



Competitive implications of software open-sourcing

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ABSTRACT

We analyze the economic trade-offs associated with open-sourcing, the business strategy of releasing free open-source versions of commercial software products. We argue that the effect of the release of open-source versions on the customers' perception of products is an important determinant of open-sourcing outcomes. Open-sourcing is modeled as a strategic option for duopolists that compete in a market for software products. We show that open-sourcing can arise as an equilibrium outcome in our simple two-stage game. If the enhancement of customer values from open-sourcing is moderate or high, firms may find it optimal to release open-source versions of their products.

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1. Introduction

In the past decade, the development of open-source software (OSS) has received considerable attention from practitioners and academics. There is very little doubt that the process of developing free, useful and complex software initiated by the OSS movement has made customers better off. Existing research on open-source has focused mainly on issues concerning the underlying motivation of programmers. Our interest here is of a different nature. We wish to investigate the observation, puzzling to many, that many firms in the current business environment choose to open-source some of their software products. In what follows, we refer to the release of a software product to the open-source community as *open-sourcing*. These open-sourced versions directly compete with the firms' commercial product offerings. The co-existence of the commercial and open-sourced versions of the same product by the same firm is our main research question.

The observation that many firms choose to open-source their products as direct competitors to their own commercial products is at first sight puzzling because open-sourcing can hardly be thought of as consistent with profit maximization. Clearly, the commercial product and its open-source counterpart are substitutable to some degree. It seems intuitive that by making a substitute product available free of charge, any software producer would lower its profit from the sale of the commercial product. Thus, we are uneasy about the tension that arises between this apparent reduction in profit

and the observation that an increasing number of software firms choose to open-source their commercial products.

Initial interest about OSS from commercial entities has been materialized by adoption of an OSS product as a core component of a commercial product. An example is IBM's adoption of the Apache web server as a core engine for their WebSphere product. Another example is Apple's development of the Mac OS X operating system, which is based on the FreeBSD open-source operating system.

We have witnessed in the past few years an interesting and intriguing trend that constitutes, in a sense, the reverse side of OSS product adoption. An increasing number of firms release their products, free of charge. For instance, in October 2004, IBM released Cloudscape, a relational database product, to the Apache Software Foundation, an active member of the OSS community.¹ Other examples of open-sourcing include the release by Sun Microsystems of Open Office Suite, a collection of office productivity programs that are derived from their commercial product Star Office. In August 2004 Computer Associates released their database product Ingres as an open-source product. Also notably, in November of 2005 Computer Associates created a new company, Ingres Corp., to provide support and services for their OSS database product. Examples of open-sourced infrastructure software products also abound. In 2009, Citrix Systems, for example, open-sourced XenServer, a software for server virtualization.

The list of examples above is by no means meant to be exhaustive. The evidence points to an increasing number of firms that release

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¹ IBM's open source product was released under the name Derby. It is interesting to note that IBM offers full customer support for the product that was released to the OSS community.

“community editions” of their commercial software to customers who can download the executable programs and their source codes and run them free of charge. We find this evidence rather intriguing. Why would a firm that enjoys a sizable stream of profit from the sale and service of a product choose to create its own competition by releasing a free open-source product? How does open-sourcing affect the competitive environment faced by software firms? And, importantly, is there an economic mechanism through which open-sourcing can contribute to software firms enhancing their competitive position?

The following two quotes suggest some explanations. According to John Prial, IBM's vice president of marketing and information management software,

“By open sourcing Cloudscape, IBM hopes to accelerate development of Java-based applications and drive more innovation around Linux and Java. [...] We think it will especially create new business opportunities [...]” (Prial [22])

Bertrand Serlet, senior vice president of software at Apple, argues that

“[With open-source code,] thousands of people look at the critical portions of source code and check those portions are right. It's a major advantage to have open-source code.” [30]

An increased pace of innovations and improved security through increased exposure are, indeed, two of the major candidate explanations for the recent examples of open-sourcing. But are these sufficient reasons to open-source a product? We argue that the answer is a qualified yes.

Open-sourcing may result in product innovation and quality. The literature mentions several other reasons for open-sourcing. An important such reason is the use of open-source products by firms who wish to gain an advantage over their competitors. Few of the explanations in the literature, however, discuss the impact of open-source products on the customer's perception of the commercial and open-source products. We argue in what follows that the release of an open-source product affects the customers' valuations for the product. We show how this change in customer valuations, in turn, is an important determinant of a firm's open-sourcing strategy.

It is unlikely that the puzzle of open-sourcing can be explained by using a small set of economic arguments. It would be a significant departure from reality to expect that one can build a simple, one-size-fits-all economic model of open-sourcing. Instead of setting out to provide such a comprehensive model of open-sourcing, we have a more modest goal, but also one that is easier to achieve. We intend to show by way of a simple model how open-sourcing can arise as an equilibrium strategy. Even though our model is somewhat stylized, we are able to capture some of the principal economic trade-offs involved in the software developer's decision to release open-source products.

We find that open-sourcing can be profitable in some situations. We show that open-sourcing can arise as a result of competition despite the apparent reduction in profit that is caused by the diminished market share of the commercial product that is due to open-sourcing. We show that if the enhancement of customer value that results from open-sourcing is moderate or high, firms may find it optimal to release open-source products. We also show that when the value gains to the customers from open-sourcing are high, firms cannot fully capture these gains. A firm's inability to funnel some of the customer value gains into higher profits is due to the increased level of competition that is due to open-sourcing. Overall, our results indicate that it is the customers, not the firms, who are likely to benefit the most from open-sourcing.

Our paper has two important managerial implications. First, we show that open sourcing is more likely to be an outcome of competition when firms anticipate that the presence of an open-source product in

the marketplace enhances customer values for its commercial counterpart. This value enhancement may be primarily attributable to new product features, to bug fixes and to improved security that arise in connection with open-sourcing. Second, as intuition suggests, increased competition from the free open-source products of their competitors erodes the profits of the firms that do not release open-source products.

The next section provides a review of the relevant literature. Section 3 gives a brief outline of the market for open-source products. We develop our model in Section 4 and summarize our results in Section 5. Concluding remarks are in Section 6. Some of the proofs and calculations are presented in the accompanying online Technical Appendix.

2. Related literature

Our work is related to the literature on OSS and to the literature on pricing of information goods. We provide first a brief review of the related literature on OSS. The recent developments associated with OSS, including the emergence of Linux as a free and viable operating system option, appear to have gained some notoriety. In turn, this has significantly stimulated the interest of academics and practitioners. A few seminal articles about OSS, notably including Raymond [24], have given rise to a wave of empirical and theoretical work. Schiff [26] provides a comprehensive survey of this early literature on OSS. The current research on OSS can be classified into three broad categories (see [32]). Analysis of the motivations of open source contributors is by far the most popular research topic, perhaps because at its core is the puzzling observation that cohorts of talented programmers choose to contribute to OSS projects with no apparent compensation. This stream of research includes empirical and theoretical papers that aim to explain the motivations of OSS contributors (see [4,13,19]).

Unlike the programmers of most commercial software projects, OSS project contributors are volunteers located in various parts of the world. Topics concerning the governance, organization and innovation processes associated with OSS constitute the second main stream of OSS research. Some of the important research issues include the challenges of managing OSS projects, such as the allocation of tasks and responsibilities, the management of innovation, and the scheduling of product feature enhancements and OSS product releases [17,20,29].

The third stream of research is focused on the competition between open source and traditional, closed-source software. This stream of research includes empirical and theoretical analyses of the public and free nature of OSS products and their impact on the marketplace [5,6,9,21]. Our paper belongs to the third stream of OSS research. We seek to provide some economic explanations for the increased incidence of firms that compete by releasing open-source counterparts of their proprietary software products. Like our analysis, a few studies examine hybrid business models that include proprietary and open source software [5,18]. Krishnamurthy [18] analyzes business models of firms that package, use or provide services for code produced primarily by the OSS community. Bonaccorsi et al. [5] survey Italian firms that have combined proprietary and open source offerings under differing licensing schemes. They provide evidence indicating that firms are keen to adopt new hybrid models. Wichmann [34] provides an early account of the motivations of large firms that participate in OSS activities. Some of the motivations of large firms suggested by Wichmann include the enhancement of a firm's business prospects in a market of a complementary good (e.g., hardware or services), strategic considerations like the adoption of Java-based technologies and the need for product standardization that could enable compatibility among various subsystems, like the adoption of open document formats for word processing software. Lerner and Tirole [19] view open-sourcing as the “razor” that is given for free (the code) to sell more “razor blades” (the hardware that is a complement for their code). They emphasize that open-

sourcing is more likely to be a strategic tool for firms that are too small to compete or who are lagging behind in the commercial segment. Fosfuri et al. [11] investigate the interest of profit-oriented firms in OSS products. Their empirical study highlights the importance of market position and technological capabilities in a commercial firm's decision to introduce OSS products. The empirical study of Rossi and Bonaccorsi [25] discusses the motivations of Italian firms that choose to open their proprietary code. An important motivation in their study is that firms that open their code expect to obtain contributions and feedback in order to fix bugs and improve the software. Other explanations for open-sourcing include, as perhaps best articulated by IBM's Jon Prial Prial [22], an increase in the rate of innovations and the resulting increase in demand for a complementary commercial product of the same firm.

A few studies examine the competition between commercial software and OSS. Casadesus-Masanell and Ghemawat [6] analyze the dynamic interaction in a vertically differentiated duopoly consisting of a profit-maximizing firm and a competitor that prices its output at marginal cost. Their model is inspired by the competition between Linux and Windows and emphasizes dynamic network externalities that arise as a result of demand-side learning. Similarly inspired by the competition between Windows and Linux, Economides and Katsamakas [9] develop a framework for the two-sided pricing strategy of a software product developer whose product serves as a platform for complementary applications. The studies of [6], and [9] assume the existence of an OSS product without specifically addressing the determinants of a firm's decision to open source.

Hawkins [14] makes an important point that the release of code may be profitable because it entails a reduction in the cost of maintaining the code. The basic economic trade-off of open-sourcing is between the increase in the buyers' willingness to pay and the loss of market share that arises as a result of providing a free substitute (and any additional costs incurred in the process of supporting the free substitute software). Mustonen [21] develops a model in which a firm can choose to support a rival "copyleft free" software to gain compatibility. The firm's decision not to support the rival software results in incompatibility between its commercial program and the freely available substitute. In Mustonen [21], compatibility is viewed as a way to increase the customer's willingness to pay for the commercial product because of network effects. The model is similar to ours in that it considers customers who are heterogeneous with respect to their valuations of the competing products, but in his model only one firm acts strategically. A similar analysis by Sen [28] explores the competition between proprietary software, an OSS product and a commercially-supported offering of the OSS product. The three products are modeled to differ in terms of their usability. Customers with the highest valuation for usability end up purchasing the proprietary software, while customers with an intermediate valuation for usability purchase the commercial open-source product, and the rest use the free open-source software. Product differentiation in Sen's model arises because of different product documentation and support services, not because of different product characteristics as proposed in our model. August et al. [1] consider a model in which a firm chooses between open- and closed-source architectures. Profits are obtained from services such as integration, support and consulting associated with the open source product. Choosing the open-source alternative enables a competitive developer to enter the market to provide services for the same product. Their model analyzes the impact of increased competition in the services market. They find that the developer may forgo profits from product sales and rely on an open-sourcing strategy to enhance the profits from the services market.

Our work is also related to the literature on the pricing of information goods, in particular, to the work on versioning of information goods [2,3,8,12,15,16,23,31,33]. These studies focus on situations in which a firm releases quality-differentiated versions of an information good. Each differentiated version creates an opportunity for increased profits through price discrimination, but the release of a new version

carries a danger of cannibalizing the sales of other versions. The versioning literature also considers additional factors like the existence of network externalities, different market structures and the type of product differentiation (vertical or horizontal) as determinants of a firm's versioning decision. While, like most models of versioning, our model views the open source product as a differentiated version of the closed-source product, our model does not view open-sourcing as a tool for price discrimination or as a source of network effects. The fundamentals of our model parallel those of versioning models, but in our model open-sourcing does not entail the same economic trade-offs that occur in connection with versioning.

The explanations given in the literature for the existence of open source software, while providing valuable insight, go only some way toward identifying the reason why software firms choose to open-source their products. In the academic literature and in the media, two stories seem to coalesce as the most likely candidate explanations for open-sourcing. First, the release of open-source products increases market size, so that firms benefit from the sale of complementary products or services. Second, the release of open-source products reduces the cost of maintaining and debugging the code. The logic of both arguments relies on the fact that open-sourcing may be, from a dynamic perspective, profitable for a software firm. Both explanations rely on the intuition that a favorable economic trade-off arises for an open sourcing software firm between short run losses in revenue that stem from "customer loss" (i.e., the reduction of revenue that arises as a result of making a substitute product available free of charge) and, in the long run, increased profitability that is due to higher revenues or lower costs. Clearly, the intuition behind this argument is misguided. If the main consequence of open-sourcing is an increase in the number of customers who use a product, market size could also be increased through free distribution of closed-source software. Free distribution could also result in better testing and reporting of bugs. Furthermore, the reduction in the cost of maintaining or debugging the source code achieved as a result of "more eyeballs" scanning the released source code for bugs could be achieved through the release of the source code to a set of qualified firms or individuals, and not to the community at large.

It is unlikely that the economic drivers of a firm's decision to release open source products could be clearly and easily enumerated. A firm's open-sourcing decision is affected by a multitude of factors. Some of these factors are identified in the literature. Our contribution is to bring to the fore an important, yet little explored aspect of open-sourcing: the impact of open source releases on the customer's valuation of the product. In the next section we highlight some of the important characteristics of open-source products and explore the ways in which these characteristics affect the customer's perception of open- and closed-source products.

3. OSS market and products

Hardly any online forum devoted to a particular software product lacks complaints concerning the product features or, more often, the absence of desired features. In their out-of-the-box state, most software products fail to meet all the requirements of firms and individuals that buy them. The adoption of a particular software product by customers (firms and individuals) is typically associated with the modification of a basic underlying software product. By modification we mean altering the characteristics and functionality of a product in order to suit the needs and to integrate within the existing infrastructure of a customer.

The lack of access to elements of the code that affect functionality makes closed-source products less modifiable than OSS products. Access to the source of the program in the latter type of product enables easier modifications by OSS users. Indeed, OSS users may go as far as to significantly change the product's functionality to integrate it with their information systems. Users of closed-source software products

are typically restricted to making only minor customization changes to the closed-source products. Some of their business processes or technologies may need to be changed in order to effectively integrate the closed software. Clearly, the time and effort spent incorporating desired functionality into OSS products or adapting to the requirements of closed-source products are reflected in costs incurred by the user. Our view is that the cost of customizing an open source product is in general lower than the cost of adapting to the requirements and customizing, to the extent possible, its commercial counterpart.

Intimately related to open-sourcing is the issue of perception of OSS by the customer. Some customers may have a hard time assessing whether an open-source product has the same performance as the original, proprietary product (or a competing developer's product).² Consider the following example. SugarCRM is a provider of commercial open source customer relationship management software for companies with several deployment options to suit the customer's security, integration and configuration needs. They offer two distinct products: Sugar Enterprise Edition and Sugar Community Edition. The Community Edition allows users to view and change the source as long as they follow the Sugar Public License (currently GPLv3). Unlike the free Community Edition, the Enterprise Edition is provided to users at a cost. In addition to price, users of the Sugar software may perceive other differences between the enterprise and the Community Editions. The Community Edition lacks the functionality required to create teams or to assign access levels to the teams [10]. The inability to keep users from deleting each other's contacts, schedules, leads, etc. makes the Community Edition relatively unfit for commercial use. The Enterprise Edition does offer these functional elements. SugarCRM employs full-time developers and the new features incorporated into the commercial product are generally missing from the free OSS product. The SugarCRM example indicates that the OSS counterpart of the proprietary software product is "crimped" in that it has reduced functionality. The concept of crimping is not new. Deneckere and McAfee [7] describe product crimping in the context of technology products. Our example from the software industry is similar in that the commercial developer incurs a cost to provide the lower functionality product. However, the analogy breaks down when we consider that sophisticated OSS users may re-establish the "crimped" functionality by re-writing the relevant code. The free availability of the source code allows the user to make changes to the product at a cost that we believe is lower than the cost of changing the functionality of the proprietary product.

Our model formalizes these features of open-source products. We examine a market where the commercial version of a product provides more functionality (and thus, more intrinsic value to the customers) than the OSS version. We analyze how the impact of open-sourcing on customer's values affects the firm's decision to provide an open-source version in addition to its commercial product offerings. We model the co-existence of open-source and commercial versions of a product by the same firm.

4. The model

We consider the incentives for open-sourcing in a duopoly where the two firms are selling comparative software products. Even though our model may seem more appropriate for desktop software, we do observe several examples of infrastructure software being released as open-source. These applications include VMWare's Zimbra and Citrix's XenServer. SugarCRM may also, at least in part, fall into this category. We would thus like to believe that our model might well be applicable to all types of software as long as the assumptions of

² In fact, comparing the original software to its open-sourced counterpart is problematic, since the code of the original, closed source version is never released. One can only compare the performance or feature set of the OSS product relative to the proprietary alternative.

price, fit cost and benefits we describe next hold.³ The strategies of the firms in our model include a decision to open-source their output by introducing an additional open-sourced versions of their products. These additional versions would compete with each firm's own commercial version as well as its competitor's open-source and/or commercial products. Prior work (Sen [28], August et al. [11]) analyzes the competition between an OSS alternative and a closed-source commercial alternative, and shows that there may be benefits to open-sourcing when services are considered in conjunction with the software product. However, these papers do not focus on the firm's incentives to open-source their products in the absence of competition in the services market. In contrast, our model analyzes the competition between closed- and open-source products as an outcome of the firm's strategic decisions to open source their products. Also, our model assumes that differentiation is embodied in the product itself and not due to differences in documentation and support services. While often software and service are not easy to disentangle, we gain some modeling flexibility by focusing only on the product market.

We model the variability of the fit of a software product to a firm's existing systems and needs using a spatial model of product differentiation. As it is commonplace in the literature on product differentiation, we assume that the two firms are located at the ends of a line segment of unit length and share a measure of customers that we normalize to one without loss of generality. We also assume that the customers are continuously (and uniformly) distributed over the unit length segment and that a customer demands at most one product. We interpret the location of a customer relative to a firm as that customer's ideal product requirement. A customer who is closer to a given firm incurs a smaller disutility to use the firm's software than a customer who is farther away. As such, we model customers as heterogeneous in their fit for the products of the two firms. We assume that the two firms are symmetric in all relevant attributes, except location. To operationalize the notion of fit, we assume that customers incur a specific *unit fit cost* (τ) to use a given software. Given the symmetry of the firms, at equal prices, a customer prefers the firm that is closer. In this sense, customers located relatively close to a firm are "captive" and thus each firm does enjoy some degree of market power.

Fig. 1 provides a depiction of our main setup. Let x denote the distance of a customer from Firm 1 on the unit line. The customer could purchase the output of either firm. We assume that customers purchase at most one unit of output from either of the two firms. If the customer buys the closed-source product of Firm 1, the customer enjoys utility $V - \tau x - P_1$. If the customer buys the closed-source product of Firm 2, the customer enjoys utility level $V - \tau(1 - x) - P_2$.

Either firm has the option of open-sourcing its software product. We note that the closed-source product provides additional value through the use of proprietary features such as specialized tools for archiving or for management, clip art, etc. Since these enhancements are available only to purchasers of the commercial product, the open-source product lacks these proprietary features. As such, the open-source product provides customers with less value than the commercial product.⁴ We denote this reduction in value by Δ_3 . In addition, we recognize that users of both products (commercial and open-source) gain additional value from the availability of the source-code of the open-source product be due to various bug fixes that are offered by the product users. It must be noted that the commercial and the open-source products share the same code-base. Hence, the availability of the source code allows all users to inspect the source code and

³ We thank an anonymous reviewer for pointing this out.

⁴ Note that this is in keeping with the examples of limited open-source versions of Star Office, SugarCRM, VMWare's Zimbra and Citrix's XenServer discussed in Sections 1 and 3.

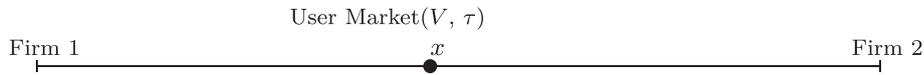


Fig. 1. Market for a software product in duopoly.

identify bug fixes or develop enhancements that are available to all users. Even though a customer may purchase the commercial version to get the additional functionality, it can and may still inspect the code-base and provide feedback, this is specifically true for infrastructure software. We denote this increase in value by Δ_1 . Accordingly, we assume that the value of the commercial product to a customer is $V + \Delta_1$. Letting $\Delta_2 = \Delta_3 - \Delta_1$, the value of the OSS product becomes $V - \Delta_2$. We assume that $\Delta_{1,2} > 0$. Note that the term $\Delta_1 + \Delta_2$ represents the difference in value associated with purchasing the commercial product over its open-source counterpart. Since we view that the OSS product is more easily modifiable than the closed-source product, we assume that a customer's fit cost for the open-source product is $\alpha\tau$ where $0 \leq \alpha \leq 1$. It follows that a customer located at distance x in product space from the first firm enjoys utility levels $UC_1 = (V + \Delta_1) - \tau x - P_1$, and $UC_2 = (V + \Delta_1) - \tau(1 - x) - P_2$ if the customer buys the closed-source product from Firm 1 and Firm 2, respectively. If the customer chooses the open-source alternative of either firm, the customer's net utility level $UO_1 = (V - \Delta_2) - \alpha\tau x$, or $UO_2 = (V - \Delta_2) - \alpha\tau(1 - x)$. Implicit in our definition of open-sourcing is that the OSS products are offered free of charge by the two firms. We take as given in our model, without loss of generality, that customers have the ability to install and use the open-source products without cost.⁵

Before analyzing the possible outcomes in market configurations involving open-sourced products, we note that our analysis focuses only on those situations where all customers in the market are served prior to the firms' decision to open-source. The parameters of our model can be chosen so that the two firms are each local monopolies. In such situations, open sourcing by a firm may result in an increase in the market share of the commercial product, and indeed open sourcing may result in higher profits. To see this, note that the two firms in our model are local monopolies prior to choosing their open-sourcing strategy when $V < \tau$. Intuitively, the higher the fit cost, the more customers become captive to the firm that is closest to them. If the fit cost is high relative to values, some customers would forgo purchases altogether, and thus a firm's pricing decision has no effect on the other firm's profit. It is easily shown that a firm's profit in a local monopoly configuration is equal to $V^2/(4\tau)$. Open sourcing in such situations may increase the market share of a firm's commercial product. In particular, when $\tau > \frac{\Delta_1 + \Delta_2}{1 - \alpha}$ (i.e., when the difference between the value of the open-source and the commercial products is small relative to the reduction of fit cost as a result of open-sourcing), the market share of each firm's commercial product is less than 1/2, so the two firms do not compete head-to-head with their commercial products. Furthermore, whenever $\Delta_1 + \Delta_2$ also satisfies $\Delta_1 + \Delta_2 > V\sqrt{1 - \alpha}$, that is, when the difference in value between the closed- and open-source products of a firm is large relative to the value prior to the release of the open-source version, it can be shown that a firm's profit increases as a result of open-sourcing. However, we find these situations strategically less interesting because in equilibrium the open-sourcing decision of a firm that maintains its local monopoly status does not affect the profits of its opponent. We thus focus only on those situations in which open-sourcing has strategic implications. We discuss next the outcomes of the various modes of competition.

4.1. Duopoly with closed-source products

The simplest case in our environment is that of two firms competing with closed-source products.

Let x_0 denote the location of the customer who is indifferent between purchasing a closed-source product from either firm. We use subscript 0 to indicate outcomes that are obtained in a closed-source duopoly. All customers to the left of x_0 prefer to purchase the output of Firm 1, whereas the customers to the right of x_0 prefer to purchase the output of Firm 2. The profit functions for Firm 1 and Firm 2 respectively are: $\pi_{10} = x_0 P_{10}$ and $\pi_{20} = (1 - x_0) P_{20}$. Since the customer located at x_0 is indifferent between purchasing either product, we have $x_0 = \frac{P_{20} - P_{10} + \tau}{2\tau}$. In equilibrium, the two firms choose their prices P_{10} and P_{20} to maximize their profit, given that their opponent's price is at the equilibrium level. Since the firms are symmetric, we are looking for a symmetric equilibrium that entails $P_{10} = P_{20}$. Fixing Firm 2's price at its equilibrium level P_{20} , Firm 1's profit as a function of its price P is:

$$\pi_1(P) = P \frac{P_{20} - P + \tau}{2\tau}$$

maximizing with respect to P and requiring that, by symmetry, the profit-maximizing price be equal to P_{20} yields $P_{10} = P_{20} = \tau$. Intuitively, as customers incur a higher fit cost they become more captive, and thus the firms enjoy more market power and could afford to increase their prices. The equilibrium profits of the two firms are $\pi_{10} = \pi_{20} = \frac{\tau}{2}$, consistent with the notion that more market power, indicated by higher customer fit costs, translates into higher profits for the two firms. Having established our benchmark, we turn next to an analysis of competition in which one of the firms also offers an open-source product.

4.2. Duopoly with only one firm offering an open-source product

Suppose Firm 1 decides to offer, free of charge, an open-source version of its commercial software product. The introduction of the open-source product has two main effects. First, some of Firm 1's customers would find it more profitable to choose the free open-source product. This effect works so as to reduce the profit of Firm 1. The second effect entails making Firm 2 compete with the free open-source product of Firm 1. This essentially works so as to dampen the effect on Firm 1's profits of changes in the price charged by Firm 2, and also as a way for Firm 1 to "steal" some of Firm 2's customers. It is important to note that the customer who is indifferent between acquiring the product of either firm is contemplating a choice between the free open-source product of Firm 1 and the commercial closed-source product of Firm 2.

Analyzing competition in the presence of an open-source product is somewhat complicated because, depending on the model parameters, three configurations are possible involving varying measures of customers who acquire some of the three products. We depict the most general situation in Fig. 2 below.

The customer located at x_{11} is indifferent between the OSS product and the commercial product offered by Firm 1. The customer located at y_{11} is indifferent between the OSS product (Firm 1's) and the commercial product offered by Firm 2.

⁵ Extensions are possible in which only a fraction of the customers has the ability to use the open-source product; we leave these for further research.

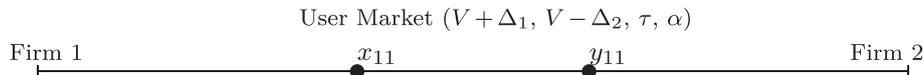


Fig. 2. Market for software products in duopoly where Firm 1 has open-sourced.

4.2.1. Interior solution

We start with an analysis of the “interior solution” in which non-zero measures of customers choose each of the three products.⁶ We use superscript *I* to identify the corresponding parameters. In this setting, all customers to the left of x'_{11} purchase Firm 1’s closed-source commercial product, while all customers located to the right of y'_{11} purchase Firm 2’s commercial product. The customers located between x'_{11} and y'_{11} find it optimal to use Firm 1’s OSS product. It follows that a fraction x'_{11} of the customers purchase Firm 1’s commercial product and that a fraction $1 - y'_{11}$ of the customers purchase Firm 2’s commercial product. The remaining fraction $y'_{11} - x'_{11}$ of customers choose Firm 1’s OSS product. Given the demands for the three products, we can write down the two firms’ profits as $\pi'_{11} = x'_{11}P'_{11}$ and $\pi'_{21} = (1 - y'_{11})P'_{21}$, where P'_i is the price charged by Firm *i*.

To find x'_{11} and y'_{11} we need to set $UC_1 = UO_1$ and $UO_1 = UC_2$. Doing so, we find that:

$$x'_I = \frac{\Delta_1 + \Delta_2 - P'_{11}}{\tau(1 - \alpha)}$$

and

$$y'_I = \frac{P'_{21} + \tau - \Delta_2}{\tau(1 + \alpha)}$$

Since in equilibrium the two firms choose prices to maximize profit, differentiating the two firms’ profits with respect to prices and solving for the two prices yields $P'_{11} = \frac{\Delta_1 + \Delta_2}{2}$ and $P'_{21} = \frac{\alpha\tau + \Delta_2}{2}$. In equilibrium, these prices give rise to values of x'_{11} and y'_{11} that can be expressed as:

$$x'_I = \frac{\Delta_1 + \Delta_2}{2\tau(1 - \alpha)}$$

and

$$y'_I = \frac{\tau(2 + \alpha) - \Delta_2}{2\tau(1 + \alpha)}$$

In equilibrium the profits of the two firms are:

$$\pi'_{11} = \frac{(\Delta_1 + \Delta_2)^2}{4\tau(1 - \alpha)}$$

and

$$\pi'_{21} = \frac{(\alpha\tau + \Delta_2)^2}{4\tau(1 + \alpha)}$$

We need to ensure that, according to our assumption, the parameters of our model are chosen so that $0 < x'_{11} < y'_{11} < 1$. It is readily verified that, given our choice of parameters, $x'_{11} > 0$ and $y'_{11} < 1$. To ensure that $x'_{11} < y'_{11}$, we require that:

$$\Delta_1 < \frac{(2 + \alpha)(1 - \alpha)\tau - 2\Delta_2}{1 + \alpha} \tag{1}$$

⁶ In our setting an “interior” solution indicates that all *x* and *y* values are strictly between 0 and 1 and the most general ordering of the customer cutoff variables is maintained.

When condition (1) is satisfied, there is a positive measure of customers who choose the free OSS version. Since some of these customers could have purchased the commercial product of Firm 1, we term the segment of customers who choose the free OSS version “customer loss.” It turns out that, depending on the choice of parameters, it is possible that customer loss could be avoided altogether by the firm that releases an open-source product. We turn next to an analysis of this situation.

4.2.2. No customer loss ($y_{11} \leq x_{11}$)

If condition 1 is not satisfied, all customers prefer Firm 1’s commercial product to its free OSS version available. Intuitively, Eq. (1) is more likely to be violated if Δ_1 or Δ_2 – or both Δ_1 and Δ_2 – is relatively high, implying that the inherent value of the additional features offered in the commercial version is sufficiently higher than in the free OSS version. Note that the firms’ commercial offerings compete head-to-head in this case. To find conditions under which there is no customer loss, we assume that while no customer finds it optimal to use the OSS version, Firm 1’s commercial product still benefits from the release of the open-source product (perhaps through a better management of code errors). Let superscript *II* denote this region. The profits of the two firms are: $\pi''_{11} = x''_{11}P''_{11}$ and $\pi''_{21} = (1 - x''_{11})P''_{21}$. Since the two commercial versions compete head-to-head, we find x''_{11} by solving for x in $UC_1 = UC_2$ (note also that we need to check that $x''_{11} \in (0, 1)$, so that Firm 2 still serves a fraction of the market). Straightforward calculations yield equilibrium prices chosen by the two firms that can be expressed as $P''_{11} = \tau + \frac{\Delta_1}{3}$ and $P''_{21} = \tau - \frac{\Delta_1}{3}$. Thus, in equilibrium

$$x''_{11} = \frac{3\tau + \Delta_1}{6\tau}$$

Note that Firm 1 enjoys a higher market share than in the benchmark case of Section 4.1 because of the higher value that customers have for its product. The equilibrium profits of the two firms can be written as:

$$\pi''_{11} = \frac{(3\tau + \Delta_1)^2}{18\tau} \tag{2}$$

and

$$\pi''_{21} = \frac{(3\tau - \Delta_1)^2}{18\tau} \tag{3}$$

If the value enhancement provided by the open-source product is large enough, Firm 2 may be driven out of the market entirely. We present an analysis of this case below.

4.2.3. Firm 2 is driven out of the market ($x_{11} \geq 1$)

We use superscript *III* to indicate the parameter region where $x_{11} \geq 1$. It can be easily checked that when the following condition holds, Firm 2 can no longer compete and Firm 1 becomes a monopoly:

$$\Delta_1 \geq 3\tau \tag{4}$$

Note that, as in the previous case, customers prefer the commercial version of Firm 1’s product to its open-source alternative. Thus, it turns out that to maximize its profit Firm 1 chooses price $P'''_{11} = \Delta_1 - \tau$ and has profit $\pi'''_{11} = \Delta_1 - \tau$.

Having exhausted the set of possible outcomes when one of the firms opens up its source code, we turn to an analysis of competition when both firms offer an open-source product.

4.3. Duopoly with open-source products

When both firms decide to open their products, there are four products in the market. The most general market situation is depicted in Fig. 3 below in which non-zero measures of customers choose to purchase one of the four products.

In Fig. 3, the customer at x_{12} is indifferent between the OSS product and the commercial product offered by Firm 1, while the customer located at distance y_{12} from Firm 1 is indifferent between the two OSS products. In addition, the customer located at x_{22} is indifferent between Firm 2's OSS product and the commercial product of Firm 2.

4.3.1. Interior solution

As above, we start with an analysis of the situation in which non-zero measures of customers choose each of the four products. Let superscript I denote the corresponding parameter region. In this setting, all customers who are located on the left of x'_{12} purchase Firm 1's closed-source commercial product and all customers located on the right of x'_{22} purchase Firm 2's commercial product. The customers who are located between x'_{22} and x'_{12} use either Firm 1's or Firm 2's free OSS product. Note that these customers do not contribute to the profits of either firm, so their choice of Firm 1's or Firm 2's OSS product has no effect on the two firms' profits. In this situation, Firm 1 sells its commercial product to a fraction x'_{12} of the customers, while a fraction $1 - x'_{22}$ of the customers choose Firm 2's commercial product. A fraction of customers equal to $x'_{22} - x'_{12}$ choose one of the two OSS products. Once again we refer to the segment of customers of measure $x'_{22} - x'_{12}$ as 'loss.' Given these demands, the profit functions of Firm 1 and Firm 2 are $\pi'_{12} = x'_{12}P'_{12}$ and $\pi'_{22} = (1 - x'_{22})P'_{22}$. Note that x'_{12} is determined by solving for x when $UC_1 = UO_1$. Similarly, y'_{12} can be found by setting $UO_1 = UO_2$ and x'_{22} is found by solving for x in $UO_2 = UC_2$. Straightforward calculations yield $x'_{12} = (\Delta_1 + \Delta_2 - P'_{12}) / (\tau(1 - \alpha))$, $y'_{12} = 1/2$ and $x'_{22} = 1 - (\Delta_1 + \Delta_2 - P'_{22}) / (\tau(1 - \alpha))$.

Differentiating the profit functions of the two firms with respect to their prices, and solving for the prices that jointly maximize the two firms' profits yield:

$$P'_{12} = P'_{22} = (\Delta_1 + \Delta_2) / 2. \tag{5}$$

The equilibrium values of x'_{12} , y'_{12} and x'_{22} are $x'_{12} = (\Delta_1 + \Delta_2) / (2\tau(1 - \alpha))$, $y'_{12} = 1/2$ and $x'_{22} = 1 - (\Delta_1 + \Delta_2) / (2\tau(1 - \alpha))$.

Hence, the equilibrium profits of the two firms can be written as:

$$\pi'_{12} = \pi'_{22} = \frac{(\Delta_1 + \Delta_2)^2}{4\tau(1 - \alpha)}. \tag{6}$$

Note that since the assumed solution entails non-zero measures of customers that use any of the four products, we need $x'_{12} < y'_{12} < x'_{22}$. Since the firms are symmetric, this translates into a single condition involving the two Δ 's. It can be checked that if the following condition is to be satisfied in order for the parameters to yield such a solution:

$$\Delta_1 < (1 - \alpha)\tau - \Delta_2. \tag{7}$$

When this condition is violated, in equilibrium both $x_{12} \geq y_{12}$ and $y_{12} \geq x_{22}$. We derive the firms' optimal pricing solution in this case next.

4.3.2. No customer loss ($x_{22} = x_{12}$)

In this case, the two firms compete head-to-head with their closed-source commercial products. As above, we maintain the assumption that the release of the open-source product increases the value that customers derive from using the commercial version of a product, even though no customer could gain utility from using an open-source product. It turns out that, with or without this assumption, the equilibrium has the same properties as the equilibrium that we analyzed in the benchmark case above (so that x''_{22} is equal to $1/2$ and the profits of the two firms are equal, $\pi''_{12} = \pi''_{22} = \tau/2$).

Having established the outcome of competition in all possible situations in our model, we turn next to an analysis of the incentives that firms may have to open-source their products.

5. Results

5.1. Unilateral open-sourcing

We analyze first the effect of open-sourcing on prices when only one of the firms chooses to open-source its code. We find that the open-sourcing firm will charge a lower price than its opponent only if there is customer loss. The optimal solution entails customer loss if the additional value that is due to open-sourcing (Δ_1) is relatively small (i.e., if Eq. (1) holds). Recall that if this is the case, the open-sourcing firm cannibalizes some of its sales of the commercial product by issuing the free open-source product. The existence of a free open-source product implies that the open-sourcing firm will need to lower its price so as to reduce the extent of customer loss. However, somewhat less intuitive is that when there is no loss, as a result of open-sourcing, a firm will be able to increase the price it charges for its commercial product. The following proposition summarizes this result.

Proposition 1. *With customer loss, the price charged by the firm that unilaterally opens its source code is lower than the price it would have charged had the firm not opened its source code. With no loss, the price charged by the open-sourcing firm for its commercial product is higher.*

Proof. Suppose Firm 1 unilaterally releases an open-source version of its product. If there is no loss, in equilibrium the open-sourcing firm sells its commercial product at $P'_{11} = (\Delta_1 + \Delta_2) / 2$ (see Eq. (5)). We show next that this equilibrium price is less than the price in the benchmark case (τ) if the following holds:

$$\Delta_1 < 2\tau - \Delta_2. \tag{8}$$

Note that condition (8) implies that there is a restriction on the firm's price, $P'_{11} < \tau$. We can easily show that Eq. (8) is satisfied when the solution is interior, as in Section 4.2.1 above. To see this, observe that the right hand side of Eq. (8) is greater than the right hand side of Eq. (1) for all values of $\alpha \in (0, 1)$. Thus, in an equilibrium with customer loss, open-sourcing forces Firm 1 to charge a lower price than in the benchmark case. With no loss, depending on the values of parameters, either Firm 2 is active on the market (in which case the price charged by Firm 1 is $\tau + \Delta_1/3$), or Firm 2 is driven out of the market by the introduction of the open-source product (in

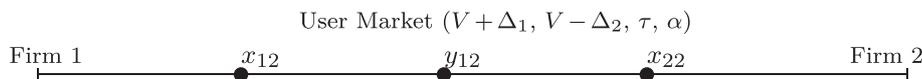


Fig. 3. Market for software products in duopoly where both firms have open-sourced.

which case the price charged by Firm 1 is $\Delta_1 - \tau$). Evidently, in both cases, Firm 1's price is greater than the benchmark price τ . \square

Since in any interior solution the open-sourcing firm lowers its price relative to the benchmark, in order for open-sourcing to be profitable the open-sourcing firm's market share has to increase to compensate the revenue loss on the customers it served in the benchmark equilibrium. This market share increase can compensate the revenue loss only for open-source products that bring about a relatively high incremental value gain Δ_1 . For small values of this incremental gain, open-sourcing is not a viable option. In the following proposition we derive the minimum Δ_1 that guarantees that unilateral open-sourcing is profitable.

Proposition 2. *A firm will increase its profit by unilaterally open-sourcing if*

$$\Delta_1 > \max\left\{0, \min\left\{\tau\sqrt{2(1-\alpha)} - \Delta_2, \frac{(2 + \alpha)(1-\alpha)\tau - 2\Delta_2}{1 + \alpha}\right\}\right\}. \quad (9)$$

Proof. Suppose that Firm 1 unilaterally releases an open-source version of its product. We first show when $\pi_{11} > \pi_{10}$ for the cases discussed in Sections 4.2.1, 4.2.2 and 4.2.3. We start with the two corner solutions. When Eq. (1) does not hold, Firm 2's market share can either be positive (as in Section 4.2.2 above), or zero (as in Section 4.2.3). When Firm 2 is active, $\pi_{11} > \pi_{10}$ is satisfied whenever $\Delta_1 > 0$. When Firm 2 is driven out of the market by the introduction of the open-source product, the first firm's profit increases relative to the benchmark profit whenever $\Delta_1 > (3\tau/2)$. This condition holds true whenever Firm 2 exits the market (i.e., whenever $\Delta_1 > 3\tau$). Therefore, when $\Delta_1 > ((2 + \alpha)(1 - \alpha)\tau - 2\Delta_2)/(1 + \alpha)$, a firm will have an incentive to open its source code unilaterally.

Suppose now that condition (1) holds, i.e., that $\Delta_1 < ((2 + \alpha)(1 - \alpha)\tau - 2\Delta_2)/(1 + \alpha)$. If so, it is straightforward to show that $\pi_{11} > \pi_{10}$ whenever $\Delta_1 > \tau\sqrt{2(1-\alpha)} - \Delta_2$ (see Section 4.3.1 above). Combining the results yields the condition in Eq. (9). \square

The next question we would like to answer concerns the effect of open-sourcing on the profit of the firm that does not open its source code. We show next that open-sourcing unambiguously makes the opponent firm worse off.

Proposition 3. *By unilaterally releasing an open-source version of its product, a firm makes its opponent worse off.*

Proof. Suppose, as before, that Firm 1 unilaterally releases an open-source version of its products and that the solution is interior. We need to show that $\pi_{21} < \pi_{20}$. Suppose to the contrary that $\pi_{21} \geq \pi_{20}$. If so, we need $(\sqrt{2(1+\alpha)} - \alpha)\tau - \Delta_2 \leq 0$. Since, for $\alpha \in (0, 1)$, $\sqrt{2(1+\alpha)} - \alpha > 1$, for $\pi_{21} \geq \pi_{20}$ to be true we require $\tau \leq \Delta_2$. Thus,

$$\frac{(2 + \alpha)(1-\alpha)\tau - 2\Delta_2}{1 + \alpha} \leq \tau(1-\alpha) - \Delta_2 \leq 0, \quad (10)$$

a contradiction, since Eq. (10) implies that the solution cannot be interior, as we assumed, since Eq. (1) is violated. Thus, Firm 2's profit is lower in this situation. Evidently, Firm 2 is also worse off when it is driven out of the market. When there is no customer loss and Firm 2 has positive market share, Firm 2 competes head-to-head with a higher-value product, Firm 2's profit is reduced. This can be easily seen by inspection (compare Eq. (3) with the benchmark profit of $\tau/2$). \square

It is interesting to note that unilateral open-sourcing leads to higher surplus for all customers, since both firms lower their prices.

We have shown that when one of the duopolists releases an open-source version of its product, its profit may increase. Furthermore, the release of the open-source version entails a reduction of the competing firm's profit. The question then naturally arises, what is the

outcome of competition when both firms release an open-source version of their products? We provide an answer in the next section.

5.2. Both firms open-source

Suppose that the parameters of the model are chosen so that all four products in the market (two commercial products and two free open-source products) have positive market shares. As discussed above, this "interior" solution requires that $0 < x'_{12} < y'_{12} < x'_{22} < 1$. Using the results presented in Section 4.3.1 above, it can be verified that $x'_{12} > 0$, $y'_{12} < 1$ and $x'_{22} < 1$ for all feasible parameter values. To ensure that all four products have positive market shares, we also require that the parameters of the model satisfy the condition imposed by Eq. (7).

We provide next an analysis of the effect of open-sourcing on the prices charged by the two firms in equilibrium.

Proposition 4. *The prices charged by the two firms in equilibrium are (weakly) lower when they both open their source code than without open-sourcing.*

Proof. Suppose that the parameters of the model are chosen so that we are in the situation discussed in Section 4.3.1. The equilibrium prices in that case are $(\Delta_1 + \Delta_2)/2$; it can be shown that prices are greater than τ (the equilibrium price with no open-sourcing) if $\Delta_1 > 2\tau - \Delta_2$. In turn, $2\tau - \Delta_2 > (1 - \alpha)\tau - \Delta_2$ for all values of $\alpha \in (0, 1)$, so as long as Eq. (7) is satisfied, the desired result is obtained. When Eq. (7) fails, as discussed in Section 4.3.2, the equilibrium price is equal to the equilibrium price with no open-sourcing. \square

It is noteworthy that firms cannot increase their prices when they both open-source their products. We assumed that the commercial versions of the two products are more valuable to the customers when an open-source version is released. Despite the higher value that customers place on the products of the two firms, the additional value accrues to the customers alone, since in equilibrium the two firms do not profit from the release of the open-source version of their products. Any potential profit gains are lost due to competition. Firms not only compete with each other, but also compete with their open-source versions. The joint release of a free open-source version leads to lower prices for customers. However, since none of the firms is able to increase its market share, the firms' profits cannot increase as a result of open-sourcing. The best the firms can do is to compete head-to-head when there is no customer loss – in this situation the release of the open-source versions of their products has no effect on prices, market shares, and consequently, profits. We summarize this result in the following proposition.

Proposition 5. *The two firms' profits cannot increase as a result of both firms releasing open-source versions of their products.*

Proof. When all four products have positive market shares, the profit for each firm is $\frac{(\Delta_1 + \Delta_2)^2}{4\tau(1-\alpha)}$ (see the calculations in Section 4.3.1 above). Suppose that Eq. (7) holds. It is straightforward to check that these profits are smaller than $\tau/2$ if $\Delta_1 > \sqrt{2(1-\alpha)}\tau - \Delta_2 := \hat{\Delta}_{15}$. In turn, $\Delta_1 > \sqrt{2(1-\alpha)}\tau - \Delta_2$ holds – for all values of $\alpha \in (0, 1)$ – whenever Eq. (7) is satisfied, so profits are indeed reduced as a result of the two firms releasing open-source versions of their products.

When Eq. (7) fails there is no customer loss and the equilibrium price and profits are unchanged from the benchmark case (see Section 4.3.2 above). \square

Our results so far indicate that under some circumstances it is profitable for a firm to unilaterally release an open-source version of its product. Our results also suggest when both firms release open-source versions, their profits are reduced. Our model is predicated on the assumption that the two firms are symmetric. While it is possible

Table 1
Payoff matrix structure.

		Firm payoffs (Firm 1, Firm 2)	
		Firm 2	
		Closed	Open
Firm 1	Closed	$\pi_{neither}, \pi_{neither}$	π_{rival}, π_{self}
	Open	π_{self}, π_{rival}	π_{both}, π_{both}

that the observed pattern of releasing open-source versions of commercial products is driven in part by asymmetries between firms related to costs, customer perception of the products, or the timing of the open-source releases, we wish to investigate next the outcome of competition when the two symmetric firms choose – simultaneously and independently – whether or not to release open-source versions of their products. We turn next to an analysis of the dynamic game induced by the firms' open-sourcing and pricing decisions.

5.3. Open-sourcing equilibrium

We first describe the sequential-move game between our two firms. The game proceeds as follows: In the first stage, the firms independently and simultaneously choose whether or not to release open-source versions. In the second stage, upon observing their opponent's open-sourcing decision, the firms, independently and simultaneously, choose their prices to maximize profit. Our equilibrium concept is subgame perfection (see [27]). A strategy profile for each of the two players is a subgame perfect equilibrium if it is an equilibrium in any of the subgames of the original game. We find the subgame perfect equilibria of our game using backward induction. We start with the second stage of the game. Depending on the firms' actions in the first stage, there are four possible open-sourcing configurations. Only three of which are distinct, due to symmetry. The optimal pricing decisions and payoffs in each of these second stage configurations are discussed in Section 4. The three main cases of Section 4 provide the necessary payoff values for the first stage problem. Thus, we can evaluate the first-stage equilibrium outcomes using the payoffs we deduced in Section 4. We denote the profit of each of the two firms when no firm releases an open-source version by $\pi_{neither}$. The profit of each of the two firms when both firms release open-source versions is denoted by π_{both} . In the asymmetric case when one of the firms releases an open-source version, we denote by π_{self} the profit of the firm that released the open-source version and by π_{rival} the profit of its opponent. Table 1 summarizes the payoffs that correspond to the first-stage actions of the two firms.⁷

The equilibrium outcome can be found by inspecting the firms' payoffs. The outcome of competition depends on the choice of the model's parameters since we have multiple solutions derived in Sections 4.2 and 4.3. Thus, a different payoff structure may exist for different regions of the parameter space. We find that there are four different symmetric payoff matrices to be considered. We relegate the derivation of these payoff matrices to the accompanying online Technical Appendix. Table A-1 in the accompanying online Technical Appendix presents these payoffs.

Relevant in the computation of equilibria is the ranking of the firms' payoffs in different competitive regimes. By choosing different values of the parameters of our model, the ranking of the profits that correspond to the first-stage actions of the two firms changes. Different equilibria were obtained that correspond to the different ranking of the firms' payoffs. We explore the parameter space in terms of the value of Δ_1 , the incremental gain in the value of the commercial product brought about by the release of its open-source version, relative to

⁷ As we shall show, there are multiple payoff matrices to consider. This is due to the existence of multiple solutions.

Table 2
Order of payoffs.

Order of payoffs for different regions	
Region A	$\pi_{neither} \geq \pi_{rival} \geq \pi_{self} = \pi_{both}$
Region B	$\pi_{neither} \geq \pi_{self} = \pi_{both} \geq \pi_{rival}$
Region C	$\pi_{neither} = \pi_{both} \geq \pi_{self} \geq \pi_{rival}$
Region D	$\pi_{self} \geq \pi_{neither} = \pi_{both} \geq \pi_{rival}$

the other parameters of the model. We find that the profits that result from the two firms' first-stage open-sourcing decisions can be ranked differently depending on how the value of Δ_1 compares to the other parameters of the model.

We start by assuming that Δ_2 and τ satisfy $\Delta_2 < \tau$. We turn to discuss next the ordering of the payoffs in the various parameter regions. The ordering of the payoffs is summarized in Table 2; a more detailed version of this table is provided as Table A-2 in the accompanying online Technical Appendix. We also relegate the definition of the cutoffs that define each region to the accompanying online Technical Appendix.

Given these parameter regions and the ordering of the firms' payoffs in each region, we can finalize our equilibrium analysis. Fig. 4 summarizes the equilibria in each of the regions of the parameter space that correspond to Table 2. We note that multiple equilibria co-exist in some of the regions of the parameter space. In region A, since $\pi_{neither} \geq \pi_{self}$ and $\pi_{rival} \geq \pi_{both}$, the firms' dominant first-stage action is not to release an open-source version. Regardless of its opponent's action, each firm is better off with a closed-source product. Therefore, in this case (the benchmark discussed in Section 4.1), in the unique equilibrium the two firms do not release open-source versions.

The equilibria that correspond to parameters that fall in region B also contain outcomes in which the two firms do not release open-source versions. No firm would consider a release of an open-source version if its opponent were not to release an open-source version (since in this region $\pi_{neither} \geq \pi_{self}$). However, not releasing an open-source version is no longer the best action irrespective of the opponent's open-sourcing decision. Given that the other firm has an open-source product, the best response would be to have an open-source product as well, $\pi_{rival} \leq \pi_{both}$. Thus, opening the source code can also be part of the equilibrium. However, both firms are better off in the equilibrium that does not involve the opening of source code.

As above, in region C, there are two equilibria in which the firms either release or do not release open-source versions. Unlike the situation that arises when the model's parameters fall within region B, in region C the firms' payoffs in both equilibria are the same (so the equilibrium that involves releasing an open-source version is no longer payoff dominated).

Inspection of the payoffs in Table 2 indicates that a firm could profitably open up their code when its opponent does not whenever the model's parameters fall within region D. In this region $\pi_{self} \geq \pi_{neither}$ and $\pi_{both} \geq \pi_{rival}$. Thus, irrespective of the action of its opponent, a firm's best first-stage action is to release its source code. Thus, the unique equilibrium has both firms releasing of an open-source version.

It can be easily seen by inspecting the values of the cutoffs that as the value of Δ_2 increases relative to τ , the two regions A and B decrease in size. When $\Delta_2 \geq \tau$ the regions I and II vanish. In that case, both firms open their source code in the unique equilibrium for all values of Δ_1 .

6. Conclusions

In this paper we analyzed the conditions under which firms find it optimal to release open-source versions of their products. Conventional wisdom suggests that open-sourcing increases the size of the market. As some would argue, as a result of open-sourcing software products gain more exposure, which in turn allows firms to reap higher profits through either increased sales of complementary

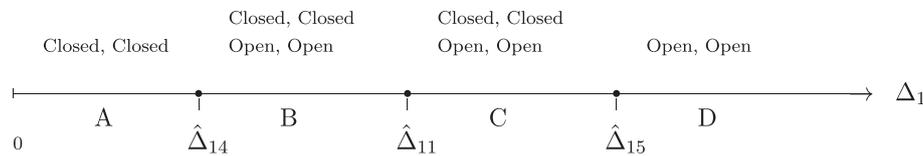


Fig. 4. The equilibria with respect to Δ_1 when $\Delta_2 \leq \tau$.

products (e.g., hardware) or through reduced future costs of maintaining and managing the software code. This explanation is incomplete and somewhat fallacious, as clearly greater profit increases could be achieved through limited releases of the source code or through free distribution of the closed-source product.

Recent research has considered the incentives for open-sourcing in relation to a complementary service market. While in today's business environment the software and service markets are hard to disentangle, we gain some insight by focusing only on the software product market. The main driving force of our model is the impact of open-sourcing on the customers' values. Open-source versions tend to provide less functionality than their commercial versions. However, customers could find the open-source product more valuable than its closed-source counterpart because of the better opportunities for customization. In our model, the "crimped" product competes head-to-head with the products of the competing firm. As a result, the release of an open-source version better insulates a firm from the pricing strategy of its opponent. All things equal, this implies that the firm that releases the open-source version has a competitive edge over its opponent. Clearly, the firm that unilaterally releases the open-source version increases its profit, provided that it can maintain its customer base. If there is customer loss (i.e., when the release of the open-source version causes some of the releasing firm's customers to migrate to the free, open-source version) the outcome is influenced by the trade-off between higher prices and a smaller customer base. We have shown how these trade-offs affect the firms' decision to release open-source products. We identified parameter regions in which the equilibrium has the firms releasing open-source products. An important managerial implication is that open-sourcing is likely to occur when the difference in customer valuation between the proprietary and the open-source products is high relative to the fit cost. It is useful to note that in most examples in which open-sourcing arises in a competitive environment, there is a sizable gap between the customers' valuations of the open- and closed-source products. Clearly, as a result, not all firms in today's software business environment have included open-sourcing in their strategic repertoire. Another implication of our analysis shows that in order to stay competitive, software firms should open-source their products whenever a competitor chose to do so.

The market for software products and services is under continuous evolution. Our model suggests that open- and closed-source software products are bound to co-exist. However, co-existence of the two types of products is more likely when the open-source product lacks significant features, or when the closed-source version becomes more valuable as a result of better code maintenance (including eliminating some bugs in the code). Also important for the open-sourcing decision of firms is the ease with which customers could modify the open-source product. Easier modification of the open-source product implies that, all other things equal, an equilibrium is more likely to arise in which competitive firms release open-source versions of their software products.

Disclaimer

The opinions expressed in this article are those of the author and do not necessarily represent the views of the Federal Communications Commission, its commissioners, or the United States Government.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.dss.2012.05.001>.

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