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## When Does a Platform Create Value by Limiting Choice?

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*(Article begins on next page)*

# When Does a Platform Create Value by Limiting Choice?\*

Ramon Casadesus-Masanell  
Harvard Business School  
Boston, MA 02163  
Phone: +1 (617) 496-0176  
Email: casadesus@gmail.com

Hanna Halaburda  
Harvard Business School  
Boston, MA 02163  
Phone: +1 (617) 495-8544  
Email: hhalaburda@gmail.com

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# When Does a Platform Create Value by Limiting Choice?

## Abstract

We present a theory for why it might be rational for a platform to limit the number of applications available on it. Our model is based on the observation that even if users prefer application variety, applications often also exhibit direct network effects. When there are direct network effects, users prefer to consume the same applications to benefit from consumption complementarities. We show that the combination of preference for variety and consumption complementarities gives rise to (i) a commons problem (to better satisfy their individual preference for variety, users have an incentive to consume more applications than the number that maximizes joint utility); (ii) an equilibrium selection problem (consumption complementarities often lead to multiple equilibria, which result in different utility levels for the users); and (iii) a coordination problem (lacking perfect foresight, it is unlikely that users will end up buying the same set of applications). The analysis shows that the platform can resolve these problems and create value by limiting the number of applications available. By limiting choice, the platform may create new equilibria (including the allocation that maximizes users' utility); eliminate equilibria that give lower utility to the users; and reduce the severity of the coordination problem faced by users.

*Classification-JEL:* D21, D42, L12, L82, L86

*Keywords:* platform governance, direct network effects, indirect network effects, complements, tragedy of the commons, equilibrium selection, coordination, foresight.

# 1 Introduction

Platforms such as computer operating systems (Windows), video game systems (Nintendo), betting exchanges (Betfair), stock exchanges (NYSE), or online gaming sites (Kaixin001) are institutions that facilitate users' access to applications (defined as opportunities to fulfill users' particular purposes—such as writing documents, playing games, betting money, or investing capital).<sup>1</sup> Among the many governance choices that platforms make, they determine the number of applications users have access to (e.g., how many games to offer by a given online gaming platform, how many firms to list by a given stock exchange, and so on). In this paper, we study the relationship between the number of applications available on a platform and users' equilibrium utility. We find that narrow choice often increases utility and thus creates value.

Platforms are characterized by the presence of *indirect* network effects: the larger the number of users means the more firms are willing to join, thus increasing the diversity of applications available, which in turn raises users' valuation of the platform. For example, firms' desire to list their shares in the New York Stock Exchange grows with the number of investors who are expected to trade there; likewise, the larger the number of firms expected to be listed in the NYSE, the more willing the investors are to invest there (Cantillon and Yin 2011). Naturally, indirect network effects induced by users' *preference for application variety* have played a prominent role in models of platforms, beginning at least from the pioneering work of Church and Gandal (1992) and Chou and Shy (1996), and spanning to recent contributions such as Hagiu (2009) and Weyl (2010).

When the value of a platform increases with the number of applications offered, common wisdom dictates that platforms should provide as many applications as possible. Indeed, suboptimal exploitation of indirect network effects may have dreadful consequences; superior platforms (better technology, better capitalized, early movers...) may perish in their competition against second-rate alternatives. Arthur (1990), for example, describes how Sony lost its battle against JVC in the 1980s whose VHS standard was inferior to Betamax, due largely to lesser movie availability on Sony's standard. Likewise, it is widely believed that Apple lost its battle against the PC in the late 1980s because of a dearth of applications. While Microsoft aggressively evangelized independent software vendors and provided them with tools and support, Apple based its approach on in-house development of a small number of applications. By the early 1990s, the number

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<sup>1</sup>Examples of applications include: word processors or spreadsheet programs (in the case of computer operating systems), games (in video game systems or online gaming sites), sports events (in betting exchanges), and listed companies (in stock exchanges).

of applications available for the Mac was a small fraction to that for the PC.

Given the wealth of evidence suggesting that maximizing application variety is a good idea, it is puzzling that successful platform providers such as Betfair, Nintendo, or Kaixin001 appear to have actively limited the number of applications available on their platforms. Betfair provides an electronic platform that allows its customers to back teams to win in sports such as soccer or horse races, but also to lay odds for others to bet on. The company began operations in the U.K. in 2000 as a second mover after Flutter.com. Although Flutter was the first mover and had better access to capital—its initial funding was \$43.7 million vs. £1 million for Betfair—Betfair won over the market.<sup>2</sup> A key difference between the two betting exchanges was that while Flutter would allow users to bet on any event they wished to create (such as next week’s weather), Betfair adamantly restricted the number of events (applications) on which users could bet. Interestingly, the platform that offered fewer applications ended up faring better.

Similarly, in the late 1980s, Nintendo restricted the number of games that developers were allowed to release each year for the Nintendo Entertainment System (NES) to five. The company also restricted the number of developers who could sell games for the NES. Nintendo went on to become the dominant player (market share and profit) for the 8-bit generation.<sup>3</sup> Likewise, the leading online social networking site, Kaixin001, provides a limited number of games for users to engage in (e.g., Parking Cars and Stealing Crops) when many more could be offered. The site offers the smallest number of social games among the top social networking sites in China and lags behind its competitors in making its platform open to third party application developers;<sup>4</sup> however, the site has the most highly active users among them.<sup>5</sup> These examples run counter to the conventional wisdom that when considering application variety in platforms “more is always better.”

In this paper, we ask: why might it be rational for a platform to limit the number of applications when indirect network effects are at play? Our answer is that by limiting the number of applications the platform may resolve three problems faced by users: a *commons* problem, an *equilibrium selection* problem, and a *coordination* problem. When the platform resolves these three problems it creates value because users achieve higher utility. Thus, our analysis focuses on how limiting the number of available applications

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<sup>2</sup>Betfair acquired Flutter in December 2001 and become the dominant betting exchange in Europe. See Casadesus-Masanell and Campbell (2008).

<sup>3</sup>The NES was the leading second-generation (8-bit) game console. Nintendo’s global market share for 8-bit consoles in 1990 was greater than 90%. See Brandenburger (1995).

<sup>4</sup><http://www.nth-wave.com/wordpress/?p=32985>.

<sup>5</sup><http://www.nytimes.com/external/venturebeat/2010/04/07/07venturebeat-chinas-top-four-social-networks-renren-kaixi-55248.html>.

affects the value created.<sup>6</sup>

Our theory is based on the observation that even when platforms enjoy indirect network effects, applications often exhibit *direct* network effects, i.e., users are better off using the same applications as other users due to *consumption complementarities*. For example, Cantillon and Yin (2010) demonstrate that there are important direct network effects in derivatives' trading. Specifically, as the number of traders for a particular derivative increases, so does liquidity. Similarly, the richness of gameplay in massively multiplayer online games (MMOG), such as World of Warcraft, is based on the number of interactions between players; MMOGs are not fun if played alone. When users have limited resources (such as finite time to enjoy applications or an income constraint) and there are many applications available, they must pick and choose which ones to use. If direct network effects are at play, users are better off by purchasing and consuming the same limited set of applications.

We show that when users prefer application variety but also benefit from consumption complementarities, three issues may arise. First, the number of applications that maximizes users' utility may not be part of an equilibrium as each user may find it optimal to unilaterally deviate to consume more applications so as to better satisfy her craving for variety. This is because agents do not internalize the negative externalities they impose on others: a single user suffers almost nothing from the decrease in consumption complementarities when he increases the number of applications consumed while, in aggregate, the loss of consumption complementarities is much greater. Second, multiple equilibria often arise. With the usual assumption that users have perfect foresight, any one of those equilibria could, in principle, be selected. While some equilibria lead to higher user utility than others, nothing guarantees that the equilibrium yielding the highest utility will be selected. Third, if users lack perfect foresight on each others' choices in equilibrium, it is unlikely that they will end up purchasing and consuming the exact same set of applications, but such coordination is necessary to fully exploit consumption complementarities.

Our analysis demonstrates that by limiting the choice of applications, the platform can accomplish three tasks. First, it can create equilibria that did not exist when application choice was broad. In particular, the allocation that maximizes users' utility can be guaranteed to be an equilibrium thus relieving the commons problem. Second, it can eliminate socially inferior equilibria, effectively resolving the equilibrium selection

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<sup>6</sup>We do not consider how the platform may capture that value through prices (access prices and/or royalties). We note, however, that generating larger user surplus allows the platform to charge higher access fees to users. A detailed analysis of platform pricing (i.e., value capture) is beyond the scope of this paper and left for future research. See Section 4 for a more detailed discussion of this issue.

problem. Third, it can reduce the severity of the coordination problem faced by users when they do not know other users' choices in equilibrium. With a smaller choice set, it is more likely that users will end up purchasing and consuming the same applications and are thus more likely to enjoy consumption complementarities. We conclude that when direct and indirect network effects are at play, platforms may create value by limiting choice.

Contrary to the recent literature on multi-sided platforms (e.g., Rochet and Tirole 2003; Caillaud and Jullien 2001; Armstrong 2006; Hagiu 2009; Casadesus-Masanell and Ruiz-Aliseda 2009), which for the most part focuses on pricing and developer entry, we study the behavior of users and consider exogenous application prices. We show, however, that the three problems faced by users due to concurrent direct and indirect network effects (i.e., commons, equilibrium selection, and coordination) arise regardless of the prices of applications.<sup>7</sup> The key implication is that the platform cannot induce users to consume the optimal number of applications by manipulating application prices.

The conventional wisdom why platforms must promote large numbers of applications is that users' consumption utility increases with the number of applications available (due to preference for variety). Obviously, larger utility allows the platform to charge higher access prices. Our results imply, counterintuitively, that when direct and indirect network effects are at play, the platform will typically be able to charge higher access prices to users—and thus earn additional profits—if it also restricts the number of applications available.

## 1.1 Literature

Our paper contributes to the literature on multi-sided platforms and two-sided markets. Pioneering work by Spulber (1996, 1999) examines how firms establish markets acting as intermediaries between buyers and sellers. The platforms that we study also establish markets as they bring users and developers together. The literature on multi-sided platforms and two-sided markets has continued to flourish on the basis of industry-specific models. Rochet and Tirole (2003), for example, is inspired by the credit card industry; Armstrong (2006) captures well the economics of newspapers; and Hagiu (2009) considers competition between video game systems. General results have been derived by Spulber (2006) who models centralized and decentralized two-sided markets through network theory. Likewise, Rochet and Tirole (2006) proposes a formal definition of two-sided markets

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<sup>7</sup>In this paper, we limit our attention to environments with symmetric prices of applications, i.e., the applications are a priori homogeneous, and each is sold at the same price.

and presents a general framework for the analysis of such markets; and Weyl (2010) develops a general theory of monopoly pricing of networks with weak constraints on the nature of user heterogeneity.

While most of the literature on platforms has examined issues related to pricing, there is a new and growing line of work studying platform governance beyond pricing. Hagiu and Jullien (2011), for example, demonstrates that platforms may have incentives to make it harder for users to gain access to the other side of the market. Likewise, Caillaud and Jullien (2003) considers the impact of matching technology on platform competition. Our paper focuses on one aspect of platform governance that has received little attention thus far: the effect of limiting the choice of applications on user behavior, and ultimately on the value created by the platform.

The only two papers we are aware of that are directly related to the question that we address here are Zhao (2010) and Hałaburda and Piskorski (2010). Zhao (2010) studies hardware/software platforms and explores the effects of quantity constraints on product quality and variety on a monopolistic two-sided platform where quality is uncontractible. He finds that when users cannot perfectly observe application quality, developers underinvest in quality and the platform can then use quantity restraints to help mitigate free-riding and increase overall application quality.<sup>8</sup> While Zhao (2010) studies the effects of quantity limitations on the behavior of developers, we study the effects on the behavior of users. A second point of differentiation is that while he provides an explanation for why it may make sense for the platform to limit the number of applications per developer, in his theory the platform gains nothing from limiting the number of developers. Therefore, contrary to ours, his theory is silent about the benefits of limiting the overall number of applications offered by the platform.

Hałaburda and Piskorski (2010) studies dating platforms, an environment with indirect network effects: men prefer a market with a larger number of women, and women prefer a market with more men. This paper shows that, nonetheless, users may benefit when dating platforms limit the number of candidates among which to find a match. This is because dating platforms limit the number of candidates on both sides. Thus by limiting choice, platforms also limit competition between agents in the same side. Some agents prefer a platform with less choice, because it increases the probability that they will find a match. The current paper differs from Hałaburda and Piskorski (2010) in two ways. First, Hałaburda and Piskorski (2010) is the best suited for markets with one-to-one

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<sup>8</sup>Hagiu (2011), in turn, studies how a platform can increase the average quality of platform participants by imposing restrictions on user access—as opposed to limiting the number of applications available.



matching, like dating or housing markets. The current paper focuses on markets where users can consume a large number of applications. Moreover, applications are infinitely duplicable: when one user consumes an application, it does not limit the availability of the same application to other users. Second, our setting lacks the competitive effect that drives the result in Halaburda and Piskorski (2010). To the contrary: as a result of consumption complementarity, the direct network effect is positive. Users gain if more users (on the same side of the market) consume the same applications. Thus, users benefit when the platform restricts choice because it helps them take advantage of consumption complementarities to a fuller extent rather than avoiding competition.

The paper is organized as follows. In Section 2 we present the game with perfect foresight, solve for equilibria under direct and indirect network effects, and discuss the utility implications of the platform limiting choice. In Section 3 we recast the model as one where users have no foresight about other users' choices in equilibrium. In Section 4 we discuss our main modeling choices as well as some extensions to the analysis. Section 5 concludes. Appendix A shows that our results hold for a generalized formulation of the model. All proofs are in Appendix B.

## 2 Game with perfect foresight

We consider a platform which brings together developers and users of applications. There is a set  $\mathbb{A}$  of available applications and  $N$  users. We denote the cardinality of  $\mathbb{A}$  by  $A$ . We treat  $N$  and  $\mathbb{A}$  as exogenous.

Let  $x_a^k$  denote user  $k$ 's consumption of application  $a$ . The consumption utility that user  $k$  derives from consuming  $\mathbf{x}^k = (x_1^k, x_2^k, \dots, x_A^k)$  applications is given by

$$u(\mathbf{x}^k; \{\mathbf{x}^l\}_{l \neq k}) = \underbrace{\left( \sum_{a \in \mathbb{A}} (x_a^k)^{1/R} \right)^R}_{\text{preference for variety}} + \underbrace{\alpha \sum_{a \in \mathbb{A}} (x_a^k \sum_{l \neq k} x_a^l)}_{\text{consumption complementarity}},$$

where  $\alpha \geq 0$  captures the strength of consumption complementarity, and  $1 \leq R < 2$  captures the intensity of the user's preference for variety.<sup>9</sup> The larger is  $\alpha$ , the more the

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<sup>9</sup>Note that when  $\alpha = 0$ , preferences are as in Dixit and Stiglitz (1977). Moreover, the analysis is only interesting for  $R < 2$ . For such  $R$ , the marginal benefit from consuming another application is positive but decreasing. Conversely, for  $R \geq 2$ , the marginal benefit from consuming another application is increasing or constant. Thus, since for  $p < X$  a user finds it beneficial to consume one application, then for  $R \geq 2$  she will always find it beneficial to consume *all* applications. To keep the analysis interesting, we restrict  $R < 2$ .

users benefit from consuming the same applications. Likewise, the larger is  $R$ , the more the users prefer application variety, i.e., consuming a larger number of applications.

Consumption utility  $u$  captures both, direct and indirect network effects. *Indirect* network effects originate from users' preference for variety: users prefer platforms with more users because it is more likely that more applications will be developed for that platform. Therefore, when  $R$  is larger, the source of indirect network effects is stronger. When  $R = 1$ , however, users have no preference for variety, and therefore there are no indirect network effects.

*Direct* network effects are present when a user's utility from consuming an application increases with other users' consumption levels of the same application. For example, users of video games enjoy a given game more if their friends also consume the same game, as they can discuss strategies to beat the game, their experiences, etc. Direct network effects are captured by the term  $\alpha \cdot x_a^k \cdot \sum_{l \neq k} x_a^l$ : user  $k$ 's enjoyment of her consumption of application  $a$  is larger the more the other users ( $l \neq k$ ) consume application  $a$ . We let  $\alpha \geq 0$ . When  $\alpha = 0$ , there are no direct network effects and as  $\alpha$  increases, direct network effects become stronger. In summary, user preferences may exhibit direct or indirect network effects, or both, depending on the value of parameters  $\alpha$  and  $R$ .

We assume that users have a budget of  $X$  units of time to consume applications and interpret  $x_a^k \geq 0$  as the amount of time that user  $k$  spends consuming application  $a$ . Thus, if user  $k$  consumes a set  $\mathbb{Q}^k \subseteq \mathbb{A}$  of applications, she must satisfy the time budget constraint:  $X \geq \sum_{a \in \mathbb{Q}^k} x_a^k$ . Each application is sold at an exogenous monetary price  $p > 0$ , regardless of how much time users spend consuming it.<sup>10</sup> Since the monetary dimension is different from the time dimension, spending  $p$  does not detract from the time budget  $X$ . We assume that  $p$  is sufficiently low for users to find it desirable to purchase and consume at least one application, i.e., we let  $p < X$ . Therefore, it follows that users consume at least one application, i.e.,  $Q^k \geq 1$ , where  $Q^k$  denotes the cardinality of  $\mathbb{Q}^k$ .

User  $k$ 's net utility from consuming  $\mathbf{x}^k$  when price is  $p$  is given by

$$U(\mathbf{x}^k; \{\mathbf{x}^l\}_{l \neq k}) = u(\mathbf{x}^k; \{\mathbf{x}^l\}_{l \neq k}) - p \cdot \sum_{a \in \mathbb{A}} \mathbf{1}(x_a^k), \quad (1)$$

where  $\mathbf{1}(\cdot)$  is an indicator function taking value 1 when its argument is different from zero.

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<sup>10</sup>As foreshadowed in footnote 7, this analysis focuses on the case where the prices of applications are symmetric. We leave the analysis of the environment with asymmetric prices for future research. The results for  $p = 0$  can be found in Appendix B of the working paper version (Casadesus-Masanell and Halaburda 2010).

Since the focus of our analysis is on the value of limiting choice, we also assume that absent action by the platform to constrain the set of available applications, the cardinality of  $\mathbb{A}$  is large. Specifically, we assume that  $A \geq \left(\frac{(R-1)X}{p}\right)^{\frac{1}{2-R}}$ . We will show (see Remark 2) this guarantees that there are sufficiently many different applications available for users to satisfy their preference for variety.

We consider the following two-stage game: In the first stage, all users decide simultaneously which applications to purchase at price  $p$ . In the second stage, users decide simultaneously how to allocate their time budget  $X$  across the applications they have purchased. We solve for the subgame-perfect Nash equilibria in pure strategies and follow Katz and Shapiro (1985) in assuming that expectations are fulfilled in equilibrium.<sup>11</sup>

Formally, given that user  $k$  has already purchased a set of applications  $\mathbb{Q}^k$ , in the second stage she chooses consumption  $\mathbf{x}^k$  to maximize her own consumption utility  $u$  given the expected consumption of all other  $N - 1$  users,  $\mathbf{x}^l$  for  $l \neq k$ :

$$\max_{x_a^k, a \in \mathbb{Q}^k} u(\mathbf{x}^k; \{\mathbf{x}^l\}_{l \neq k}) \quad \text{subject to} \quad X \geq \sum_{a \in \mathbb{Q}^k} x_a^k. \quad (2)$$

In the first stage, users choose the set of applications to purchase,  $\mathbb{Q}^k \subseteq \mathbb{A}$ , anticipating their own consumption and that of all other users in the second stage. User  $k$ 's objective is to maximize her own net utility  $U$ .

We end the description of the model by presenting two definitions that are helpful for the discussion of equilibria.

**Definition 1 (balanced strategy)** *Let  $\mathbb{Q}^k = \{a | x_a^k > 0\}$  be the set of applications consumed by user  $k$ , and let  $Q^k$  be the cardinality of  $\mathbb{Q}^k$ . We say that user  $k$ 's strategy is balanced if  $x_a^k = \frac{X}{Q^k}$  for all  $a \in \mathbb{Q}^k$ .*

Thus, a balanced strategy is one where the user allocates her time budget equally across all the applications she consumes. Note that balanced strategies are pure strategies and that for any  $\mathbb{Q}^k$  there is a unique balanced strategy.

**Definition 2 (balanced equilibrium)** *An equilibrium is balanced if all users play balanced strategies.*

In this section, we solve the game under the assumption that users have perfect foresight about other users' choices in equilibrium. This is a classic assumption of rational

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<sup>11</sup>As we argue in Section 4, solving for the subgame perfect Nash equilibrium in a two-stage game leads to the same results as the single-stage formulation, but is technically more convenient.

beliefs—a part of Nash equilibrium. Later, in Section 3 we relax the perfect foresight assumption.

In the remainder of this section, we investigate each type of network effect separately before considering the interplay of both types together. We first study the model with direct network effects and find that users consume one single application so as to take full advantage of consumption complementarities (Section 2.1). Then, we move on to the model with pure indirect network effects and find that users choose to consume a large number of applications driven by their preference for variety (Section 2.2). Next, we study the interplay between the two types of network effects and find that there is a tradeoff between harnessing consumption complementarities and the utility gains from product variety. In the equilibrium that yields the highest utility to users, they always consume a smaller number of applications than under pure indirect network effects (Section 2.3). Finally, we show that the platform can create value by limiting the number of applications available even if users have perfect foresight about each others’ purchase and consumption decisions (Section 2.4).

## 2.1 Direct network effects

There are pure direct network effects when users derive utility from consuming the same applications as other users but not from product variety. Therefore, consumption utility  $u$  exhibits pure direct network effects when  $R = 1$  and  $\alpha > 0$ . In this case, user  $k$ ’s net utility (1) takes the form

$$U_D(\mathbf{x}^k; \{\mathbf{x}^l\}_{l \neq k}) = \sum_{a \in \mathbb{A}} x_a^k + \alpha \sum_{a \in \mathbb{A}} (x_a^k \sum_{l \neq k} x_a^l) - p \cdot \sum_{a \in \mathbb{A}} \mathbf{1}(x_a^k).$$

User  $k$ ’s consumption of application  $a$  in an equilibrium is denoted by  $\hat{x}_a^k$ . Let  $\mathbb{Q}_D^k \subseteq \mathbb{A}$  be a set of applications that user  $k$  consumes in equilibrium in an environment with pure direct network effects. Then, the cardinality of  $\mathbb{Q}_D^k$  is  $Q_D^k = \sum_{a \in \mathbb{A}} \mathbf{1}(\hat{x}_a^k)$ . Remark 1 characterizes the equilibria in this case.

**Remark 1** *When  $R = 1$  and  $\alpha > 0$ , in every equilibrium  $\mathbb{Q}_D^k = \mathbb{Q}_D$  for all  $k$  and the number of applications consumed is  $Q_D^k = Q_D = 1$  for all  $k$ . There are  $A$  equilibria. All equilibria are balanced and yield the highest possible utility to the users.*

**Proof.** See Appendix B, page 33.

Because  $R = 1$ , users derive no utility from product variety. However, because  $\alpha > 0$ , they derive utility from other users consuming the same applications for longer periods of time. Indeed, user  $k$ 's marginal utility of consuming application  $a$  is increasing in other users' aggregate consumption of  $a$ ,

$$\frac{\partial u_D(\mathbf{x}^k; \{\mathbf{x}^l\}_{l \neq k})}{\partial x_a^k} = 1 + \alpha \cdot \sum_{l \neq k} x_a^l.$$

Therefore, the more other users consume application  $a$ , the more user  $k$  desires to consume  $a$ . Since the same applies to all users, in equilibrium all users consume the same application. Users could coordinate on any one of the  $A$  applications available, since all users and all applications are homogeneous.

## 2.2 Indirect network effects

There are pure indirect network effects when users derive utility from product variety but not from consuming the same applications as other users. Therefore, consumption utility  $u$  exhibits pure indirect network effects when  $1 < R < 2$  and  $\alpha = 0$ . In such a case, user  $k$ 's net utility (1) takes the form

$$U_I(\mathbf{x}^k; \{\mathbf{x}^l\}_{l \neq k}) = \left( \sum_{a \in \mathbb{A}} (x_a^k)^{1/R} \right)^R - p \cdot \sum_{a \in \mathbb{A}} \mathbf{1}(x_a^k). \quad (3)$$

Note that (3) is essentially the same as the setup in Dixit and Stiglitz (1977), with two exceptions. First, the cost of time spent using application  $a$  is set in our model to 1 for all  $a \in \mathbb{A}$ . Second, we impose a price  $p > 0$  that users must pay to use an application.<sup>12</sup> Remark 2 characterizes the equilibria under pure indirect network effects.

**Remark 2** *Assume  $1 < R < 2$  and  $\alpha = 0$ . In every equilibrium the number of applications consumed is  $Q_I^k = Q_I$  for each user  $k$ , where  $Q_I = \max\{1, (\frac{(R-1)X}{p})^{\frac{1}{2-R}}\}$ . All equilibria are balanced and yield the highest possible utility to the users.<sup>13</sup>*

<sup>12</sup>More precisely, our cost of time (which we normalize to 1) corresponds to the application prices in the original Dixit-Stiglitz's formulation. In contrast to Dixit-Stiglitz, we assume that users must pay a fixed price for access to each application she consumes,  $p > 0$ . This price is independent of the usage. For example, when users buy a particular videogame title, they pay for it once regardless of the usage, then they allocate scarce time to playing the game. In our model, the price of the game is  $p$  and the opportunity cost of time allocated to playing the game is 1.

<sup>13</sup>There are  $\frac{N \cdot A!}{Q_I!(A-Q_I)!}$  pure-strategy subgame-perfect Nash equilibria and continuum mixed strategy equilibria.

**Proof.** See Appendix B, page 34.

To understand this result, notice that Dixit and Stiglitz (1977) implies that when  $\alpha = 0$  and  $p \rightarrow 0$ , the solution to optimization problem (2) is  $Q_I \rightarrow \infty$  and  $\hat{x}_a^k = \frac{X}{Q_I} \rightarrow 0$ . Users derive utility from product variety and find it optimal to consume as many applications as possible in equal proportions. The result is driven by the fact that, as long as  $R > 1$ , applications have infinite marginal consumption utility around zero,

$$\lim_{x_a^k \rightarrow 0} \frac{\partial u_I(\mathbf{x}^k; \{\mathbf{x}^l\}_{l \neq k})}{\partial x_a^k} = \infty,$$

and that this marginal utility decreases as consumption increases. Therefore, spreading the time budget evenly across  $Q + 1$  applications yields more utility than spreading the same time budget across  $Q$  applications.

To determine how many applications to purchase, users must compare the additional benefit from consuming an additional application and the price  $p$  that they must pay for that application. Specifically, if  $Q$  applications are consumed by a user in optimal consumption schedule, her utility is  $(Q(\frac{X}{Q})^{\frac{1}{R}})^R - pQ = Q^{R-1}X - pQ$ . Therefore, the marginal benefit from increasing  $Q$  is  $(R-1)Q^{R-2}X$ . The marginal cost of an additional application is  $p$ . The number of applications at which the marginal benefit and marginal cost are equal is  $(\frac{(R-1)X}{p})^{\frac{1}{2-R}}$ .

As customary in the platforms literature (e.g., Ellison and Fudenberg 2003), we ignore the integer problem and treat the number of applications  $Q$  as a continuous variable. As indicated on page 7, users consume at least one application. Thus, if  $(\frac{(R-1)X}{p})^{\frac{1}{2-R}} < 1$ , the user consumes one application. That is, the optimal consumption is characterized by  $Q_I = \max\{1, (\frac{(R-1)X}{p})^{\frac{1}{2-R}}\}$ . As we show later, the number of applications consumed under direct and indirect network effects is never larger than  $Q_I$ . Therefore, to focus on non-trivial analysis, from now on we assume  $Q_I > 1$ ,<sup>14</sup> which implies  $Q_I = (\frac{(R-1)X}{p})^{\frac{1}{2-R}}$ .

Let  $\mathbb{Q}_I^k \subseteq \mathbb{A}$  be the set of applications that user  $k$  consumes in equilibrium in an environment with pure indirect network effects. Remark 2 states that all users consume the same number of applications in equilibrium, i.e.,  $Q_I^k = Q_I$  for all  $k$ . However, it does not need to be that users consume the same applications, i.e., it may be that  $\mathbb{Q}_I^k \neq \mathbb{Q}_I^l$  for  $k$  and  $l \neq k$ . This is because users gain no utility from consuming the same applications as others. Thus, any  $N$  subsets of  $\mathbb{A}$  with cardinality  $Q_I$  constitutes an equilibrium.

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<sup>14</sup>The working paper version (Casadesus-Masanell and Halaburda 2010) also considers the case where  $Q_I = 1$ .

### 2.3 Interplay between direct and indirect network effects

Now we investigate what happens when users in the platform experience both direct and indirect network effects so that they derive utility from product variety and from consuming the same applications as other users. In such a case,  $1 < R < 2$  and  $\alpha > 0$ . Let  $\mathbb{Q}_{DI}^k \subseteq \mathbb{A}$  be a set of applications that user  $k$  consumes in equilibrium in an environment with direct and indirect network effects, and let  $Q_{DI}^k$  be the cardinality of  $\mathbb{Q}_{DI}^k$ . Note that in the cases of pure direct and of pure indirect network effects, all equilibria could be uniquely characterized by the number of applications user  $k$  consumes in equilibrium, i.e.,  $Q_D^k = 1$  and  $Q_I^k = \left(\frac{(R-1)X}{p}\right)^{\frac{1}{2-R}} > 1$ . However, as we show below, when both direct and indirect network effects are present, multiple values of  $Q_{DI}^k$  are possible.

The study of this hybrid specification is substantially more complex than the cases of pure direct and pure indirect network effects. We will show that there is always a set of equilibria close to  $Q_I$ , the number of applications that users would choose if only indirect network effects were at play. And if consumption complementarity is sufficiently strong relative to preference for variety, another set of equilibria emerges around consuming  $Q_D = 1$  (the equilibrium number of applications consumed under pure direct network effects). Specifically, under hybrid network effects, equilibria emerge which are not equilibria under pure network effects of either type. Moreover, possible cardinalities of the consumption set in an equilibrium depend on the strength of consumption complementarity relative to that of preference for variety. We present the analysis in parts, beginning with two helpful lemmas.

**Lemma 1** *Assume that  $1 < R < 2$  and  $\alpha > 0$ . In every balanced equilibrium  $\mathbb{Q}_{DI}^k = \mathbb{Q}_{DI}$  for all  $k$ .*

**Proof.** See Appendix B, page 35.

**Lemma 2** *Assume that  $1 < R < 2$  and  $\alpha > 0$ . If  $Q_{DI}$  is the cardinality of the consumption set in a balanced equilibrium, then any set of applications  $\mathbb{Q}_{DI} \subseteq \mathbb{A}$  of cardinality  $Q_{DI}$  constitutes a balanced equilibrium.*

**Proof.** See Appendix B, page 36.

Lemma 1 says that in every balanced equilibrium all users consume the same applications. It is driven by presence of direct network effects. Lemma 2 says that if  $Q_{DI}$  is the number of applications consumed in a particular balanced equilibrium, then

there are  $C_{Q_{DI}}^A$  equilibria with the same number of applications consumed. For example, if  $A = \{1, 2, 3, 4\}$ ,  $Q_{DI} = 2$  characterizes six balanced equilibria:  $\mathbb{Q}_{DI_1} = \{1, 2\}$ ;  $\mathbb{Q}_{DI_2} = \{1, 3\}$ ;  $\mathbb{Q}_{DI_3} = \{1, 4\}$ ;  $\mathbb{Q}_{DI_4} = \{2, 3\}$ ;  $\mathbb{Q}_{DI_5} = \{2, 4\}$ ; and  $\mathbb{Q}_{DI_6} = \{3, 4\}$ . It is easy to see that users derive the same utility in all of these equilibria and, thus, we think of them as equivalent. The lemmas imply that in the case of  $1 < R < 2$  and  $\alpha > 0$  we may completely characterize balanced equilibria by simply stating equilibrium cardinalities  $Q_{DI}$ . For clarity of exposition, we refer to balanced equilibria by just indicating their cardinality,  $Q_{DI}$ .

Suppose that all users play balanced strategies and consume the same set of applications of cardinality  $Q$ . Then, each user's net utility (1) is given by  $V(Q)$ :

$$V(Q) = Q^{R-1}X + \alpha \frac{X^2}{Q}(N-1) - pQ. \quad (4)$$

Function  $V(Q)$  is helpful in studying balanced equilibria. Not every  $Q$  constitutes an equilibrium. However, Lemma 1 implies that the net utility in every balanced equilibrium must be given by  $V(Q)$ .

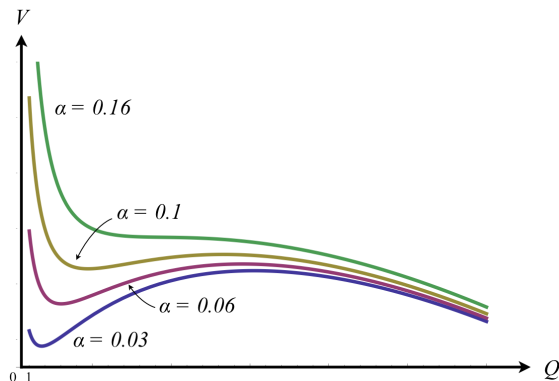


Figure 1: Shape of  $V$  for different values of  $\alpha$ .  
( $R = 1.7135$ ,  $A = 30$ ,  $X = 2$ ,  $N = 16$ ,  $p = 0.646$ .)

Figure 1 illustrates the shape of  $V$  for different values of  $\alpha$ . The shape of  $V$  is driven by the weight of consumption complementarity relative to that of preference for variety. As shown by Remark 1, consumption complementarity and the resulting direct network effects induce users to consume one application only. Remark 2, however, shows that preference for variety and the resulting indirect network effects induce users to consume more applications. The graph in Figure 1 shows that when users have strong preference for variety compared to consumption complementarity (low  $\alpha$  relative to  $R$ ), indirect network



effects outweigh direct network effects and the  $Q$  that maximizes  $V$  is interior. When preference for variety is weak relative to consumption complementarity direct network effects outweigh indirect network effects and  $Q = 1$  maximizes  $V$ .

Let

$$\widehat{Q} = \max \left\{ 1, Q \text{ such that } \frac{dV}{dQ} = 0 \right\}.$$

If  $V$  has interior maxima, then  $\widehat{Q}$  is the unique interior maximum. Otherwise,  $V$  reaches its maximum at  $\widehat{Q} = 1$ . As we can see in Figure 1, when  $\alpha$  is large,  $\widehat{Q} = 1$  (cf.  $\alpha = 0.16$  in the figure). Otherwise,  $\widehat{Q} > 1$  (other values of  $\alpha$  in the figure). The value  $\widehat{Q}$  is important for the shape of  $V$ . Specifically, for  $Q > \widehat{Q}$ ,  $V$  is always decreasing. However, for  $\widehat{Q} > 1$ , when  $Q < \widehat{Q}$ ,  $V$  first decreases and then increases. It is possible for some  $Q < \widehat{Q}$  that  $V(Q) > V(\widehat{Q})$ . Let  $Q_*$  be  $Q < \widehat{Q}$  such that  $V(Q_*) = V(\widehat{Q})$ , when  $\widehat{Q} > 1$ . (See Figure 2, below, for an example.)

The following remark states that  $\widehat{Q}$  is lower than  $Q_I$ , the equilibrium number of applications consumed when there are no direct network effects (as defined in Remark 2).

**Remark 3** *Assume that  $1 < R < 2$ ,  $\alpha > 0$  and  $Q_I > 1$ . Then  $\widehat{Q} < Q_I$ .*

**Proof.** See Appendix B, page 36.

Intuitively, the presence of direct network effects prompts users to allocate their limited time budget to fewer applications. Consumption complementarity, due to other users consuming the same applications, compensates for the loss of application variety. The fact that we consider  $Q_I > 1$  guarantees that the comparison between  $\widehat{Q}$  and  $Q_I$  is nontrivial.<sup>15</sup>

As noted above,  $\widehat{Q} > 1$  is the unique interior maximum of  $V$ . The following proposition shows that when  $\widehat{Q} > 1$ , users face a commons problem. Specifically, when all users consume  $\widehat{Q} > 1$  applications, every user finds it profitable to unilaterally deviate upward. However, when all of them deviate, they receive a lower utility. Notice that  $\widehat{Q} > 1$  when preference for variety,  $R$ , is large relative to consumption complementarity,  $\alpha$ .

**Proposition 1 (commons problem)** *Assume that  $1 < R < 2$  and  $\alpha > 0$ . If  $\widehat{Q} > 1$ , then  $\widehat{Q}$  is not a balanced equilibrium. Specifically, for any user  $k$ ,  $U(Q^k = \widehat{Q} + \varepsilon, \{Q^l = \widehat{Q}\}_{l \neq k}) > V(\widehat{Q}) > V(\widehat{Q} + \varepsilon)$ .*

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<sup>15</sup>For  $Q_I = 1$ ,  $\widehat{Q} = Q_I = 1$ .

**Proof.** See Appendix B, page 37.

The proposition states that when  $\widehat{Q}$  is interior, it cannot be a balanced equilibrium. This is because there is a profitable unbalanced upward deviation, i.e., each user has incentive to consume more applications. To see this, consider a unilateral *balanced* deviation to  $\varepsilon$  more applications. The deviator consumes  $X/(\widehat{Q} + \varepsilon)$  of each application. We now show that such deviation brings no additional utility. Note that the payoff from this upward deviation under balanced consumption is

$$U_{DI}(\widehat{Q} + \varepsilon | \text{balanced}) = \left(\widehat{Q} + \varepsilon\right)^{R-1} X + \cancel{Q} \alpha \frac{X}{\widehat{Q} + \varepsilon} (N-1) \frac{X}{\cancel{Q}} - p \left(\widehat{Q} + \varepsilon\right),$$

which is the same as  $V(\widehat{Q} + \varepsilon)$ . Therefore, because  $V'(\widehat{Q}) = 0$ ,  $V(\widehat{Q} + \varepsilon)$  is maximized at  $\varepsilon = 0$ . This means that an incremental upward deviation with balanced consumption from  $\widehat{Q}$  yields 0 benefit.

We now argue that an unbalanced deviation is strictly profitable. Note that the  $\widehat{Q}$  applications are also consumed by all other users while the new applications are consumed by the deviator only. Because of consumption complementarity, the marginal benefit from the  $\widehat{Q}$  applications is larger than that from the applications that only the deviator consumes. Therefore, shifting some consumption from the additional applications to any of the  $\widehat{Q}$  applications will lead to higher utility than the balanced deviation. Therefore, an optimal upward deviation is strictly profitable. Just as in the tragedy of the commons, all users have the same incentives and every user will deviate. When every user chooses to consume  $\widehat{Q} + \varepsilon$ , each of them will receive payoff  $V(\widehat{Q} + \varepsilon)$ , which is lower than  $V(\widehat{Q})$ .

The following lemma shows that there is a large set of  $Q$ s that cannot characterize balanced equilibria. The result is helpful because it significantly constrains the set of  $Q$ s that may characterize equilibria.

**Lemma 3** *Assume that  $1 < R < 2$  and  $\alpha > 0$ . Then for any  $Q$  such that  $\max\{1, Q_*\} \leq Q < \widehat{Q}$  or  $Q > Q_I$ ,  $Q$  cannot characterize a balanced equilibrium.*

**Proof.** See Appendix B, page 37.

Figure 2 illustrates Lemma 3.

To understand this result, consider first  $Q > Q_I$ . Given that all other users consume  $Q$  applications, any user has incentive to deviate downward to  $Q_I$ . The utility for user  $k$

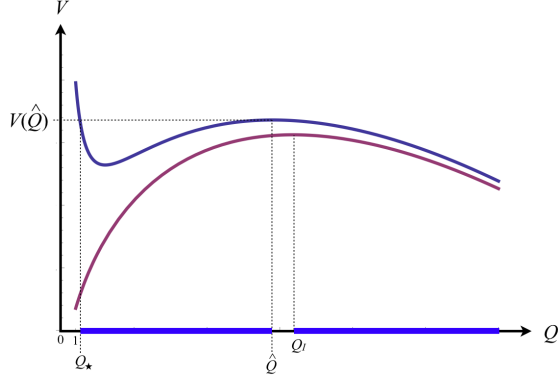


Figure 2: Intervals of  $Q$  that cannot be an equilibrium as described in Lemma 3.

from deviating to  $Q^k < Q$  is

$$U_{DI}(Q^k \leq Q) = (Q^k)^{R-1} X + \underbrace{\alpha Q^k \frac{X}{Q^k} (N-1) \frac{X}{Q}}_{\text{consumption complementarity}} - p Q^k. \quad (5)$$

Note that the consumption complementarity term is independent of  $Q^k$ . Since she consumes  $Q^k < Q$ , the deviator consumes only applications also consumed by the other users. Each of those applications is consumed by all other users at the level of  $(N-1)\frac{X}{Q}$ . The deviator divides her time budget  $X$  amongst the  $Q^k$  applications that she consumes,  $Q^k \cdot \frac{X}{Q^k}$ . Therefore, the benefit of the direct network effect is constant, no matter what  $Q^k < Q$  the deviator chooses. However, the net benefit of variety  $(Q^k)^{R-1} X - p Q^k$  is maximized at  $Q_I$  which is lower than  $Q$ . As a consequence, the deviator would want to deviate to  $Q_I$ . We conclude that  $Q > Q_I$  may not be an equilibrium. Intuitively, consuming more than  $Q_I$  applications leads to *too much* application variety for the price. Moreover, if it had an effect, consumption complementarity would push users to consume fewer applications also.

For  $Q \in [\max\{1, Q_*\}, \widehat{Q})$ , however, there is a profitable deviation upward. In what follows, we impose that the deviator balances her time budget across all the applications that she consumes. Even though this is not the optimal deviation, we show that it is a profitable deviation (and therefore, the optimal deviation is also profitable). Given that all other users consume  $Q$  applications in a balanced way, the utility of the deviator from a balanced consumption of  $Q^k$  applications is:

$$U_{DI}(Q^k \geq Q) = (Q^k)^{R-1} X + \underbrace{\alpha Q \frac{X}{Q^k} (N-1) \frac{X}{Q}}_{\text{consumption complementarity}} - p Q^k. \quad (6)$$

Note that  $U_{DI}(Q^k \geq Q)$  is the same function of  $Q^k$  as  $V$  in equation (4) which has a local maximum at  $\widehat{Q} > Q$ . Moreover, for all  $Q \in [\max\{1, Q_\star\}, \widehat{Q})$ ,  $U_{DI}(\widehat{Q} > Q) > U_{DI}(Q)$ . Thus, for all those values of  $Q$ , there is a profitable upward deviation. We conclude that  $Q \in [\max\{1, Q_\star\}, \widehat{Q})$  may not be an equilibrium.

Intuitively, consuming more applications satisfies the deviator's preference for variety to a greater extent. However, consuming less of each application consumed by other users means that the utility from consumption complementarity is lower. When  $Q \in [Q_\star, \widehat{Q}]$  the tradeoff is resolved in favor of consuming more applications.

Note that for  $Q \in [1, Q_\star]$  and  $Q \in [\widehat{Q}, Q_I]$  the same tradeoff is at play. However, it is possible that the tradeoff is resolved in favor of consumption complementarity which means that it is not worth it for users to deviate upward. In combination with Lemma 4, this observation implies that equilibria are possible in the intervals  $Q \in [1, Q_\star]$  and  $Q \in [\widehat{Q}, Q_I]$ . Lemmas 5 and 6 show that multiple equilibria exist in these intervals. We show that there are two aspects to this multiplicity. First, as described in Lemma 2, for any given cardinality  $Q_{DI}$  there may exist multiple sets  $\mathbb{Q}_{DI}$ —each constituting a separate equilibrium. Second, there may exist many different values of  $Q_{DI}$  that characterize equilibria. The former type of multiplicity is of no consequence to user utility while the latter has important utility implications. Thus, we focus only on the second type of multiplicity in our analysis.

The following lemma assures that so long as  $Q \leq Q_I$ , it is never beneficial for user  $k$  to deviate to a strategy with a lower number of applications. Thus, in searching for balanced equilibria we need to focus only on deviations to a larger number of applications.

**Lemma 4** *Assume that  $1 < R < 2$  and  $\alpha > 0$ . If all users play balanced strategy  $\mathbb{Q}$  with cardinality  $Q \leq Q_I$ , then any unilateral deviation by user  $k$  to any other strategy with  $Q^k < Q$  leads to lower utility for player  $k$ .*

**Proof.** See Appendix B, page 38.

To understand this result, suppose that all users are consuming  $Q \leq Q_I$  and consider a deviation to  $Q^k < Q$ . We do not restrict the user to deviate to a balanced strategy with  $Q^k$ . However, from among all possible deviations to  $Q^k < Q$ , a balanced consumption of  $Q^k$  applications from the set  $\mathbb{Q}$  is the most profitable. Thus, the utility from the most

profitable deviation to  $Q^k$  is given by formula (5):

$$U_{DI}(Q^k \leq Q) = (Q^k)^{R-1} X + \underbrace{\alpha Q^k \frac{X}{Q^k} (N-1) \frac{X}{Q}}_{\text{consumption complementarity}} - p Q^k.$$

Note that  $U_{DI}(Q^k \leq Q)$  is increasing for all  $Q^k \leq Q_I$  and therefore it is maximized at  $Q^k = Q$ . Thus, if  $Q \leq Q_I$ , there is no incentive to deviate downward.

Intuitively, consuming fewer applications satisfies user  $k$ 's preference for variety to a lesser extent. At the same time, there is no benefit from consumption complementarity. The reason is that each of the applications used by the deviator are consumed by all other users at the level of  $(N-1)\frac{X}{Q}$ . Therefore, it is optimal to the deviator to divide her time budget  $X$  equally among the  $Q^k$  applications that she consumes, whereby she consumes  $\frac{X}{Q^k}$  of each. Since  $Q^k \cdot \frac{X}{Q^k} = X$ , the benefit of the direct network effect is constant no matter what  $Q^k$  the deviator chooses.

We use Lemma 4 to prove the result in Lemma 5. Lemma 5 states that there always exists a balanced equilibrium where all users consume  $Q_I$  applications and that  $Q$ s close but lower than  $Q_I$  also characterize equilibria. Together with Lemma 3, Lemma 5 indicates that  $Q_I$  is the equilibrium with the largest number of applications consumed.

**Lemma 5** *When  $1 < R < 2$  and  $\alpha > 0$ , there always exist balanced equilibria with  $Q_{DI} = Q_I$ , where  $Q_I = \left(\frac{(R-1)X}{p}\right)^{\frac{1}{2-R}} > 1$ . Furthermore, there exists  $Q^o < Q_I$  such that any  $Q \in [Q^o, Q_I]$  characterizes balanced equilibria, i.e.,  $Q = Q_{DI}$ .*

**Proof.** See Appendix B, page 39.

Figure 3a illustrates the result in Lemma 5. This result means that so long as users exhibit preference for variety, no matter how small, there are balanced equilibria with the same number of applications,  $Q_I$ , that users would choose to consume if there were no direct network effects.

To understand why  $Q_I$  is an equilibrium, by Lemma 4 we need only consider deviations upward. By the same argument to that following equation (6), a deviation upward (balanced or unbalanced) cannot improve the utility from consumption complementarity. Moreover,  $Q_I$  maximizes utility from preference for variety. Therefore, there are no incentives to deviate and  $Q_I$  is an equilibrium.

A deviation upward always decreases utility from consumption complementarity. Notwithstanding, for  $Q < Q_I$  there is some benefit from increased variety. For  $Q$  less than but

close to  $Q_I$ , however, this benefit is infinitesimally small (the FOC is satisfied at  $Q_I$ ) and it is outweighed by the utility loss from consumption complementarity. Therefore,  $Q$ s less than but close to  $Q_I$  also characterize equilibria.

Lemma 6 shows that for some parameters there may also exist equilibria with  $Q_{DI} = 1$ .

**Lemma 6** *Assume that  $1 < R < 2$  and  $\alpha > 0$ . There exist parameter values such that  $Q_{DI} = 1$  while  $Q_I > 1$ .*

**Proof.** See Appendix B, page 40.

Notice that if  $\hat{Q} > 1$ , it is necessary that  $V(Q = 1) > V(\hat{Q})$  for  $Q = 1$  to be an equilibrium. It follows from Lemma 3. However, there is nothing in the proof that connects  $Q_{DI} = 1$  to  $Q^o$ . So the equilibrium at  $Q_{DI} = 1$  may be disconnected from the set of equilibria around  $Q_I$ .

The result of Lemma 6 is illustrated in Figure 3b. There we can see that equilibria exist in two disconnected intervals: one interval around  $Q = 1$  (recall that following Remark 1  $Q_D = 1$  is the equilibrium under pure direct network effects) and the other one around  $Q_I$ . In the interval around  $Q_D = 1$ , the strong consumption complementarities (users consume the same few applications intensely) guarantee that users do not want to deviate to consume more applications. In the interval around  $Q_I$ , the weak consumption complementarities (users consume little of many applications) guarantee that users do not want to deviate to consume fewer applications.

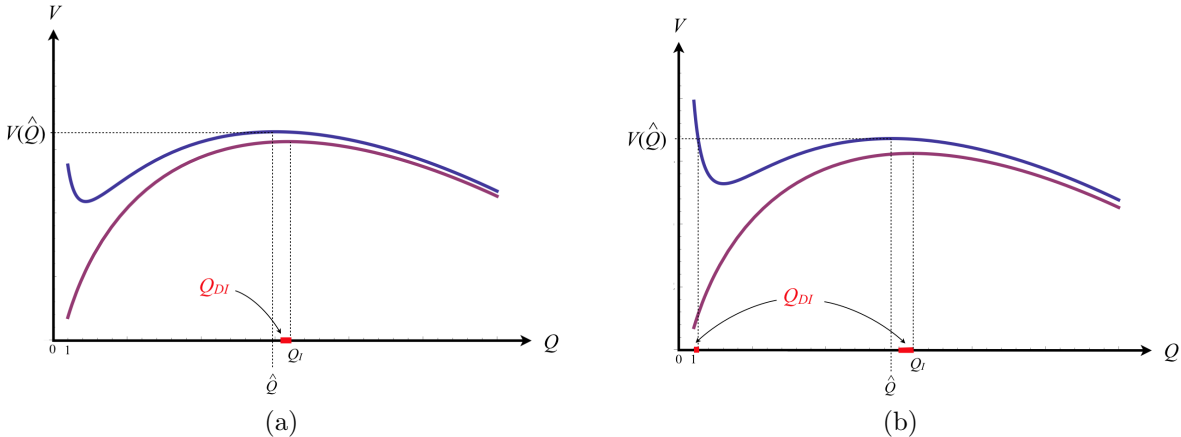


Figure 3: Intervals of  $Q_{DI}$ .

Lemmas 5 and 6 show that there are always multiple equilibria. We now show that the equilibria can be ranked according to users' utility. In particular, equilibria with

fewer applications consumed yield higher utility than equilibria with more applications. However, even when consumption complementarity is large relative to the preference for variety and the allocation that maximizes users' utility is an equilibrium, the model does not predict which of the many equilibria will be played or the utility that users will achieve. Therefore, users face an equilibrium selection problem.

**Proposition 2 (equilibrium selection problem)** *When  $1 < R < 2$  and  $\alpha > 0$  there exist multiple balanced equilibria with different values of  $Q_{DI}$ . Equilibria with smaller  $Q_{DI}$  yield higher utility than equilibria with larger  $Q_{DI}$ .*

**Proof.** See Appendix B, page 41.

To understand the intuition, recall that function  $V(Q)$  is user utility in a situation where every user consumes  $Q$  applications in a balanced way. Therefore, for values of  $Q_{DI}$  that constitute a balanced equilibrium,  $V(Q_{DI})$  is the utility that users obtain in equilibrium. As follows from Lemma 3 and illustrated by Figure 2, equilibria only occur for values of  $Q$  such that  $V(Q)$  is decreasing. Therefore, equilibrium utility must be decreasing in  $Q_{DI}$ .

In conclusion, Propositions 1 and 2 identify two undesirable properties of equilibria in environments where both direct and indirect network effects are present. When preference for variety is large relative to consumption complementarity, users face a commons problem because the allocation that maximizes users' utility is not an equilibrium. Moreover, regardless of the values of  $\alpha$  and  $R$  there are always multiple equilibria which yield different levels of utility. Thus, users also face an equilibrium selection problem, even when consumption complementarity is large relative to preference for variety and the allocation that maximizes users' utility is an equilibrium. In the following subsection we show how the platform can alleviate these problems by limiting the number of applications available.

## 2.4 On the role of the platform: creating value by limiting choice

We conclude Section 2 by showing that users may benefit when the platform limits the number of applications available, but only when both direct and indirect network effects are present. To examine the platform's choice of the number of applications available,  $A$ , we relax the assumption that  $A \geq \left(\frac{(R-1)X}{p}\right)^{\frac{1}{2-R}}$ .

Notice first that when pure direct network effects are present (i.e.,  $R = 1$  and  $\alpha > 0$ ), users achieve the same net utility in all equilibria, for any  $A \geq 1$ . Thus, the platform cannot change the net utility that users achieve in an equilibrium by manipulating  $A$ . Likewise, the platform cannot improve the equilibrium outcome under pure indirect network effects (i.e.,  $1 < R < 2$  and  $\alpha = 0$ ). From Section 2.2 we know that when  $A \geq Q_I$  in an equilibrium under pure indirect network effects, every user consumes  $Q_I$  applications. When the platform sets  $1 < A < Q_I$  then there exists a unique equilibrium—a balanced equilibrium in which all users consume all  $A$  applications. But this yields lower utility than consuming  $Q_I$  applications. Therefore, in the case of pure indirect network effects the platform can only decrease users’ utility when limiting the number of available applications.<sup>16</sup>

We now turn to the case where both direct and indirect network effects are present (i.e.,  $1 < R < 2$  and  $\alpha > 0$ ). The following definition is helpful for the arguments that follow. Let

$$Q^{**} = \arg \max V(Q). \quad (7)$$

From the shape of  $V$  follows that  $Q^{**}$  may be either 1 or  $\widehat{Q}$ . In both cases  $Q^{**} \leq \widehat{Q} < Q_I$ .<sup>17</sup> When  $Q^{**} = \widehat{Q} > 1$ , then by Proposition 1,  $Q^{**}$  never characterizes a balanced equilibrium. When  $Q^{**} = 1$ , it may characterize a balanced equilibrium (as Lemma 6 shows), but it not always does. We show that by limiting choice when  $Q^{**}$  is not an equilibrium, the platform helps users solve the commons problem shown in Proposition 1; i.e., the platform creates an equilibrium at  $Q^{**}$ . And when  $Q^{**}$  is an equilibrium, it will typically be one of many equilibria where other equilibria yield lower utility than  $Q^{**}$ . Thus, in this case by limiting choice, the platform helps users solve the selection problem in Proposition 2.

Proposition 3 shows that regardless of whether  $Q^{**}$  is in the equilibrium set of the original game, the platform can ensure that  $Q^{**}$  becomes the only equilibrium of the game by restricting  $A$  to  $Q^{**}$ .

**Proposition 3** *Assume that  $1 < R < 2$  and  $\alpha > 0$ . If the platform sets  $A = Q^{**}$ , then there exists a unique balanced equilibrium where all users consume  $Q^{**}$  applications.*

**Proof.** See Appendix B, page 41.

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<sup>16</sup>When  $A < Q_I$ , users strictly gain from access to a larger number of applications. And when  $A \geq Q_I$ , the users do not gain or lose by having more applications available.

<sup>17</sup>Notice that whether  $Q^{**} = 1$  or  $Q^{**} = \widehat{Q} > 1$  depends on the value of  $\alpha$  relative to  $R$ . For small  $\alpha$  (as  $\alpha = 0.03$  in Figure 1)  $Q^{**} = \widehat{Q} > 1$ . For larger  $\alpha$  (as  $\alpha = 0.06$  and  $\alpha = 0.1$  in the figure),  $\widehat{Q} > 1$ , but  $Q^{**} = 1$ . For even larger  $\alpha$  (as  $\alpha = 0.16$  in the figure),  $Q^{**} = \widehat{Q} = 1$ .



The proposition implies that the equilibrium set may change with changes in  $A$ . In particular, when the platform sets  $A = Q^{**}$ ,  $Q^{**}$  becomes the unique equilibrium.<sup>18</sup> Therefore, when  $Q^{**}$  is in the original equilibrium set, if the platform constrains  $A$  to be equal to  $Q^{**}$ , it eliminates all equilibria that yield lower utility for the users and, thus, eliminates the possibility that users select an inferior equilibrium. Hence,

**Corollary 1** *Assume that  $1 < R < 2$  and  $\alpha > 0$ . When  $Q^{**}$  is in the equilibrium set, users may benefit when the platform restricts the number of available applications to  $Q^{**}$ .*

On the other hand, if  $Q^{**}$  is not in the original equilibrium set, when the platform constrains  $A$  to be equal to  $Q^{**}$ , it creates a new equilibrium that makes users better off than all the original equilibria. Thus,

**Corollary 2** *Assume that  $1 < R < 2$  and  $\alpha > 0$ . When  $Q^{**}$  is not in the equilibrium set, users strictly benefit when the platform restricts the number of available applications to  $Q^{**}$ .*

In summary, when consumption complementarity is large relative to preference for variety, then  $Q^{**}$  is in the equilibrium set and the platform can eliminate other equilibria (which yield lower utility) by limiting the number of applications available. When preference for variety is large relative to consumption complementarity, then  $Q^{**}$  is not in the equilibrium set, and by limiting the number of applications, the platform creates a new, unique, equilibrium that yields the highest possible utility.

If users gain higher utility from participation in the platform, the platform provider may collect higher access fees from them. For example, in environments where user access fees are the only source of revenue to the platform, users' utility maximization is perfectly aligned with the platform's profit maximization. Perfect alignment may be lost when the platform has other revenue streams (such as royalties). We elaborate on this in Section 4.

### 3 Game with no foresight

Whenever direct network effects are present, the equilibria studied in Section 2 require users to know exactly which applications are consumed by all other users. That is, our

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<sup>18</sup>We note that not all changes in  $A$  result in reducing the equilibrium set to a singleton. Put differently, it is not the case that the platform can ensure that any  $Q$  will be played in equilibrium by setting  $A = Q$ . For example, if the platform sets  $A = Q_I$  it cannot ensure that the equilibrium with  $Q_I$  applications will be played, as many other equilibria are possible in this case.

assumption has been one of *perfect foresight* about other users' choices in equilibrium. Under perfect foresight player  $k$  knows the cardinality and the identity of the applications that all other users will consume; moreover, she also knows how much of each application other users consume. In many environments, such perfect foresight may be difficult to achieve. As an alternative, now we assume *no foresight* by which we mean that users initially assign equal probability to any feasible strategy of other users. However, they refine their beliefs by Bayesian updating and eventually reach equilibrium beliefs.<sup>19</sup> The literature has pointed out that in the presence of network effects, equilibria are influenced by the way users form their expectations.<sup>20</sup> Therefore, we study in this section how equilibria change when we step away from perfect foresight in beliefs formation.

Only the assumption about user beliefs differentiates this game from the game in Section 2. Recall that  $\mathbf{x}^k = \{x_1^k, x_2^k, \dots, x_A^k\}$  such that  $\sum_{a \in \mathbb{A}} x_a^k = X$  denotes a feasible consumption vector. We use  $\mathbf{x}^k$  to also denote a pure strategy. Let  $\mathbb{X}$  denote the set of all pure strategies for any given user.<sup>21</sup> Let  $\phi_l^k \sim U[\mathbb{X}]$  denote user  $k$ 's beliefs on user  $l$ 's choice of pure strategy. Let  $\boldsymbol{\phi}^k = \{\phi_l^k\}_{l \neq k}$  be a vector that denotes user  $k$ 's beliefs on all other users' choices of pure strategy.

With this, user  $k$ 's utility from consuming vector  $\mathbf{x}^k$  is

$$\mathbf{E}_{\boldsymbol{\phi}^k} u(\mathbf{x}^k) = \left( \sum_{a \in \mathbb{A}} (x_a^k)^{1/R} \right)^R + \alpha \sum_{a \in \mathbb{A}} (x_a^k \mathbf{E}_{\boldsymbol{\phi}^k} \sum_{l \neq k} x_a^l),$$

and the optimization problem (2) becomes:  $\max_{x_a^k, a \in \mathbb{A}} \left\{ \mathbf{E}_{\boldsymbol{\phi}^k} u(\mathbf{x}^k) - p \cdot \sum_{a \in \mathbb{A}} \mathbf{1}(x_a^k) \right\}$ , subject to  $X \geq \sum_{a \in \mathbb{A}} x_a^k$ .

It is straightforward to show that under no foresight the expectation over consumption of any application  $a$  by any other user  $l \neq k$  is  $\mathbf{E}_{\phi_l^k} x_a^l = \frac{X}{A}$  and  $\mathbf{E}_{\boldsymbol{\phi}^k} \sum_{l \neq k} x_a^l = (N - 1) \frac{X}{A}$ .<sup>22</sup> Note that this expectation does not depend on how many applications or which applications all other users consume, therefore there is no interdependence between users' choices. Given this, we now can find the optimal choice by user  $k$  (which in our setting is independent of what all other users do). Whatever is the number of applications  $G^k$  that user  $k$  wishes to consume, her optimal consumption pattern is balanced consumption, i.e., dividing the time budget equally among the applications consumed. Once user  $k$  decides that  $G^*$  is the optimal number of applications for her to consume, it does not matter

<sup>19</sup>We consider such updating to be realistic. In the experiment of El-Gamal and Grether (1995) overwhelming majority of subjects used Bayes updating rule.

<sup>20</sup>See, for example, Hurkens and Lopez (2010).

<sup>21</sup>Because all users are identical, they all have access to the same set of pure strategies.

<sup>22</sup>For formal proofs of these equalities see Section 3 of Casadesus-Masanell and Halaburda (2010).

which subset of  $\mathbb{A}$  she chooses, as all yield the same expected utility. Therefore,  $G^*$  fully describes  $k$ 's set of best responses.

User  $k$  updates her beliefs using Bayes' Rule. Therefore, she assigns zero probability to dominated strategies and equal probability to undominated strategies. Since with no foresight she does not know which applications they consume, she believes that every subset of  $\mathbb{A}$  with cardinality  $G^*$  is equally likely to be consumed by user  $l \neq k$ . User  $k$  recalculates her best response under the updated beliefs, until the recalculated best response is exactly the same as the original best response. If every user behaves this way, beliefs are consistent with strategies and this constitutes a ***no-foresight equilibrium***.

We consider the case where both direct and indirect network effects are present (i.e.,  $1 < R < 2$  and  $\alpha > 0$ ).<sup>23</sup> Let  $G_{DI}^k$  be the number of applications consumed by user  $k$  in a no-foresight equilibrium.

**Proposition 4 (coordination problem)** *Suppose  $1 < R < 2$  and  $\alpha > 0$ . In every no-foresight equilibrium, every user  $k$  consumes  $G_{DI}^k = G_{DI} = Q_I$  applications in equal amount, where  $Q_I = \left(\frac{(R-1)X}{p}\right)^{\frac{1}{2-R}} > 1$ . The expected equilibrium net utility is*

$$\mathbf{E}U_{DI}(G_{DI}) = G_{DI}^{R-1}X + \alpha X(N-1)\frac{X}{A} - pG_{DI}. \quad (8)$$

Moreover, the platform maximizes users' net utility by setting the number of available applications to  $A = Q^{**}$ , where  $Q^{**}$  is given by (7).

**Proof.** See Appendix B, page 41.

In the game with no foresight, users face a *coordination problem*. Since users do not know which applications are consumed by other users, some of the benefit to the direct network effects is lost. The utility that users can achieve in this environment is lower than in the environment with perfect foresight, because users cannot exploit consumption complementarities as well due to lack of coordination. In such a situation, the platform can create value by limiting the number of available applications. So long as  $A > Q^{**}$ , the equilibrium is inefficient, especially when  $A$  is large. Only when  $A = Q^{**}$ , the efficient outcome is an equilibrium. By providing fewer applications, the platform creates a new equilibrium and alleviates this coordination problem. We note that under no foresight, users do not face neither equilibrium selection nor commons problems.

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<sup>23</sup>The analysis of pure direct and pure indirect network effects is straightforward and can be found in the working paper Casadesus-Masanell and Halaburda (2010).

## 4 Discussion

In this section we discuss several aspects of our approach.

**Consumption complementarity and preference for variety.** Although for expositional simplicity we have presented the model with reference to network effects, all that we need for the results to go through is the presence of consumption complementarities and preference for variety. Consumption complementarities always imply direct network effects. Preference for variety, however, does not always imply indirect network effects. To illustrate this point, note a key difference between hardware-software platforms (e.g., Nintendo) and betting platforms (e.g., Betfair). In the case of Nintendo, users benefit from game variety as provided by a large number of independent developers, and developers benefit from a large number of users to sell games. Thus, preference for variety and indirect network effects go hand-in-hand in this case. This contrasts with Betfair where punters (back and lay sides) benefit from a large variety of sporting events to bet on, but where there are no *independent* event providers that benefit from there being more punters (as Betfair is the only provider of events on its platform). Although there are no indirect network effects in this case, our analysis and results apply.

**Exogenous  $p$ .** We have analyzed the user side only and assumed that the price of accessing an application,  $p$ , is exogenous. While to better understand the interactions between users and developers it would be interesting to extend the model to endogenous  $p$ , to do so would require imposing substantial assumptions on industry structure on the developer side (entry conditions, production cost, number of games sold by each developer, and so on). Of course, the equilibrium  $p$  would not be innocuous to such assumptions. However, a critical implication of our analysis is that the platform cannot induce users to consume the optimal number of applications by manipulating  $p$ .<sup>24</sup> Put differently, we have shown that *regardless of the value of  $p$* , the commons, equilibrium selection, and coordination problems will arise when, in addition to preference for variety, there are direct network effects. Therefore, our conclusion that it is valuable for platforms to manage the number of applications available holds regardless of whether  $p$  is endogenous

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<sup>24</sup>The exception is a situation where the platform drives  $p$  so high that  $Q_I = 1$ , which we assumed away on page 11. In this case, users consume one application which is the optimal number. For details, see the working paper version (Casadesus-Masanell and Halaburda 2010).

or exogenous.<sup>25, 26</sup>

**Value creation and value capture.** We have analyzed how limiting the number of available applications affects value created; that is, user surplus. However, we have not considered how the platform may capture that value through prices (access prices and/or royalties). A detailed analysis of platform pricing is beyond the scope of this paper and left for future research. Pricing decisions may depend on specific institutional or competitive details. Our analysis applies to the user side of the market regardless of these details. One can imagine extending our analysis to a particular institutional setting to find the optimal pricing strategy.

Consider first the case where the platform can only charge access fees to users (no royalties to developers). Then, the profit-maximizing number of applications coincides with  $Q^{**}$  and access price to users is equal to users' net utility. This will not be the case when the platform charges only royalties and no access fees. In this case, the platform earns higher profit when a larger number of applications are purchased. Therefore, selling  $Q_I$  applications maximizes profits, and the platform does not benefit from limiting the number of applications below  $Q_I$ . Even when the platform offers  $Q_I$  or more applications, there are still multiple equilibria. Thus, the platform cannot guarantee that  $Q_I$  applications are purchased. Nonetheless, in any equilibrium users consume more than  $Q^{**}$  applications (the number of applications that maximizes user surplus), since the commons problem remains. However, the commons problem does not affect the platform's revenue. Finally, consider a platform that collects both access prices and royalties. In this case, the profit-maximizing number of applications will lie somewhere between  $\widehat{Q}$  and  $Q_I$ . The commons problem does not go away but it becomes less relevant to the platform.

**Implementing quantity restrictions.** While the method we have considered in Sections 2.4 and 3 for correcting the commons, equilibrium selection, and coordination problems—outright restriction on the number of applications available—might seem brutally direct, there are indirect ways to implement it. One such way is through manipula-

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<sup>25</sup>Although  $p$  is often endogenous, it is not hard to think of cases where it is exogenous, particularly when technological reasons constrain  $p$  to be zero. For example, open television channels are free to users as it is impossible to exclude access to them. In this case,  $p$  may not be used as a coordinating device. Although we have assumed that  $p > 0$ , our results apply when  $p = 0$  as well. Interested readers can find the complete analysis of the case  $p = 0$  in Appendix B of the working paper version (Casadesus-Masanell and Halaburda 2010).

<sup>26</sup>In this paper, we have considered a situation where users pay price  $p > 0$  to access each application, and face a time budget constraint  $X$ . However, there is no monetary cost of using applications (i.e., no rental cost). Under rental cost, the commons, equilibrium selection, and coordination problems may also occur. For details see Appendix B of the working paper, which considers the case of  $p = 0$ , and is equivalent to a setting where there is a rental cost for applications but no access price.

tion of the access fees and/or royalties charged to developers. High prices to developers will lead to less entry and a smaller set of applications available, resulting in possibly more value for users. An interesting and counterintuitive implication of our results is that to the extent that higher access prices to developers result in net utility gains to users, the platform will be able to charge higher prices to the user side. Of course, this runs counter to the conventional wisdom that to earn more from one side of the market, the platform must set lower prices to the other side.

Another indirect way to narrow down the set of applications available is by tinkering with user search. For example, in the late 1980s and 1990s, Nintendo used *Nintendo Power*—an in-house magazine priced to break even and carried no advertising—to promote particular games. Two years after it had launched, it had become the highest-circulation publication targeted to children in the United States. Games not featured on *Nintendo Power* were much less likely to become commercial successes.<sup>27</sup> Likewise, the current search capabilities on Apple’s App Store are notoriously deficient.<sup>28</sup> Applications appear ranked by number of downloads which, of course, reinforces direct network effects for applications—such as word processors (*Pages*), spreadsheet programs (*Numbers*), or presentation software (*Keynote*)—that exhibit consumption complementarities.

**Royalties and double marginalization.** Our results suggest a possible resolution to an issue in the video game market that has traditionally been seen as a puzzle. Console makers typically charge royalties to game developers. This seems like a bad idea due to double marginalization. One explanation is that royalties are an instrument to compel developers to raise the quality of games. Because games are more expensive in the presence of royalties, fewer, but better, games are developed. Thus, royalties are often seen as resolving a tradeoff between quality and quantity. Our analysis shows that there may be no tradeoff because the platform may prefer both, better-quality games but also fewer games. Moreover, because they ultimately limit the number of applications available, the motive for royalties in the video game industry could be exactly the same as the rationale for Betfair to limit the number of betting events on its platform. To the best of our knowledge, the idea that *royalties* and *restrictions on application variety* might be derived from the same underlying force is new to the literature.

**Competing platforms.** While analysis of competing platforms is beyond the scope of this paper, it is easy to see an interesting tradeoff that is likely to emerge when direct

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<sup>27</sup>See Brandenburger (1995).

<sup>28</sup>See, for example, <http://accidentaltechnologist.com/apple/apple-please-fix-the-app-store-search/> or <http://www.eweek.com/c/a/Mobile-and-Wireless/10-Apple-App-Store-Problems-That-Need-Fixing-Now-412975/>.

and indirect network effects are at play. Consider a situation with two platforms competing for a given set of users. If one of the platforms limits the number of applications when there is preference for variety, users will likely expend some of their budget on applications from the second platform. Thus, by limiting choice, the platform may potentially create additional value, but users are more likely to multi-home and crowd out some of their limited resources to the other platform. As a result, competition for users is likely to have a mitigating effect on the platform’s desire to limit choice.

**Subgame perfection.** This paper analyzes subgame-perfect equilibria of a two-stage game. We now argue that we are not losing any balanced equilibria by using the subgame perfection refinement of Nash equilibria. To see this, note first that strategies that involve buying applications that are not consumed are strictly dominated and therefore will never be played in any Nash equilibrium. Moreover, the same argument that allowed us to focus on equilibria where all users purchase and use the same applications (Lemma 1) also applies to all Nash equilibria. This means that all Nash equilibria have users buying and consuming the same applications. Therefore, every equilibrium can be characterized by  $Q$ , the number of applications bought and consumed. Now we can show that every  $Q$  that does not characterize a subgame perfect Nash equilibrium cannot be a Nash equilibrium (without refinement). As we show in the paper, if  $Q$  does not characterize a subgame perfect Nash equilibrium, then there exists a profitable unilateral upward or downward deviation to a different number of applications. But the same deviation is available even without the subgame perfection refinement. Therefore, such a  $Q$  cannot be a Nash equilibrium. In the paper, we focus on subgame perfection for technical convenience.<sup>29</sup>

**Generalized formulation.** In this paper we have analyzed a micro-founded model. A micro-foundation has allowed us to clearly discuss the intuition behind the economic forces driving our main results. In Appendix A we present a generalized formulation of the problem and show that our main results continue to hold in this more general setting. Specifically, the generalization suggests that the results do not depend on our restriction to balanced equilibria. Moreover, since the generalization does not involve any refinements of equilibria, it reinforces our earlier point that subgame perfection entails no loss of generality.

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<sup>29</sup>If the game was solved as a one-stage game, then users would directly maximize utility as given by equation (1), subject to the budget constraint. Note that the first-order conditions in the users’ maximization problem involve dealing with derivatives of indicator functions. In the two-stage formulation, this problem does not arise. Thus, analyzing the two-stage game is technically more convenient and entails no loss of generality.

## 5 Conclusion

We have shown that when users enjoy application variety but also benefit from consumption complementarities, three problems may arise: the socially optimal number of applications may not be part of an equilibrium; multiple equilibria ensue; and users will likely find it hard to coordinate consumption. The analysis has demonstrated that by limiting the number of applications, the platform can provide a solution to these problems. Specifically, by limiting choice the platform may create new equilibria that do not exist when application choice is broad. In addition, it can eliminate equilibria that yield lower utility. Moreover, it can reduce the severity of the coordination problem faced by users.

The overall conclusion is that when direct and indirect network effects are at play, an important governance decision that platforms face is the choice of the number of applications that should be allowed to run on them. To implement such a choice, the platform may directly suppress access to developers and impose quantity constraints, or it may limit the number of applications indirectly through setting high access prices to developers.

While we have shown that the platform may create value by limiting choice, the recommendation to practitioners is obviously not “provide as few applications as possible.” Rather, it is that even in settings where users have a strong preference for variety, the platform provider must be cognizant that there may be a number beyond which offering more applications will decrease users’ utility and, thus, overall platform value. This recommendation is in stark contrast to the conventional wisdom that platforms should encourage the development of complements to the maximal possible extent.

The obvious next step in this research is the endogenization of access prices in a setting with competing platforms and direct and indirect network effects. Given the complexity of the analysis when users are the only strategic players, we expect these extensions to be challenging. It is our hope to have provided a solid first step on which to build general theories of platform competition that will shed further light on the value that platforms may create by acting as gatekeepers.



# APPENDIX

## A Generalized formulation

In this appendix we present a generalized formulation of the micro-founded model of the main paper. In this formulation we abstract from the intensive margin (how  $X$  is allocated across applications). The analysis demonstrates that we do not lose any generality by focusing on balanced equilibria in the main paper.

Given the consumption of other users ( $\{Q^l\}_{l \neq k}$ ), the net utility of user  $k$  is:

$$U^k(Q^k, \{Q^l\}_{l \neq k}) = v(Q^k) + w(Q^k, \{Q^l\}_{l \neq k}) - p Q^k,$$

where  $v$  represents the utility derived from variety, and  $w$  represents the utility resulting from consumption complementarity. We assume that  $v$  is increasing and concave, that is  $v' > 0$  and  $v'' < 0$ . Therefore, consuming more applications brings higher utility from variety. However, the additional value of more applications decreases as more applications are being consumed. In our micro-foundation, the concavity of  $v$  is due to the fixed time budget  $X$ : consuming more applications implies consuming less of each application. In the generalized formulation, it is also possible that concavity is driven to other reasons such as users getting fed up with too much variety—due, for example, to limited attention.

Although  $w$  is a function of  $N$  arguments, we sometimes write  $w(Q)$  to mean that  $Q^l = Q$  for all  $l$ . To simplify notation, we use  $w(Q^k, Q)$  to mean  $w(Q^k, \{Q^l\}_{l \neq k})$  when  $Q^l = Q$  for all  $l \neq k$ .<sup>30</sup> We assume  $w'(Q) < 0$  and  $w''(Q) < -v''(Q)$ .<sup>31</sup> In our micro-foundation,  $w$  is decreasing because as all users consume more applications, they consume less of each one, which implies that they do not fully exploit consumption complementarities. In the generalized formulation, this may be due to other factors such as increasing returns to spending more effort on one particular application consumed with other users. We also assume:

$$\left. \frac{\partial w(Q^k, Q)}{\partial Q^k} \right|_{Q^k=Q} \begin{cases} = 0, & Q^k < Q \\ < 0, & Q^k > Q. \end{cases}$$

This derivative accounts for individual deviations by user  $k$  from  $Q$ . A deviation downward has no effect on the payoff from consumption complementarity. This is a natural assumption that is validated by our micro-foundation. We later explore the consequences of relaxing this assump-

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<sup>30</sup>It is easy to show that in equilibrium it must be the case that all users consume the same applications. Thus, in considering deviations by user  $k$ , it is enough to consider deviations given that all other users consume the same applications.

<sup>31</sup>Note that in the model in the main text, this condition is not always satisfied. However, it is satisfied on the relevant range of  $Q$ s. Specifically, it is satisfied for  $Q \geq \hat{Q}$ .

tion. A deviation upward decreases the utility from consumption complementarity because the user takes away time from consuming the same applications as other users consume. We also assume that  $\frac{\partial w(Q^k, Q)}{\partial Q^k} > w'(Q)$  for all  $Q$ . This means that in an unilateral deviation upward, the user loses less than if everybody increases consumption.

Due to homogeneity of agents and consumption complementarity, it follows that in any equilibrium all users will consume exactly the same applications. We use this fact to characterize the allocation  $\widehat{Q}$  that maximizes net utility.

**Lemma A1** *Suppose that  $v > 0$ . Then, in an interior solution, the utility maximizing allocation  $\widehat{Q}$  satisfies  $v'(\widehat{Q}) + w'(\widehat{Q}) = p$ .<sup>32</sup>*

Note that when there is only preference for variety ( $w = 0$ ), every user consumes  $Q_I$  applications, where  $v'(Q_I) = p$ . It is easy to see that when  $w > 0$ ,  $\widehat{Q} < Q_I$ .

Propositions A1 and A2 below show that in this set up, the commons problem and multiplicity of equilibria are still present. It is convenient to define  $V(Q) = v(Q) + w(Q) - pQ$ .

**Proposition A1 (commons problem)**  *$\widehat{Q}$  is not an equilibrium. Specifically, for any user  $k$ ,  $U(Q^k = \widehat{Q} + \varepsilon, \widehat{Q}) > V(\widehat{Q}) > V(\widehat{Q} + \varepsilon)$ .*

**Proof.** Consider a unilateral upward deviation from  $\widehat{Q}$ . The deviator's utility is:

$$U(\widehat{Q} + \varepsilon, \widehat{Q}) = v(\widehat{Q} + \varepsilon) + w(\widehat{Q} + \varepsilon, \widehat{Q}) - p(\widehat{Q} + \varepsilon).$$

Now we will show

$$\left. \frac{\partial U(\widehat{Q} + \varepsilon, \widehat{Q})}{\partial \varepsilon} \right|_{\varepsilon=0^+} > 0,$$

which means that there exists a profitable unilateral deviation from  $\widehat{Q}$ . Note,

$$\left. \frac{\partial U(\widehat{Q} + \varepsilon, \widehat{Q})}{\partial \varepsilon} \right|_{\varepsilon=0^+} = v'(\widehat{Q}) + \frac{\partial w(\widehat{Q} + \varepsilon, \widehat{Q})}{\partial \varepsilon} - p > v'(\widehat{Q}) + w'(\widehat{Q}) - p = 0.$$

The last equality follows from Lemma A1, and the inequality from our assumption  $\frac{\partial w(Q^k, Q)}{\partial Q^k} > w'(Q)$ . Thus, every individual has the incentive to deviate upward. When all users choose to consume  $\widehat{Q} + \varepsilon$  for some  $\varepsilon > 0$ , each user ends up receiving payoff  $V(\widehat{Q} + \varepsilon)$ . But this must be less than  $V(\widehat{Q})$ , since  $\widehat{Q}$  maximizes  $V$ .

**Proposition A2 (equilibrium selection problem)** *There exist multiple equilibria with different values of  $Q_{DI}$ . Equilibria with smaller  $Q_{DI}$  yield higher utility than equilibria with higher  $Q_{DI}$ .*

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<sup>32</sup>Our assumption  $w''(\widehat{Q}) < -v''(\widehat{Q})$  guarantees that the second order condition is satisfied.

**Proof.** We will examine incentives to deviate downward and upward from any given  $Q$ . We will find that there are no profitable deviations downward from  $Q < Q_I$ , and that there are no profitable deviations upward from  $Q < Q_I$  but “close” to  $Q_I$ .

Consider deviations downward. Consider a situation where all users consume  $Q$  applications. We now explore whether user  $k$  has an incentive to deviate downward. Note,

$$\underbrace{\frac{\partial w(Q + \varepsilon, Q)}{\partial \varepsilon} \Big|_{\varepsilon=0^-}}_{=0} + \begin{cases} v'(Q) - p & \text{if } Q < Q_I \\ - & \text{if } Q > Q_I \end{cases} \begin{cases} > 0 & \text{if } Q < Q_I \\ < 0 & \text{if } Q > Q_I. \end{cases} \quad (9)$$

Because (9) is negative when  $Q > Q_I$ , user  $k$  benefits by deviating downward. Conversely, the user loses by deviating downward from  $Q < Q_I$ . Thus, none of  $Q > Q_I$  can be an equilibrium.

Now, let's consider upward deviations. Note,

$$\underbrace{\frac{\partial w(Q + \varepsilon, Q)}{\partial \varepsilon} \Big|_{\varepsilon=0^+}}_{<0} + \begin{cases} v'(Q) - p & \text{if } Q < Q_I \\ - & \text{if } Q > Q_I \end{cases} \quad (10)$$

Notice that for all  $Q \geq Q_I$ , (10) is strictly negative. Hence, there is no incentive to deviate upward. Moreover, from the proof of Proposition A1 we know that (10) is strictly positive at  $\widehat{Q}$ . Therefore, by continuity, there must exist  $Q \in (\widehat{Q}, Q_I)$  such that (10) is also negative. We conclude that for those  $Q$  there are no incentives to deviate upward or downward. Therefore, the equilibrium set includes  $Q_I$  and these  $Q \in (\widehat{Q}, Q_I)$  for which (10) is negative.

We now turn to proving the second part of the proposition. The fact that equilibria with smaller  $Q_{DI}$  yield higher utility than equilibria with higher  $Q_{DI}$  follows from  $w''(Q) < -v''(Q)$ . Since in all equilibria all users consume the same applications, each user's utility in an equilibrium  $Q$  is given by  $V(Q)$ . Since  $w''(Q) < -v''(Q)$ ,  $V(Q)$  is strictly decreasing for  $Q > \widehat{Q}$  and all equilibria are  $Q > \widehat{Q}$ . Hence, equilibria with smaller  $Q$  yield higher utility.

## Extensions

Here, we explore the implications of different versions of our assumptions. In particular, we consider the role of our assumptions on  $\partial w(Q^k, Q)/\partial Q^k$ . Let

$$\frac{\partial w(Q^k, Q)}{\partial Q^k} \Big|_{Q^k=Q} = \begin{cases} a, & Q^k > Q \\ b, & Q^k < Q. \end{cases} \quad (11)$$

In the baseline model, we have assumed that  $a < 0$  and  $b = 0$ . For other values of  $a$  and  $b$ , we can use the proof of Proposition A2 to see that  $a$  regulates value  $Q_a$ , below which the

user has incentive to deviate upward. Thus, no  $Q < Q_a$  can be an equilibrium. Similarly,  $b$  regulates value  $Q_b$ , above which the user has incentive to deviate downward. Thus, no  $Q > Q_b$  can be an equilibrium. However, for  $Q \in [Q_a, Q_b]$  the user has no incentive to deviate upward nor downward, hence those values constitute equilibria.

**Remark A1** *Suppose that  $a$  and  $b$  characterize the derivative in equation (11).*

- *When  $a = b$ , then  $Q_a = Q_b$ , and there is a unique equilibrium.*
- *When  $a < b$ , then  $Q_a < Q_b$ , and there is a nonempty interval  $[Q_a, Q_b]$  of equilibrium values.*
- *When  $a > b$ , then  $Q_a > Q_b$ , and the interval  $[Q_a, Q_b]$  is empty, and there is no pure-strategy equilibrium.*

*If the platform sets  $A \leq Q_a$ , then  $Q_{DI} = A$  is a pure-strategy equilibrium.*

The remark says that we obtain multiple equilibria only if  $a < b$ . In this case, as in the main paper, the platform creates value by limiting the number of applications available because that prevents suboptimal equilibria from being played. When  $a > b$  there is no pure-strategy equilibrium. However, there is still value in the platform limiting the number of applications available. By doing so, the platform creates a pure-strategy equilibrium which should bring higher utility than any mixed-strategy equilibrium.

The next result identifies the relation between  $Q_a$ ,  $Q_b$ , and  $Q_I$ .

**Remark A2** *For  $j = a, b$ , if  $j < 0$  then  $Q_j < Q_I$ , if  $j = 0$  then  $Q_j = Q_I$ , and if  $j > 0$  then  $Q_j > Q_I$ . Therefore, a non-empty interval  $[Q_a, Q_b]$  may include  $Q_I$ , be entirely below, or entirely above  $Q_I$ .*

Thus, our qualitative results hold for more general conditions (on  $w$ ) than what we have considered in the main part of this appendix.

Contrary to the generalized formulation presented in this appendix, the micro-founded model in the main body of the paper is more closely related to the phenomenon that we study. Indeed, the main properties of functions  $v$  and  $w$  assumed in the generalized formulation are derived from the more specific utility function and textured environment in the micro-founded model. This allows us to better understand how the forces driving our results play out in the market.

## B Proofs

**Proof of Remark 1 (page 9).** First, we find the optimal consumption pattern for user  $k$ , given that  $k$  has access to some set  $\mathbb{Q} \subseteq \mathbb{A}$  of applications. Let  $\mathbf{x}^l$  be a pure strategy of user

$l \neq k$  and  $a'$  be an application such that  $\sum_{l \neq k} x_{a'}^l \geq \sum_{l \neq k} x_a^l$  for all  $a \in \mathbb{Q}$ . In equilibrium, user  $k$  does not consume other applications than  $a'$ . If there is only one  $a'$ , the best response of user  $k$  is to consume only this one application, i.e.,  $x_{a'}^k = X$  and  $x_a^k = 0$  for  $a \neq a'$ . If there is more than one  $a'$ , any allocation of time budget  $X$  across all those applications yields exactly the same consumption utility.

Given this optimal consumption pattern, user  $k$  needs to decide on the set of applications that she consumes,  $\mathbb{Q}$ , in order to maximize her net utility. If there exists unique  $a' \in \mathbb{A}$  such that  $\sum_{l \neq k} x_{a'}^l \geq \sum_{l \neq k} x_a^l$  for all  $a \in \mathbb{A}$ , then the optimal choice of applications for user  $k$  is a singleton  $\mathbb{Q}_D^k = \{a'\}$ . Notice that it leads to an equilibrium, where all users allocate their whole time budget to the same application, i.e.,  $\mathbb{Q}_D^k = \mathbb{Q}_D = \{a'\}$  and  $x_{a'}^k = X$  for all  $k$ . Therefore, it is a balanced equilibrium. Since any  $a' \in \mathbb{A}$  would constitute such an equilibrium, there are  $A$  equilibria of this form.

Finally, to see that there is no other equilibrium, suppose that there are more than one  $a'$  such that  $\sum_{l \neq k} x_{a'}^l \geq \sum_{l \neq k} x_a^l$ . Since the price of an application is strictly positive, user  $k$ 's best response is to consume only one of such applications. Therefore, there cannot be an equilibrium with  $Q_D \geq 2$ .

**Proof of Remark 2 (page 10).** The assumption that  $\alpha = 0$  implies that user  $k$ 's consumption utility (and net utility) does not depend on other users' strategies and thus subgame perfect equilibrium is equivalent to nonstrategic optimal choices by all player. Given this, we first find the optimal consumption pattern, given that user  $k$  has access to some set  $\mathbb{Q}$  of applications, where cardinality of  $\mathbb{Q}$  is  $Q \geq 1$ . The first order condition for utility maximization implies that every application is consumed in the same amount, i.e.,  $\hat{x}_a^k = \hat{x}$  for all  $a \in \mathbb{Q}$ . Since the utility function is strictly monotone, the constraint  $X \geq \sum_{a \in \mathbb{Q}} x_a^k$  needs to bind. Therefore  $Q \cdot \hat{x} = X$  and  $\hat{x} = \frac{X}{Q}$ . That implies that every equilibrium must be a balanced equilibrium.

With  $\hat{x} = \frac{X}{Q}$ , the maximal consumption utility given  $\mathbb{Q}$  is

$$u_I(\hat{x}; \mathbb{Q}) = \left( \sum_{a \in \mathbb{Q}} \left( \frac{X}{Q} \right)^{\frac{1}{R}} \right)^R = \left( Q \left( \frac{X}{Q} \right)^{\frac{1}{R}} \right)^R = Q^{R-1} X,$$

and thus user  $k$ 's maximal net utility is  $U_I(\hat{x}; Q) = Q^{R-1} X - pQ$ .

The optimal number of applications consumed by user  $k$  is characterized by the first order condition

$$(R-1) Q^{R-2} X = p \iff Q = \left( \frac{X(R-1)}{p} \right)^{\frac{1}{2-R}} := q_I. \quad (12)$$

The number of applications consumed cannot be greater than  $A$  or smaller than 1. Recall that we have assumed that  $A \geq q_I$ .<sup>33</sup> Therefore, the optimal number of applications consumed

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<sup>33</sup>If we had allowed for  $A < q_I$ , it would be optimal for a user to consume all  $A$  applications. This is

by any user  $k$  is  $Q_I^k = \max\{1, q_I\}$ .

Since the optimal number of applications consumed is the same for all users, let  $Q_I$  denote  $Q_I^k$  for any  $k$ . Thus,  $\{Q_I^1, \dots, Q_I^N\}$  constitutes an equilibrium if and only if the cardinality of  $Q_I^k$  is  $Q_I$  for all  $k$ . All equilibria clearly yield the same, highest possible utility to the users.

**Proof of Lemma 1 (page 12).** Suppose, to the contrary, that in some equilibrium  $Q^k \neq Q^l$  for some  $l$  and  $k$  (we drop the subscript  $DI$  in this proof for clarity of exposition).

First, consider the case where  $Q^k = Q^l$ , i.e., user  $k$  and user  $l$  consume the same amount of applications, but different ones. Take an application  $a'$  that  $k$  consumes, but  $l$  does not, and application  $a''$  that  $l$  consumes but  $k$  does not. Suppose, without loss of generality, that  $\sum_{j \neq l, k} x_{a'}^j \leq \sum_{j \neq l, k} x_{a''}^j$ . User  $k$ 's net utility in such a candidate equilibrium is

$$\left( \sum_{a \in Q^k} \left( x_a^k \right)^{\frac{1}{R}} \right)^R + \alpha \sum_{a \in Q^k \setminus \{a'\}} \left( x_a^k \sum_{j \neq k} x_a^j \right) + \alpha x_{a'}^k \sum_{j \neq k, l} x_{a'}^j - p Q^k.$$

If user  $k$  spends  $x_{a''}^k$  consuming application  $a''$  instead of  $a'$  (without changing anything else), she increases her utility to

$$\left( \sum_{a \in Q^k} \left( x_a^k \right)^{\frac{1}{R}} \right)^R + \alpha \sum_{a \in Q^k \setminus \{a'\}} \left( x_a^k \sum_{j \neq k} x_a^j \right) + \alpha x_{a''}^k \underbrace{\left( \sum_{j \neq k, l} x_{a''}^j + x_{a''}^l \right)}_{> \sum_{j \neq k, l} x_{a'}^j} - p Q^k.$$

Therefore, it is not an equilibrium since  $\alpha > 0$ .

Second, consider the case where  $Q^l > Q^k$  in a balanced equilibrium. In this case, for the same reason as above,  $Q^k \subset Q^l$ . Since they play balanced strategies,  $x_a^l = \frac{X}{Q^l}$  for  $a \in Q^l$ , and  $x_a^k = \frac{X}{Q^k}$  for  $a \in Q^k$ , and  $x_a^k = 0$  for all other applications. For  $k$ , it is optimal to consume  $Q^k$ . Such consumption yields the net utility

$$\left( Q^k \right)^{R-1} X + \alpha \frac{X}{Q^k} \sum_{a \in Q^k} \left( \sum_{j \neq k, l} x_a^j \right) + \alpha \frac{X}{Q^k} Q^k \frac{X}{Q^l} - p Q^k.$$

In particular, consuming  $Q^k$  applications yields higher utility for user  $k$  than consuming the same  $Q^l$  applications as user  $l$ , i.e.,

$$\left( Q^l \right)^{R-1} X + \alpha \left( \frac{X}{Q^l} \right)^2 Q^k + \alpha \frac{X}{Q^l} \sum_{a \in Q^l} \left( \sum_{j \neq k, l} x_a^j \right) - p Q^l \leq \left( Q^k \right)^{R-1} X + \alpha \frac{X^2}{Q^l} + \alpha \frac{X}{Q^k} \sum_{a \in Q^k} \left( \sum_{j \neq k, l} x_a^j \right) - p Q^k \implies$$

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because the derivative of  $U_I(\hat{x}; Q)$  is strictly positive for all  $Q < q_I$ . So it would be positive on the whole domain  $[1, A]$  for  $A < q_I$ .

$$\begin{aligned} \Rightarrow X \left( (Q^l)^{R-1} - (Q^k)^{R-1} \right) + \alpha X \left( \frac{1}{Q^l} \sum_{a \in \mathbb{Q}^l} \left( \sum_{j \neq k, l} x_a^j \right) - \frac{1}{Q^k} \sum_{a \in \mathbb{Q}^k} \left( \sum_{j \neq k, l} x_a^j \right) \right) - p(Q^l - Q^k) &\leq \\ &\leq \alpha \frac{X^2}{Q^l} \left( 1 - \frac{Q^k}{Q^l} \right). \end{aligned} \quad (13)$$

For  $l$ , consuming  $Q^l$  applications yields higher utility for user  $l$  than consuming only  $Q^k$  applications, i.e.,

$$X \left( (Q^l)^{R-1} - (Q^k)^{R-1} \right) + \alpha X \left( \frac{1}{Q^l} \sum_{a \in \mathbb{Q}^l} \left( \sum_{j \neq k, l} x_a^j \right) - \frac{1}{Q^k} \sum_{a \in \mathbb{Q}^k} \left( \sum_{j \neq k, l} x_a^j \right) \right) - p(Q^l - Q^k) \geq \alpha X^2 \left( \frac{1}{Q^k} - \frac{1}{Q^l} \right). \quad (14)$$

However, for  $Q^l > Q^k \geq 1$ ,  $\alpha \frac{X^2}{Q^l} \left( 1 - \frac{Q^k}{Q^l} \right) < \alpha X^2 \left( \frac{1}{Q^k} - \frac{1}{Q^l} \right)$ . Therefore, both inequalities (13) and (14) cannot be satisfied at the same time. Thus, it cannot be that there is a balanced equilibrium where  $Q^l > Q^k$ .

**Proof of Lemma 2 (page 12).** By Lemma 1, we know that all users consume the same  $Q_{DI}$  applications. Since the net utility of users is the same as long as all users consume the same  $Q_{DI}$  applications, any subset of applications  $\mathbb{Q}_{DI}$  of cardinality  $Q_{DI}$  constitutes an equilibrium.

**Proof of Remark 3 (page 14).** The remark directly follows from Lemma 7.

**Lemma 7** For all parameters  $\alpha \geq 0$  and  $1 \leq R < 2$ ,  $Q_I \geq \widehat{Q}$ . Moreover when  $Q_I > 1$ , then  $\widehat{Q} < Q_I$ , and when  $Q_I = 1$ , then  $\widehat{Q} = Q_I$ .

**Proof.**  $Q_I$  and  $\widehat{Q}$  are defined based on the solution ( $q_I$ ) to the following first order conditions, respectively:

$$\underbrace{(R-1)Q^{R-2}X - p}_{D_I(Q)} = 0. \quad (15)$$

$$\widehat{D}(Q) = \underbrace{(R-1)Q^{R-2}X - p}_{D_I(Q)} - \underbrace{\alpha X(N-1) \frac{X}{Q^2}}_{+} = 0. \quad (16)$$

Therefore, whenever  $\widehat{D} = 0$  for some  $\widetilde{Q}$ , then  $D_I > 0$  for this  $\widetilde{Q}$ . Moreover, since the derivative  $D_I$  is decreasing,  $D_I = 0$  for a larger  $Q$  than  $\widetilde{Q}$ . Therefore, the solution to the first order condition (15) (denoted by  $q_I$ ) is always larger than any solution to the first order condition (16), if the solution to the latter exists.

We focus on the non-trivial case when  $Q_I > 1$ .<sup>34</sup> This happens when  $q_I > 1$ . The value of

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<sup>34</sup>For  $Q_I = 1$ , which happens when  $q_I < 1$ , any solution to (16) must also be smaller than 1. Then  $\widehat{Q} = 1 = Q_I$ .

$\widehat{Q}$  is either a solution to (16) or 1. In either case  $\widehat{Q} < q_I = Q_I$ .

**Proof of Proposition 1 (page 14).** Consider a unilateral balanced deviation to  $\varepsilon$  more applications. The deviator consumes  $X/(\widehat{Q} + \varepsilon)$  of each application. Note that the payoff from this upward deviation under balanced consumption is

$$U_{DI}(\widehat{Q} + \varepsilon | \text{balanced}) = \left(\widehat{Q} + \varepsilon\right)^{R-1} X + \cancel{Q} \alpha \frac{X}{\widehat{Q} + \varepsilon} (N-1) \frac{X}{\cancel{Q}} - p \left(\widehat{Q} + \varepsilon\right),$$

which is the same as  $V(\widehat{Q} + \varepsilon)$ . Therefore, because  $V'(\widehat{Q}) = 0$ ,  $V(\widehat{Q} + \varepsilon)$  is maximized at  $\varepsilon = 0$ . This means that such an upward deviation with balanced consumption from  $\widehat{Q}$  brings no additional utility.

We now argue that an unbalanced deviation is strictly profitable. Suppose that the deviator consumes  $\varepsilon$  of new applications (which nobody else consumes), in addition to  $\widehat{Q}$  of old applications (which all other agents consume). It is easy to show that the deviator optimally consumes the same amount of each of  $\widehat{Q}$  old applications; we call this amount  $\widehat{x}$ . She also consumes in the same amount each of  $\varepsilon$  new applications; we call this amount  $x_\varepsilon$ . However, without imposing balanced consumption,  $\widehat{x}$  and  $x_\varepsilon$  may be different. Thus, the consumption utility from upward deviation to  $\widehat{Q} + \varepsilon$  is

$$u_{DI}(\widehat{Q} + \varepsilon) = \left(\widehat{Q}(\widehat{x})^{\frac{1}{R}} + \varepsilon(x_\varepsilon)^{\frac{1}{R}}\right)^R + \alpha \widehat{x} X (N-1) = \left(\widehat{Q}(\widehat{x})^{\frac{1}{R}} + \varepsilon^{1-\frac{1}{R}}(X - \widehat{x}\widehat{Q})^{\frac{1}{R}}\right)^R + \alpha \widehat{x} X (N-1).$$

The last equality follows from the constraint  $\widehat{x}\widehat{Q} + x_\varepsilon\varepsilon = X$ . To maximize the consumption utility, the agent chooses  $\widehat{x}$  to satisfy FOC:

$$\left(\widehat{Q}(\widehat{x})^{\frac{1}{R}} + \varepsilon^{1-\frac{1}{R}}(X - \widehat{x}\widehat{Q})^{\frac{1}{R}}\right)^{R-1} \widehat{Q} \left(\widehat{x}^{\frac{1}{R}-1} - \varepsilon^{1-\frac{1}{R}}(X - \widehat{x}\widehat{Q})^{\frac{1}{R}-1}\right) + \alpha X (N-1) = 0.$$

Because other terms are positive,  $\widehat{x}$  satisfies the FOC only if  $\widehat{x}^{\frac{1}{R}-1} - \varepsilon^{1-\frac{1}{R}}(X - \widehat{x}\widehat{Q})^{\frac{1}{R}-1} \equiv \widehat{x}^{\frac{1}{R}-1} - x_\varepsilon^{\frac{1}{R}-1} < 0$ . And since  $1 < R < 2$ , it implies  $\widehat{x} > x_\varepsilon$ . Therefore, the optimal upward deviation is characterized by unbalanced consumption, and is strictly better than the best possible balanced deviation. Hence, the optimal upward deviation is strictly profitable. This implies that  $\widehat{Q}$  is not a balanced equilibrium.<sup>35</sup>

**Proof of Lemma 3 (page 15).** Suppose that all users play a balanced strategy where they consume a set of applications  $\mathbb{Q}$  with cardinality  $Q$ .

<sup>35</sup>Notice the implication of this result for the incentives in the market: Suppose that the platform limits the number of applications to  $\widehat{Q}$ , and  $\widehat{Q}$  is optimal. Thus, the platform guarantees users the best equilibrium outcome. Nonetheless, the users are not happy with this restriction. They may believe (because they look at their profitable deviation upward) that if one more application would be available, they would be better off. But, of course, in an equilibrium they would not.



In the first step of the proof, suppose that  $Q > Q_I$ . Given that  $1 < R < 2$  and  $\alpha > 0$ , if user  $k$  consumes  $Q$  or fewer applications, i.e.,  $Q^k \leq Q$ , she consumes the same applications as other users, i.e.,  $\mathbb{Q}^k \subseteq \mathbb{Q}$ , according to a balanced consumption schedule:  $\frac{X}{Q^k}$  of each. Therefore, the net utility when user  $k$  consumes  $Q^k \leq Q$  applications is

$$U_{DI}(Q^k \leq Q) = (Q^k)^{R-1} X + \alpha \frac{X}{Q^k} (N-1) \frac{X}{Q} - p Q^k.$$

Since  $p > 0$ , the optimal number of applications that user  $k$  would like to consume is characterized by the first order condition

$$\frac{\partial U_{DI}(Q^k \leq Q)}{\partial Q^k} = (R-1) (Q^k)^{R-2} X - p = 0. \quad (17)$$

Note that this is the same condition as (12) in the proof of Remark 2. So  $Q^k = q_I$  is the only positive value satisfying this condition. Therefore, for any  $Q > Q_I$ , user  $k$  can profitably deviate to consuming  $Q_I$  applications.

In the second step of the proof, we turn to  $Q$  such that  $\max\{1, Q_\star\} \leq Q < \widehat{Q}$ , and we show that an upward deviation with a balanced consumption schedule is profitable for any user. The net utility from user  $k$ 's balanced consumption of  $Q^k \geq Q$  applications is

$$U_{DI}(Q^k \geq Q | \text{balanced}) = (Q^k)^{R-1} X + \alpha \frac{X}{Q^k} (N-1) \frac{X}{Q} - p Q^k.$$

Note that  $U_{DI}(Q^k \geq Q | \text{balanced})$  is the same as  $V(Q)$  in equation (4) which has a local maximum at  $\widehat{Q} > Q$ . Moreover, if there does not exist  $Q_\star \leq 1$ , then for any  $Q \in [1, \widehat{Q})$ , and when  $Q_\star \leq 1$  exists, then for any  $Q \in (Q_\star, \widehat{Q})$ ,  $U_{DI}(\widehat{Q} > Q) > U_{DI}(Q)$ . Also, by the definition of  $Q_\star$ ,  $U_{DI}(\widehat{Q} > Q) = U_{DI}(Q_\star)$ . The most profitable deviation, however, involves a non-balanced consumption schedule, and yields strictly higher utility than  $U_{DI}(Q^k > Q)$ . Therefore, the optimal deviation away from  $Q_\star$  is profitable.

**Proof of Lemma 4 (page 17).** Given that  $\alpha > 0$ , if user  $k$  consumes  $Q$  or fewer applications, i.e.,  $Q^k \leq Q$ , she consumes the same applications as other users, i.e.,  $\mathbb{Q}^k \subseteq \mathbb{Q}$ . Also, by usual arguments we find that the consumption schedule maximizing the consumption utility, under the constraint  $\sum_{a \in \mathbb{Q}^k} x_a^k \leq X$  is balanced strategy, i.e.,  $x_a^k = \frac{X}{Q^k}$  for all  $a \in \mathbb{Q}^k$ .

Therefore, the net utility of user  $k$  from consuming  $Q^k$  applications is

$$U_{DI}(Q^k; Q) = (Q^k)^{R-1} X + \alpha X (N-1) \frac{X}{Q} - p Q^k. \quad (18)$$

Drawing on properties of  $U_I$ , notice that  $U_{DI}$  increases with  $Q^k$ . That is, the user achieves a lower utility if she deviates from  $Q < Q_I$  to  $Q^k < Q$ .

**Proof of Lemma 5 (page 18).** Since Lemma 4 shows that there is no profitable deviation downward, it is enough to show that there is no profitable deviation upward.

Consider user  $k$  who consumes  $Q^k > Q_I$  applications. When user  $k$  diverts part of her time  $y$  away from the  $Q_I$  applications that all other users consume, it is optimal for her to consume the same amount of each application in  $Q_I, \frac{X-y}{Q_I}$ . Moreover, it is also optimal to consume the same amount of each application that user  $k$  consumes outside  $Q_I, \frac{y}{Q^k - Q_I}$ . Then, the net utility of user  $k$  is

$$U_{DI}(Q^k > Q_I | y) = \left( Q_I \left( \frac{X-y}{Q_I} \right)^{\frac{1}{R}} + (Q^k - Q_I) \left( \frac{y}{Q^k - Q_I} \right)^{\frac{1}{R}} \right)^R + \alpha \frac{X(X-y)}{Q_I} (N-1) - p Q^k.$$

Consider first only the part of the net utility without the direct network effects, i.e., the first and third terms. This is the same as the utility under pure indirect network effects. We know from the proof of Remark 2 that for any  $Q^k$ , the utility maximizing consumption schedule is balanced. However, since  $\alpha > 0$ , in this case the optimal deviation upward must involve un-balanced consumption (in an optimal deviation user consumes more of each application that other users consume and less of each applications that she alone consumes), i.e.,  $y < \frac{X}{Q^k}(Q^k - Q_I)$ . Therefore, if  $Q^k > Q_I$ , then

$$\left( Q_I \left( \frac{X-y}{Q_I} \right)^{\frac{1}{R}} + (Q^k - Q_I) \left( \frac{y}{Q^k - Q_I} \right)^{\frac{1}{R}} \right)^R - p Q^k < \left( Q^k \left( \frac{X}{Q^k} \right)^{\frac{1}{R}} \right)^R - p Q^k.$$

Recall that  $Q_I$  maximizes the net utility under pure indirect network effects. Therefore, for  $Q^k > Q_I$ ,

$$\left( Q^k \left( \frac{X}{Q^k} \right)^{\frac{1}{R}} \right)^R - p Q^k < \left( Q_I \left( \frac{X}{Q_I} \right)^{\frac{1}{R}} \right)^R - p Q_I.$$

Moreover, for any  $y > 0$ ,

$$\alpha \frac{X(X-y)}{Q_I} (N-1) < \alpha \frac{X^2}{Q_I} (N-1).$$

Therefore, any positive deviation,  $y > 0$ , toward consuming more applications,  $Q^k > Q_I$ , yields strictly worse net utility for user  $k$ ,

$$\begin{aligned} U_{DI}(Q^k > Q_I | y) &< \left( Q_I \left( \frac{X}{Q_I} \right)^{\frac{1}{R}} \right)^R + \alpha \frac{X(X-y)}{Q_I} (N-1) - p Q_I < \\ &< \left( Q_I \left( \frac{X}{Q_I} \right)^{\frac{1}{R}} \right)^R + \alpha \frac{X^2}{Q_I} (N-1) - p Q_I = U_{DI}(Q_I). \end{aligned}$$

Therefore, any set of applications  $\mathbb{Q}_I$  with cardinality  $Q_I$  constitutes a balanced equilibrium.

Suppose that  $\widehat{Q} > 1$ . By Lemma 4, for any  $Q$  such that  $\widehat{Q} < Q < Q_I$ , no user has a profitable deviation downward. Any such  $Q$  constitutes a balanced equilibrium if there is also no profitable deviation upward.

For  $Q$  such that  $\widehat{Q} < Q < Q_I$ , suppose that all other users consume  $Q$  applications, while user  $k$  consider diverting  $y$  of her time toward more applications,  $Q^k > Q$ . Let  $U_{DI}(Q^k > Q | y > 0)$  be utility at this deviation and denote the profitability of the deviation by

$$DevProf(Q) = \max_{y>0, Q^k>0} U_{DI}(Q^k > Q | y > 0) - V(Q).$$

From Proposition 1, we know that  $DevProf(\widehat{Q}) > 0$ . We can also show that  $DevProf(Q_I) < 0$ . This follows from the fact that an infinitesimal upward deviation from  $Q_I$  under pure indirect effects yields 0 profit. Due to the loss of the consumption complementarity, under both indirect and direct network effects the optimal deviation yields smaller utility. Therefore, the deviation is not profitable. Function  $DevProf(Q)$  is continuous in  $Q$ . Therefore, there must exist  $Q^0$ ,  $\widehat{Q} < Q^0 < Q_I$  such that  $DevProf(Q^0) = 0$ . If there are multiple  $Q$  satisfying this condition, let  $Q^0$  be the largest. Then, for all  $Q \in [Q^0, Q_I]$ ,  $DevProf(Q) \leq 0$ , i.e., there is no profitable deviation from  $Q$ . Hence, all  $Q \in [Q^0, Q_I]$  constitute balanced equilibria.

**Proof of Lemma 6 (page 19).** Suppose that  $Q_I > 1$ . When all users consume one application only, their consumption utility is  $u(Q=1) = X + \alpha X^2(N-1)$ . Now, if a user deviates to consume  $y$  of second application, her consumption utility is:

$$u(Q=2) = \left( (X-y)^{\frac{1}{R}} + y^{\frac{1}{R}} \right)^R + \alpha X(N-1)(X-y).$$

The optimal level of deviation  $y^*$  is characterized by the first order condition:

$$\frac{\partial u(Q=2)}{\partial y} = \left( (X-y^*)^{\frac{1}{R}} + y^{*\frac{1}{R}} \right)^{R-1} \left( \left( \frac{1}{y^*} \right)^{1-\frac{1}{R}} - \left( \frac{1}{X-y^*} \right)^{1-\frac{1}{R}} \right) - \alpha X(N-1) = 0.$$

Notice that  $y^*$  decreases with  $N$  and  $y^* \rightarrow 0$  as  $N \rightarrow \infty$ .

To find out if the value of the optimal deviation is larger than the price of the second application, we compute:

$$\begin{aligned} u(Q=2 | y=y^*) - u(Q=1) &= \\ &= \left( (X-y^*)^{\frac{1}{R}} + y^{*\frac{1}{R}} \right)^R + \alpha X(N-1)(X-y^*) - (X + \alpha X^2(N-1)) < \\ &< \left( (X-y^*)^{\frac{1}{R}} + y^{*\frac{1}{R}} \right)^R - X. \end{aligned}$$

Note that  $((X - y^*)^{\frac{1}{R}} + y^{*\frac{1}{R}})^R - X$  is continuous, takes value zero at  $y^* = 0$  and it is strictly increasing in  $y^*$ . Therefore for any price  $p$ , we can find  $N$  large enough so that  $y^*$  is low enough so that  $u(Q=2|y=y^*) - u(Q=1) < p$ , and the deviation is not profitable.

**Proof of Proposition 2 (page 20).** Directly from Lemma 5 we obtain the existence of multiple equilibria with different values of  $Q_{DI}$ .

The result that the equilibria with a smaller  $Q_{DI}$  yield higher utility follows directly from the shape of  $V(Q)$  and Lemma 3: All possible equilibria need to be included in the interval  $[1, Q_\star) \cup (\widehat{Q}, Q_I]$ . (The set of equilibria is a strict subset of this interval). The utility obtained by every user in each equilibrium  $Q$  is  $V(Q)$ . Since  $V(Q)$  is strictly increasing on the interval  $[1, Q_\star) \cup (\widehat{Q}, Q_I]$ , a lower equilibrium  $Q$  yields higher utility for every user than a higher equilibrium  $Q$ .

**Proof of Proposition 3 (page 21).** The shape of  $V$  implies that either  $Q^{**} = 1$  or  $Q^{**} = \widehat{Q}$ .

First, suppose that  $Q^{**} = \widehat{Q} > 1$ . Then,  $Q_\star$  (as defined for Lemma 3) does not exist. Therefore, by Lemma 3, no  $Q < \widehat{Q}$  may constitute a balanced equilibrium. As in the proof of Lemma 3, users are better off deviating upward to consuming  $\widehat{Q}$  applications. When  $A > \widehat{Q}$ , then  $\widehat{Q}$  is not a balanced equilibrium, by Proposition 1. This is because there exists profitable deviation upward, toward consuming larger number of applications. However, when  $A = Q^{**} = \widehat{Q}$ , such deviation is not possible. Therefore, consuming all  $\widehat{Q}$  constitutes the only equilibrium.

Now, suppose that  $Q^{**} = 1$ . When platform sets  $A = Q^{**} = 1$  then trivially, in the only equilibrium all users consume the only application in the market.

**Proof of Proposition 4 (page 24).** Suppose that user  $k$  consumes  $G^k$  applications in a no-foresight environment. For any given number of applications,  $G^k$ , the optimal consumption schedule is a balanced consumption. This is because for any application, the expected level of consumption by other users is the same:  $(N - 1)\frac{X}{A}$ . User  $k$ 's expected net utility is then

$$\mathbf{E}U_{DI}(G^k) = \left(G^k\right)^{R-1} X + \alpha(N - 1)\frac{X^2}{A} - pG^k.$$

Note that the benefit from the direct network effect does not depend on  $G^k$ . This leads to a result similar to the one in Remark 2: The above function  $U_{DI}$  is maximized by  $G^k = q_I = \left(\frac{(R-1)X}{p}\right)^{\frac{1}{2-R}}$ , for any  $k$ .

Since  $Q_I > 1$ ,<sup>36</sup> when  $A \geq Q_I = \left(\frac{(R-1)X}{p}\right)^{\frac{1}{2-R}}$ , the expected net utility of a user in equilib-

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<sup>36</sup>When  $Q_I = 1$ , the expected net utility of any user in equilibrium for  $A \geq 1$  is  $\mathbf{E}U_{DI}^*(Q_I = 1) = X + \alpha(N - 1)\frac{X^2}{A} - p$ , which is maximized by  $A = 1$ . By Lemma 7,  $\widehat{Q} = 1$  when  $Q_I = 1$ . Thus, the unique maximum of  $V(Q)$  is always  $Q^{**} = 1$ . In result, the platform maximizes user's net utility when

rium,  $\mathbf{E}U_{DI}^*(Q_I|A \geq Q_I)$ , is maximized for  $A = Q_I$ .

Since  $\mathbf{E}U_{DI}(G^k)$  strictly increases in  $G^k$  for  $G^k < Q_I$ , every user consumes all applications if there are fewer applications available than  $Q_I$ . Thus, for  $A \leq Q_I = \left(\frac{(R-1)X}{p}\right)^{\frac{1}{2-R}}$ , the expected net utility of a user in equilibrium is  $\mathbf{E}U_{DI}^*(A|A \leq Q_I) = (A)^{R-1}X + \alpha(N-1)\frac{X^2}{A} - pA$ . Note that this function of  $A$  is the same as  $V$  (with the exception that  $V$  is a function of  $Q$ ). Moreover, since  $Q_I > 1$ , it must be that  $Q^{**} < Q_I$ . Because  $Q^{**}$  is the value that maximizes  $V$ , then  $A = Q^{**} < Q_I$  also maximizes the expected net utility  $\mathbf{E}U_{DI}^*(A|A \leq Q_I)$ . Moreover, notice that  $\mathbf{E}U_{DI}^*(Q_I|A \geq Q_I)$  is maximized at  $A = Q_I$ , but  $\mathbf{E}U_{DI}^*(Q^{**}) > \mathbf{E}U_{DI}^*(Q_I)$ . So,  $A = Q^{**}$  maximizes the expected utility  $\mathbf{E}U_{DI}^*$  on the whole range  $A \geq 1$ .

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it sets the number of available applications to  $A = Q^{**} = 1$ .

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