q_1-q_2-3\tilde{\alpha}q_1)}\right) \quad \text{(D.6)}$$

The sign of (D.6) is ambiguous in general. However, we note that first, when $\tilde{\alpha} = 0$, $\hat{\beta}_1^O - \hat{\beta}_2^C = 0$; and second, when $\tilde{\alpha}$ is close to 0, $sign[\partial(\hat{\beta}_1^O - \hat{\beta}_2^C)/\partial\tilde{\alpha}] = sign[4q_1^{\,2} - 7q_1q_2 + 8q_2^{\,2}]$, while the right-hand-side of the equation is always positive. This shows that $\hat{\beta}_1^O > \hat{\beta}_2^C$ for small $\tilde{\alpha}$. As we know, the necessary conditions for (C, O) to be equilibrium are: 1. firm 2 can not increase profit by deviating to closed-source, i.e. $\tilde{\beta} \leq \hat{\beta}_2^C$, and 2. firm 1 cannot increase profit by deviating to open-source, i.e. $\tilde{\beta} \geq \hat{\beta}_1^O$. Apparently both cannot be satisfied at the same time. Therefore, (C, O) cannot be an equilibrium when $\tilde{\alpha}$ is small.

When $\tilde{\beta} \geq \max\{\hat{\beta}_1^C, \hat{\beta}_2^C\}$, neither firm can increase profit through open-source, so (C, C) is an equilibrium.

When $\tilde{\beta} \leq \hat{\beta}_1^O$, (O, O) is an equilibrium, as neither firm can increase profit by going back to closed-source.

We have shown above that $\hat{\beta}_1^C < \hat{\beta}_1^O$, and that $\hat{\beta}_2^C < \hat{\beta}_1^O$ for small $\tilde{\alpha}$.. This means that when $\tilde{\beta}$ is within a certain range, namely $\max\{\hat{\beta}_1^C, \hat{\beta}_2^C\} \leq \tilde{\beta} \leq \hat{\beta}_1^O$, the game has two equilibria: (C, C) and (O, O). In this case, neither firm wants to open source if the competitor does not. But at the same time, neither firm would remain closed-source if the other opens.

Lastly, we compare the two threshold values $\hat{\beta}_2^{CO}$ and $\hat{\beta}_2^C$:

$$\hat{\beta}_2^C - \hat{\beta}_2^{CO} = \frac{1}{c}\left(\frac{(q_1-\tilde{\alpha}q_2)(1-\tilde{\alpha})(q_1-q_2)}{q_2(4q_1-q_2-3\tilde{\alpha}q_2)^2} - \frac{(1-\tilde{\alpha})q_1(q_2-\tilde{\alpha}q_1)(q_1-q_2)}{q_2^{\,2}(4q_1-q_2-3\tilde{\alpha}q_1)^2}\right) \quad \text{(D.7)}$$

This difference can be shown algebraically as positive, so $\hat{\beta}_2^C > \hat{\beta}_2^{CO}$. This is quite intuitive: when firm 1 opens source, there is a free version in the market, so it is harder for firm 2 to achieve higher profit under open-source than if both firms choose closed-source. This, however, makes the situation where $\max\{\hat{\beta}_1^C, \hat{\beta}_2^{CO}\} < \tilde{\beta} < \hat{\beta}_2^C$ (we have shown in previous section that $\hat{\beta}_1^C < \hat{\beta}_2^C$ when the qualities of two firms do not differ significantly) quite interesting: in this situation, (O, O) is the only equilibrium. However, in this equilibrium *both firms make lower profits than if both firms remain closed-source*, resulting in prisoner's dilemma.

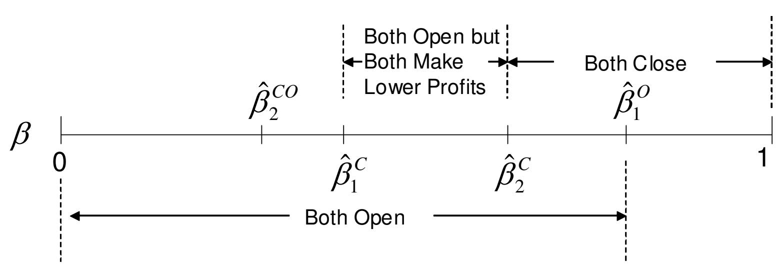

Figure 2: Illustration of Open-Source Equilibria

The discussions above are illustrated in figure 2 and summarized in the following proposition:

Proposition 9: When both firms simultaneously make open-source decision, the equilibrium outcome could be either that both firms remain closed-source, or that both choose open-source, or both. That the high-quality firm chooses open-source while the low quality firm chooses closed-source can never be an equilibrium. And *when $\tilde{\alpha}$ is small, that high-quality firm chooses closed-source while low quality firm chooses open-source cannot be an equilibrium, either. When $\tilde{\beta}$ is within a certain range, both firms will open source, yet both make lower profit than if both remain closed-source.*

Alternatively, we can investigate a Stackelberg model where firms make decisions in a sequential setting, in which case an interesting question to study is whether a firm's open-source decision would make another firm, which would not open otherwise, open source. Our analysis can be easily carried over to that setting, and show that one firm's open-source would encourage the other firm to do the same, with the effect more pronounced if the first to open is the high quality firm. Interestingly, this is consistent with a recent event in industry: in April 2007, Adobe made Flex, a software for building expressive web applications, open-source. Within a week, Microsoft responded by making its competing product, Silverlight, open-source as well. Our result suggests that such response may indeed by optimal, especially given that Flex is perceived to have higher quality than Silverlight.

When firms make open-source decisions sequentially, we could also expect *open-source to be deterred* in certain cases. Specifically, when $\hat{\beta}_2^{CO} < \tilde{\beta} < \hat{\beta}_2^{C}$, if firm 2 decides first, it will choose to remain closed-source: it can increase profit through open-source if firm 1 remains closed-source, however, it knows that firm 1 will respond with open-source if it opens, which in turn makes firm 2's profit lower. This suggests that firm 1's ability to open source effectively deters the open-source of firm 2.

Discussions and Conclusion

Open-source business strategies are much hyped in industry, but a clear understanding on the voluntary open-source by profit-seeking firms remain to be established. The significance of open-source in IT industry calls for focused studies on this issue and motivates our study. Existing research on information goods strategies shed light on this issue. Specifically, the theory of two-sided network effects, which shows that firms may rationally give out their products for free, can be used to partially explain certain open-source examples. However, voluntary open-source goes beyond two-sided network effects: First, the two-sided network effect does not explain why firms "open" rather than just giving out products for free. Second, only a subset of software products can be characterized as belonging to two-sided markets. Third, the two-sided network effects characterize the demand-side, while open-source has significant supply-side implications as well.

Our study complements the existing literature on open-source case studies, economic modeling of open-source platforms, and two-sided network effects. We analyze the incentive to voluntarily open source from firm's perspective and demonstrates its implications on quality and welfare. We show that supply-side externality must be present to justify firms' decision to make their products open-source. Supply-side externality is an important factor that has not been studied in existing literature. We show that open-source increases social welfare when product quality is exogenously given, confirming conventional wisdom, yet the social welfare could be lower when quality is strategically chosen by the firm under open source, because supply-side externality may make the firm deviate from the optimal cost structure, an issue that has not been called to attention. Our study shows that open-source induces firm to increase the quality of the open-source product, but if the complementarity is only at the product level, the firm will also reduce the quality of the complementary product.

Open-source raises the possibility of losing control of product quality. Our analysis shows that monopolist should be more concerned of cost side rather than revenue side of the equation. When cost is highly uncertain, firm may have to rein in the amount of work offloaded to external community.

A firm may open source to battle competition. Nonetheless, our result shows that even in competition, supply-side benefit is a necessary condition to open source. In addition, we find that the high quality firm has higher incentive to open source when its quality advantage is significant compared to the low quality firm, while the low quality one's incentive is higher when the qualities of the two firms do not differ significantly. When competing firms all have options to open source, we find that one firm's open-source encourages others to do the same. We also find that, somewhat surprisingly, that all firms may be forced to open source even when doing so reduces all firms' profits, suggesting that the option to open source may lead to prisoner's dilemma. In a sequential setting, firm's open-source decision may be deterred by competing firms' option to do the same. Our result is confirmed by observations in industry.

Our study makes several unique contributions to the literature: First, we highlight the importance of supply side externality to the voluntary open source. Second, we explore the implication of potential loss of control (or quality uncertainty) of an open-source product. And finally, we study the role of competition and firms' strategic interaction on open-source decisions, and our study highlights their implications to decision makers. To our knowledge, these factors have not been explored in the literature.

Our study has several limitations which call for further work. It does not consider different types of open-source licenses. Different open-source licenses exist in industry, each with different implications. Our study also does not account for standardization, while a firm may open source to establish technology standards which could benefit its other products even though they are not complements. Furthermore, in addition to whether to open, a firm may also need to decide when to open as products go through upgrade cycles. Finally, our study calls for empirical research to verify the implications suggested by our analysis. Open-source related business strategies are still in their early stage. Further study is needed and additional insights are expected as this phenomenon unfolds in industry.

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