Platform Ecosystems: How Developers Invert the Firm

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17-August-2016

For a period starting in 2015, Apple, Google, and Microsoft became the most valuable companies in the world. Each was marked by an external developer ecosystem. Anecdotally, at least, developers matter. Using a formal model of code spillovers, we show how a rising number of developers can invert the firm. That is, firms will choose to innovate using open external contracts in preference to closed vertical integration. The locus of value creation moves from inside the firm to outside. Distinct from physical goods, digital goods afford firms the chance to optimize spillovers. Further, firms that pursue high risk innovations with more developers can be more profitable than firms that pursue low risk innovations with fewer developers. More developers give platform firms more chances at success. Our contribution is to show why developers might cause a shift in organizational form and to provide a theory of how platform firms optimize their own intellectual property regimes in order to maximize growth. We use stylized facts from multiple platform firms to illustrate our theory and results.

Keywords: Open Innovation, Sequential Innovation, Platforms, R&D Spillovers, Intellectual Property, Network Effects, Network Externalities, Bundling, Two-Sided Networks, Two-Sided Markets, Vertical Integration, Standard Setting Organizations, Platform.

JEL Codes: D02, D21, D62, D85, L00, L17, L22, L24, L5, O3, O31, O32, O34.

1 Introduction and Background

One of the most important questions a firm can ask is how to efficiently create value: should it produce its own output or should it orchestrate the output of others. In the case of code, the choice increasingly favors orchestration over production. Apple, Google, and Microsoft, for example, became the three most valuable companies in the world in 2015, having passed energy and investment firms Exxon-Mobile and Berkshire-Hathaway.[1]

We argue that developer communities are inverting the firm. That is, firms must now manage value creation that occurs externally just as carefully as they manage the value they create internally. And, this is not just outsourcing. Firms are relinquishing product specifications to third parties that they do not even know. We provide a formal theory of why this is happening and ask what levers platform firms have to encourage external developers to innovate on their behalf. Our particular focus is on digital innovations that developers create to extend platforms. Digital platforms differ from physical systems such as automobiles because the subsystem boundaries can be more loosely defined, which makes recombination of elements less costly, and because information is non-rival. Reusable code, for example, facilitates knowledge spillovers. Interestingly, however, even firms that produce product platforms such as automobiles, tractors, and turbines are adding a digital layer to create an Internet of Things (Evans and Annunziata, 2012).

The role of developers has become so central in digital ecosystems that firms have developed strategies for "platform evangelism" to manage third party contributions that have become central to platform success.[2] Reasons that developers are so important in digital platforms include well known features of digital technology such as malleability of the code,

[1]http://finance.google.com. Accessed 9 Nov. 2015.

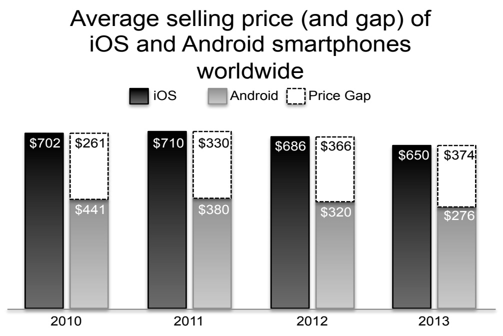
[2]The Open Automotive Alliance?s mission statement provides an example of the trend towards digital innovation on top of physical products: "The members of the Open Automotive Alliance share a vision for the connected car, and are committed to collaborating around a common platform to make this vision a reality." http://www.openautoalliance.net/. Accessed 9 Nov. 2015.

the low cost of investing in tools to develop code, close to zero cost reproduction, and the potential to profit from application successes while shedding the costs of failures. Put more broadly, developers are key to a platform?s ability to scale rapidly because what the platform firm does is not limited by the processes of hiring, training, project selection, and coordination. Instead, these processes are distributed outside of the platform, allowing much more rapid growth (Parker et al., 2016).

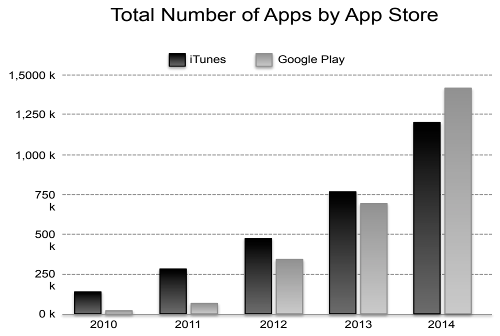
Others have observed the importance of digital ecosystems and the strategies that firms have to seek advantage. In an agenda setting paper for the field, Yoo et al. (2010) note that firms need to ask what they should open and what they should close in a digital product platform. Kallinikos et al. (2013) adopt the term "digital artifact" and characterize digital objects as open, reprogrammable, and accessible by other digital objects.

We are far from alone in observing that an historic shift is underway, driven by rapid improvements in network connectivity and computing power (Brynjolfsson and McAfee, 2014). Earlier improvements in transportation technology changed the locus of economic activity from vertically integrated firms to firms organized around a nexus of supplier networks. We believe that the current shift goes farther still. Using loosely affiliated ecosystems, firms are able to harness a global network of partners they don't even know beforehand who can connect through digital networks to innovate on top of a core set of resources thereby creating highly valuable products and services for their users.

In our context, a relevant innovation is any digital application, including a product or service, that is produced by an ecosystem partner using core platform resources. The rate of innovation is the rate at which developers produces digital applications for the platform. A platform can be conceived as a "layered architecture of digital technology" (Yoo et al., 2010). This includes a device layer, network layer, service layer and content layer. To this definition, we also add the governance rules that organize the ecosystem. The platform owner then influences developer innovation by exposing more platform resources e.g. by opening the architecture (APIs, SDKs, code libraries, templates, etc.), and by offering more favorable standard licensing agreements (SLAs), e.g. by offering exclusivity for new apps.



(a) The more open system has the lower price. Source: Statista using IDC data.



(b) The more open system grows faster. Source: AppFigures.

Figure 1: Openness entails a tradeoff. It nets less revenue on the core platform but fosters more applications development.

The battle between Apple iOS and Google Android provides a useful example of different platform choices around layered architecture and openness. Although Apple courts third party developers, it remains a relatively closed system along the dimensions catalogued in Eisenmann et al. (2009). For example, developers who wish to publish iOS applications must submit to Apple's rigorous quality review and Apple controls the only distribution channel. Eaton et al. (2015) describe the tensions between Apple, developers who build on top of iOS, and its end-users many of whom have "bricked" their devices in order to gain access to apps outside Apple's control. In contrast, Google has released Android under an open source license and has attracted more developer attention even though it launched after iOS.[3] Google's Android system is open to hardware manufacturers to the point that Google published reference designs to reduce their fixed costs in creating Android handsets (McAllister, 2011). To retain modest control over Android, Google makes API access dependent upon a Google Play subscription (Amadeo, 2013). Parker and Van Alstyne (2014) describe the strategic challenges such firms face when competing as platform ecosystems.

[3] http://readwrite.com/2014/01/08/app-store-sales-google-play-android

The different decisions have led to different market outcomes for both the price each platform charges and the number of applications provided by developers. As Figure 1a shows, the closed Apple platform is able to charge higher prices for the core platform, giving Apple much higher margins. By contrast, Figure 1b shows that the more open Android platform has attracted more applications development. The number of Android apps passed those of Apple iOS in 2014. Openness therefore entails a tradeoff. It nets less revenue on the core platform but fosters more applications development.

The need to open a platform to facilitate developer innovation is nicely stated by Laursen and Salter (2014): "... in order to obtain knowledge, organizations have to reveal some parts of their own knowledge to external actors" (page 868). In effect, this argues for the benefit of knowledge spillovers. Attaching to and building on others' ideas is easier conditional on access to these ideas. Importantly, in the case of software, Eilhard and Ménière (2009) provide empirical evidence that open code produces significant knowledge spillovers. In a study of 10,553 open source projects on SourceForge, they find evidence of non-decreasing returns to scale. Productivity of developers rises substantially with access to code libraries, especially if modules use the same language. The decision to fold new private code back into an existing public code library thus represents a design parameter of a healthy ecosystem.

Unsurprisingly, given the complexity of platform markets, executives struggle and have disagreed over how to manage their developer ecosystems (Libert et al., 2014). At the closed end of the spectrum, Tivo used provisions of the Digital Millennium Copyright Act to lock out industry players who sought to attach to its proprietary systems (Slater and Schoen, 2006). This allowed Tivo to charge more for its innovations. However, closure kept its ecosystem small. Ironically, the iPhone was also completely closed when Apple introduced it in 2007. Not until hackers broke into it in order to add new features did Apple release an approved System Development Kit (SDK) (Eaton et al., 2015). At the open end of the spectrum, UNIX firms have lost control over Application Programming Interfaces (APIs) to committees and have reduced pricing power as a result (West, 2003). RedHat, for example, uses standard GNU Public License terms that give anyone who receives their code the right to modify and distribute copies of the enhanced code for free. This fosters ecosystem participation, but competitors promptly absorb all valuable innovations.

Based upon our interviews with the global heads of platforms at Cisco, Haier, SAP, and Thomson Reuters, we examine two key decisions that platform managers must make. These are (1) how much of the core platform to open in order to spur developer innovation and (2) how long to grant developers the right to benefit from sales on top of the platform before the platform absorbs those innovations into the core. We explore how these decisions are affected by competition, level of vertical integration, number of developers, and the risk of innovation failure.

Despite considerable research on prices, quantities, and network effects, Yoo et al. (2010) note that little formal analysis has investigated broader platform business models. In addition, Tiwana (2013) calls for research on how platform governance affects ecosystem innovation. A growing literature has focused on leadership (Gawer and Cusumano, 2008), economics (Bresnahan and Greenstein, 1999; Farrell et al., 1998), launch (Bhargava et al., 2012), and strategies for managing platforms (Boudreau, 2010; Cusumano, 2010). Markovich and Moenius (2009) analyze competitive platform dynamics and show that weak developers can benefit from value added by strong developers. Zhu and Iansiti (2012) show how a platform entrant can overcome an incumbent based on the strength of developers' indirect network effects. Huang et al. (2012) show that developers with stronger property rights can more successfully resist expropriation by the platform. Scholten and Scholten (2011) identify control points that allow the platform sponsor to charge for access. The two-sided literature conceives of platforms as mediating markets with network externalities that cross distinct user groups and shows how subsidies to one group become optimal (Parker and Van Alstyne, 2000a,b; Caillaud and Jullien, 2003; Rochet and Tirole, 2003; Parker and Van Alstyne, 2005;

Eisenmann et al., 2006; Rysman, 2009).

To build the ecosystem, platform sponsors often embrace modular technologies and encourage partners to supply downstream complements in competitive markets (Baldwin and Clark, 2000; Fine, 1999; Boudreau, 2010). Loose integration promotes layered industries. In the personal computer industry, for example, these layers consist of semiconductor manufacture, PC assembly, operating system, and application software, among others (Baldwin and Clark, 2000; Grove, 1996; Shapiro and Varian, 1999). The credit card and telecommunications industries are similarly layered (Evans et al., 2006).

Ondrus et al. (2015) study platform openness with a focus on how the openness decision at the firm level (within and across industries), the technology level, and the user level affects the overall market potential. The key issue they study is the likelihood of a particular platform achieving critical mass. In our study, we approach the openness decision from the opposite direction and focus on how competition, technical success, size of developer base, and network effects change the decisions platform managers make around openness and time-to-bundle.

To make progress toward understanding the trade-offs inherent in managing platforms, we use tools from the economics of industrial organization. Specifically we begin with a baseline analytic model introduced to the literature by Parker and Van Alstyne (2015). This work provides a tractable model of the core elements of a platform and ecosystem economy including production and recursive innovation. We extend this model by adding competition among multiple developers to gain additional insight into the behavior of platform systems. Our results also add to our understanding of the platform corporate form relative to vertical integration. We extend the base model to add N developers who compete with one another. From this baseline, we develop the following new results around optimal openness σ, optimal developer innovation duration t, competition among developers, and network effects.

Our analysis then yields the following three results that show how platforms invert the firm by increasing the need to manage innovation and production that occurs externally. (1) Platforms bundle innovation more quickly as the number of developers N_d increases and as the likelihood of developer technical success increases so long as the second period number of developers is equal to or below the number in the first period. Platforms also increase their openness σ in both the number of developers and the likelihood of technical success increases until a threshold level of N after which the platform reduces openness. (2) Platform-to-platform competition strictly increases the level of openness as a function of the number of developers. (3) Firms with small developer bases and minimal network effects will prefer vertical integration or closed sub-contracting to open innovation. We develop each of these results and discuss their meaning below.

This paper addresses key topics of this special issue. In particular, we adopt the view that IT platforms can reshape innovation ecosystems. When the number of developers is sufficiently high, a platform with a default contract provides a new architecture for digital innovation. Decisions about how long to protect developer innovation, and especially how much to open the platform are at the intersection of IT, organizational design, and innovation and, as such, respond to the questions raised in the call for papers.

2 Model with Developer Competition

We extend Parker and Van Alstyne (2015) by explicitly incorporating N_d, the number of developers in the analytical framework. Such an extension enables analysis of how the key platform decisions of exclusionary period and openness are affected by technical risk, levels of competition (among developers and among platforms) and network effects. It also permits analysis of how spillovers across developers can change organizational form.

2.1 Platform Formulation

Ecosystem participants include platform sponsors, developers, and consumers. Table 1 in the Appendix summarizes variable definitions. We draw the following elements from Parker and Van Alstyne (2015). V is the value of the core platform before developers add applications. This is what a user would would pay for a standalone platform. For example, when the Apple iPhone first shipped, it had network connectivity, an email reader, a web browser, a calendar app and a handful of basic applications. In 2007, it was closed and did not offer third party applications until 2008 (Eaton et al., 2015).

To capture sequential innovation, let time span two periods of equal length t. At time zero, a platform sponsor makes fraction σ of its platform's value publicly available to developers, representing free access to reference diagrams, code libraries, APIs and SDKs. The other $(1-\sigma)$ portion remains private and is held by the platform sponsor. As a motivating example, consider the "Price Gap" in Figure 1a. This value, represented by public code σV, is not captured by the platform owner. Instead, the platform owner captures only the residual private code $(1-\sigma)V$. By contrast, a fully closed system would capture V and thus have higher baseline profit.

Developers add value according to a standard Cobb Douglas production function with technology parameter α. We denote the output of an individual developer in each period as y_1 and y_2 respectively. Period one output is $y_1 = k(\sigma V)^\alpha$ and period two output is $y_2 = k(y_1)^\alpha = k^{1+\alpha}(\sigma V)^{\alpha^2}$. Assume code reuse $k > 0$ and concave technology $0 < \alpha < 1$. Developer innovation is thus recursive. If developer code stays closed, other developers cannot build upon it, there are no spillovers, and 3^{rd} party production has no value. If developer code goes open, a choice the platform determines in its contract, developers can build on it in the next period, and there are code spillovers. Although the production function stays constant and concave, the effect of reuse rises from k to kk^α and the effect of technology strengthens from

$(\sigma V)^\alpha$ to $((\sigma V)^\alpha)^\alpha$. This formulation has the attractive property of capturing knowledge spillovers such as those found in Eilhard and Ménière (2009). Their use of the translog production function for econometric analysis is a direct generalization of the Cobb Douglas form used here.

If code is open, it is public and easily copied. No one can charge for public code. If code is closed, it is private and developers can charge for what they produce. The platform cannot tax developers who have no revenues. Openness thus has a benefit of increasing code spillovers and boosting innovation but a cost of decreasing ability to charge. To balance these conflicting interests, the platform sets an exclusionary or non-compete period t during which developers can charge for their code. Like a patent, however, the platform will make the code public after the non-compete period expires. We have direct evidence that the non-compete period is a strategic variable whose duration companies choose. For example, SAP publishes an 18–24 month roadmap that articulates "white space," alerting developers that they will not copy their their innovations until after this time. After that, any developer innovation may be absorbed into the SAP core. Apple reserves the right to appropriate developer innovations and reuse them in its ecosystem.[4] Similarly, Cisco bundles features that have appeared among multiple developer products into its core network operating system where they can be accessed via API calls by ecosystem partners. "Developers don't like it but realize it's good for the ecosystem."[5]

At the time developer innovations become open, the competitive price falls to zero. Knowing apps will be free in the future, a strategic customer optimizes between consuming the innovation at $p = v$ or waiting until time t, which at a conventional interest rate

[4] "Apple works with many application ... developers and some of their products may be similar to or compete with your applications. Apple may also be developing its own ... competing applications ... or may decide to do so in the future. ... Apple will be free to use and disclose any licensee [code] on an unrestricted basis without notifying or compensating you." Section 10.3 of the standard iOS license. https://developer.apple.com/programs/terms/ios/standard/ios_program_standard_agreement_20140909.pdf. Accessed Nov. 9, 2015.

[5] Authors' interview with Guido Jouret CTO Emerging Markets Group, Cisco Systems Inc. 9-8-2006.

implies a discount of $\delta = e^{-rt}$. The option to wait thus means that a customer will only pay for the incremental value of immediate consumption v relative to the discounted value of future consumption δv. The indifferent consumer thus accepts a price no higher than $p = v - \delta v = v(1-\delta)$. For simplicity, we assume market size is 1, and that a developer charges the highest price possible to the indifferent consumer, who then enjoys surplus δV.

Deviating from the original setup in Parker and Van Alstyne (2015), we then introduce a new parameter, $N_d \geq 1$, to represent the number of developers who compete with one another. This will interact with the production technology and the choice of openness to drive spillovers. Platform sponsor profit can then be written as:

$$\pi_p \;=\; V(1-\sigma) + \frac{1}{2}v(1-\delta)k(\sigma V)^{\alpha} + \delta\frac{1}{2}v(1-\delta)k^{1+\alpha}N_d^{\alpha}(\sigma V)^{\alpha^2}. \qquad (1)$$

Increasing the number of developers N_d raises output in period one such that $\tilde{y_1} = N_d\, y_1$. Recursive production then yields $\tilde{y_2} = N_d^{1+\alpha}y_2$, where the additional N_d^{α} follows from production spillovers $y_2(N_d y_1)$ of period one developers. Additional developers, however, reduce the pricing power of any given developer in the manner of Cournot competition. The exact formula for price under Cournot competition is $\tilde{p} = \frac{1}{N+1}p$.[6] To make analysis more tractable, simply interpret N_d as $N-1$, representing the number of *other* developers beyond the first one. This allows us to use the simpler form $\tilde{p} = \frac{1}{N_d}p$.

Finally, splitting profit between platform sponsor and developers, we have

$$\begin{aligned}
\pi_p &= V - \sigma V + \tfrac{1}{2}\tilde{p}\tilde{y}_1 + \delta\tfrac{1}{2}\tilde{p}\tilde{y}_2 \\
&= V(1-\sigma) + \tfrac{1}{2}1/N_d p N_d y_1 + \delta\tfrac{1}{2}1/N_d p N_d^{\alpha+1}y_2 \\
&= V(1-\sigma) + \tfrac{1}{2}v(1-\delta)y_1 + \delta\tfrac{1}{2}v(1-\delta)N_d^{\alpha}y_2 \\
&= V(1-\sigma) + \tfrac{1}{2}v(1-\delta)k(\sigma V)^{\alpha} + \delta\tfrac{1}{2}v(1-\delta)k^{1+\alpha}N_d^{\alpha}(\sigma V)^{\alpha^2},
\end{aligned} \qquad (2)$$

[6] See, e.g., Tirole (1988), p. 220.

which confirms Eq. (1).

3 Model Analysis

To facilitate the analysis below, we introduce a generic parameter β and re-write platform sponsor profit as

$$\pi_p \quad = \quad V(1-\sigma) + \frac{1}{2}v(1-\delta)k(\sigma V)^{\alpha} + \beta\delta\frac{1}{2}v(1-\delta)k^{1+\alpha}(\sigma V)^{\alpha^2}. \tag{3}$$

Eqn (1) is recovered when β is substituted back as $\beta_D = N_d^{\alpha}$. Conceptually, we can interpret β as a measure of the spillover effect. We will later see in this and the next section that platforms exposed to developer technical risk and platforms subject to network effects would experience different levels of spillover, say β_{TR}, or β_{NE}. Nonetheless, the dependency of the platform's choice of σ and δ on the $\beta's$ is directionally the same.

3.1 Optimization under Competition and Developer Risk

Consider the situation where individual developers face the risk of technical failure (with probability ρ). Given failure in earlier rounds, the number of developers in the ecosystem may decline over time. Assume the number of developers on Stage 1 is N_d and denote the number of developers who survive to Stage 2 as n. n follows a Binomial distribution with parameter N_d and ρ. The mean of the total value generated in Stage 1 remains $y_1 = (\sigma V)^{\alpha}$, and in Stage 2, it becomes $E(n^{\alpha})y_2$.

Consequently, the corresponding platform profit can be expressed in terms of the generic form Eqn (3) with $\beta_{TR}(N_d, \rho) = E(n^{\alpha})$. For the special case $\rho = 0$, $n = N_d$, and $\beta_{TR}(N_d, 0) = \beta_D = (N_d)^{\alpha}$. For the general case $0 < \rho < 1$, it is clear that $0 < \beta_{TR}(N_d, \rho) < (N_d)^{\alpha}$, and it monotonically increases in N_d and in $\omega = 1 - \rho$. Denoting $N_r := [E(n^{\alpha})]^{1/\alpha}$, we have

$\beta_{TR}(N_d, \rho) = N_r^\alpha$, and the mean value of platform profit under technical risk, still denote by π_p, can be written as

$$\begin{aligned}
\pi_p &= V(1-\sigma) + \frac{1}{2}v(1-\delta)k(\sigma V)^\alpha + \beta_{TR}(N_d,\rho)\delta\frac{1}{2}v(1-\delta)k^{1+\alpha}(\sigma V)^{\alpha^2}, \qquad (4)\\
&= V(1-\sigma) + \frac{1}{2}v(1-\delta)k(\sigma V)^\alpha + (N_r)^\alpha\delta\frac{1}{2}v(1-\delta)k^{1+\alpha}(\sigma V)^{\alpha^2}. \qquad (5)
\end{aligned}$$

In other words, the mean profit of a risk-prone platform system is identical to that of a no-risk system (Eqn. (1)) with the number of developers at a reduced level of N_r instead of N_d. Further, define $R := (\alpha v)/(2N_r)$, $U := \left(N_r k\right)/V^{1-\alpha}$, and $\overline{\delta} := \frac{1-\sqrt{\frac{\alpha}{2-\alpha}}}{2} < 1/2$. We have the following characterization of the optimal interior solution (σ^*, δ^*). Denote $\overline{N_d}$ as the unique N_r that induces optimal δ at $\overline{\delta}$.

Proposition 1 *Given $k, v, V, N_d > 0$, $0 < \alpha < 1$, $0 \leq \rho < 1$. Under condition $R, U < 1$, the optimum (σ^*, δ^*) of the risk-prone platform system corresponds to the optimum in the no-risk platform system with an equivalent number of developer $N_r < N_d$. Consequently, the following results hold true.*

(i) An interior optimum $\delta^* \in (0, \overline{\delta}]$ uniquely exists.

(ii) An interior optimum $0 < \sigma^* < 1$ uniquely exists.

(iii) Optimum δ increases monotonically in N_r. Consequently, it also increases in N_d and in $\omega = 1 - \rho$.

(iv) σ monotonically increases in δ when $\delta \leq \overline{\delta}$ and in N_r (N_d, ω) when $N_r \leq \overline{N_d}$; and σ monotonically decreases in δ when $\delta \geq \overline{\delta}$ and in N_r (N_d, ω) when $N_d \geq \overline{N_d}$.

Proof. Please see Appendix ■

To interpret the result, we first note that, $N_r < N_d$ suggests that risk damps the spillover effect, consequently lowering the level of incentive for bundling. In the meantime, an increased success rate encourages earlier bundling. In the case that the bundling durations are too long for reasons not modeled (such as fundamental change in the industry), then enlisting additional developers could compensate for technical risk and then maintain (or speed up) the bundling process. The result that having more developers helps mitigate risk is consistent with both logic and empirical research that finds handheld device platforms opened to more developers precisely to reduce the risk of technological innovation (Boudreau, 2010). For the same reason, social network platforms encourage developers to experiment because "much remains unknown concerning preferences and technical approaches to social applications" (Boudreau and Hagiu, 2009, p. 11).

The finding that σ first increases in N and then decreases after a threshold level has an important antecedent in the literature. Laursen and Salter (2006, 2014) find a concave relationship between appropriability and openness. To join their context and ours, additional developers can be interpreted as increasing collaboration. An interesting case arises when there is friction in adjusting σ. In this situation, the firm might anticipate growth in the developer base at launch and set a non-optimal σ and then hope that platform adoption would make the choice better over time. This parallels platform launch as described in Ondrus et al. (2015).

3.2 Platform Competition

We now analyze competition among platforms. Continuing with the Green and Scotchmer (1995) approach, we let competition moderate platform pricing power in the same way that it moderates developer pricing power, reducing platform price from V to $\frac{V}{N_p}$ where $N_p \geq 1$ is the number of platform competitors. Note from the proof of Proposition 1 that the optimum δ^* is independent to V, and that σ^* depends on σV. We conclude that increasing N_p implies a linear dependence $N_p\sigma^* := \sigma_p^*$ until σ_p^* hits 1, complete openness, meaning the platform sponsor would give away 100% of its original value. We summarize this discussion formally.

Corollary 1 *Increasing the intensity of platform competition has no effect on* t^**, but proportionally increases* σ^* *to* $\min\{N_p\sigma^*, 1\}$*.*

Proof. *The claims follow from Proposition 1 by substituting* $\frac{V}{N_p}$ *for* V*.* ■

Holding all else constant, greater platform competition reduces the sponsor's direct platform profits. The sponsor's incentive is therefore to open the platform in order to increase indirect profits from developer innovation. In terms of competition policy, the social planner should promote platform competition, which motivates sponsors to open up platforms and seek growth. This result directly parallels empirical findings. Based on case studies of IBM, Sun Microsystems, and Apple, West (2003) concluded that sponsors prefer the higher rents from closing their systems unless their platforms face pressure from rival platforms.

4 Permissionless versus Negotiated Platform Access

To this point, our analysis has assumed a platform with default contracts that allow developers to innovate on top. In this setting, it is always strategically optimal to open it up ($\sigma > 0$) at least some degree. However, a more fundamental question remains to be answered: is opening the platform to all developers the best way to organize for innovation? Might not vertical integration, which implies closing off developer access and only working with negotiated parternships, be better? The two-stage platform model suggests that one mechanism, the network spillover effect, could help open innovation to gain competitive advantage. In fact, the spillover effect β induced by multiple developers N_d scales up profit in the second stage. Below, we will examine how a network effect scales up the ecosystem by mobilizing both developers and users. The generic form Eqn (3) facilitates the analysis through analysis of the spillover factor β_{NE} that is implied by a network effect.

4.1 Negotiated Platform Access

Numerous mergers and acquisitions are predicated on the theory that a rational firm could improve profits by buying developers to acquire their technology. By only allowing negotiated platform access in our model, the sponsor might gain three advantages over permissionless innovation. First, closing the platform saves the open innovation subsidy σV, which increases profits from direct platform sales. Second, the developer can build on the *entire* platform, not just the portion opened; so output rises from $y(\sigma V)$ to $y(V)$. Third, application prices rise to monopoly levels $p = v$ because users cannot acquire apps by waiting for them to becomes a public good. Thus app profits rise. Allowing developers to keep half the value of their technology, based on Nash bargaining, the platform's profit under vertical integration becomes $\pi_{vi} = V(1-\sigma)\mid_{\sigma=0} + y_1 \mid_{\sigma=1} + y_2 \mid_{\sigma=1}$ which simplifies to

$$\pi_{vi} = V + \frac{1}{2} v k V^{\alpha} + \frac{1}{2} \delta v k^{1+\alpha} V^{\alpha^2}. \tag{6}$$

The corresponding platform system with $N_d = 1$ is listed below for comparison.

$$\pi_p = V(1-\sigma) + \frac{1}{2} v(1-\delta) k(\sigma V)^{\alpha} + \delta \frac{1}{2} v(1-\delta) k^{1+\alpha} (\sigma V)^{\alpha^2}. \tag{7}$$

Apparently, vertical integration (Eqn (6)) yields higher profit than open platform with one developer (Eqn (7)). It has higher output; it has no subsidy cost; and it has higher prices.[7] We then ask how might profits from open innovation *ever* dominate those from vertical integration? Following Eqn (3) and viewing the platform profit π_p as an increasing function of β, denoted as $\pi_p(\beta)$, we conclude

[7]Model analysis can easily extend to subcontracting, an organizational form between vertical integration and open innovation, by choosing different levels of σ.

Proposition 2 *Vertical integration outperforms an open platform when there is no spillover which reduces the spillover multiplier to $\beta = 1$. However, there is a unique breakeven spillover parameter $\overline{\beta}$ such that with all other parameters remaining constant, the open platform system outperforms vertical integration if and only if $\beta \geq \overline{\beta}$.*

Proof. Notice that the profit in the second stage is the only item depending on β; more specifically, proportionally increases in β, we claim that increasing the spillover effect β would improve the profit of open system $\pi_p(\beta)$, which ultimately outperforms the vertically-integrated system π_{vi}. ■

We posit two distinct answers to the question of whether to negotiate access or allow "permissionless innovation" (Cerf, 2012). One is that there exist developers the sponsor does not know and therefore cannot acquire. The other is that network effects can increase disproportionately under openness. The former might arise if there are numerous small developers who participate if they see an opportunity. Permissionless innovation matters to developers who risk disclosing their novel ideas by identifying themselves or their applications to the platform sponsor. Owning the indispensable asset, the sponsor has bargaining power and needs only the ideas to steal them (Bessen and Maskin, 2009; Parker and Van Alstyne, 2000a, 2012). Commitment to stay out of the developer's market during the exclusionary period provides the incentive such developers need to step forward. The law literature (Eisenberg, 1976) notes that making such a commitment will affect the downstream conduct of other parties whenever the mere act of negotiating reveals sensitive information. This result is clearly in evidence in SAP's platform, for example, where, as noted above, the platform sponsor commits to stay out of "white spaces," functionality that anyone is free to develop, for minimum periods of 18–24 months.

The second answer arises because, relative to closed systems, open systems invite more third party participation. Mechanisms by which openness might increase participation include transparency, bug reporting and feedback that can reduce R&D costs and increase platform quality, and user ability to modify open systems (Chesbrough, 2003; West, 2003). Openness can reduce negotiation costs, facilitate free redistribution (Raymond, 1999), and serve as a low price commitment analogous to second sourcing (Farrell and Gallini, 1988). It can aid horizontal integration (Farrell et al., 1998). The "two-sided" network literature (Parker and Van Alstyne, 2000a, 2005; Rochet and Tirole, 2003) specifically demonstrates how openly subsidizing one community (i.e., developers), can increase value to and participation of another community (i.e., end-users). For a variety of reasons, openness can increase both value and participation.

As both answers rely on growing the platform microeconomy, we now modify the earlier open platform model to include classic two-sided network effects across consumers and developers who value one another's participation on the platform (e.g., Parker and Van Alstyne (2005)). For tractability, we develop a novel yet simplified version of two-sided network effects to understand how their strength affects a sponsor's choice to provide access to all developers versus working with a select few. Thus we introduce market multiplier $M_i, i \in (u, d)$ derived from two-sided market feedback in order to represent the sizes of spillover externalities from content creation and content consumption.

4.2 Network Effect

While advantages of vertical integration include eliminating the subsidy, increasing prices, and increasing output, the advantage of open innovation is growing the market. Higher adoption and network effects can then justify open innovation relative to vertical integration.

To gain some insight about network effects which we label M_i, consider the following mechanism that allows more users to attract more developers and more developers to attract more users. Based on an externality spillover e_{ud}, augment baseline developers N_d

proportional to the number of users N_u, increasing developers by $e_{ud}N_u$. Likewise, based on externality spillover e_{du}, augment baseline users N_u proportional to the number of developers N_d, increasing users by $e_{du}N_d$. New users attract additional new developers, and vice versa, in amounts $e_{du}e_{ud}N_u$ and $e_{ud}e_{du}N_d$, a recursion process that defines Cauchy sequences for both groups. Developer size increases according to $N_d(1+e_{ud}\, e_{du}+(e_{ud}\, e_{du})^2+(e_{ud}\, e_{du})^3+...)$ and similarly for users. To keep market size finite, impose the constraint $e_{du}e_{ud} < 1$. These sequences converge to $N_dM_d = N_d\frac{1}{1-e_{ud}\, e_{du}}$ and $N_uM_u = N_u\frac{e_{du}}{1-e_{ud}\, e_{du}}$ respectively.

We can now present the platform profit function increased by network effects as follows.

$$\pi_{open} \;\; = \;\; M_u\Big(V(1-\sigma)+\frac{1}{2}v(1-\delta)k(\sigma V)^{\alpha}+\frac{1}{2}\delta v(1-\delta)k^{1+\alpha}(N_dM_d)^{\alpha}(\sigma V)^{\alpha^2}\Big). \quad (8)$$

Effectively, the network effect has two impacts: (1) the spillover effect at the level of $\beta_{NE} := (N_dM_d)^{\alpha}$, (2) re-scaling of the total platform profit proportional to the scale of the user population M_u. These two impacts jointly work to make open permissionless innovation outperform negotiated access-vertical integration. The following results parallel those of Proposition 2.

Proposition 3 *For the platform system with network effects, there exists a monotonically decreasing threshold curve $\overline{NM_d}(M_u)$ such that for any given user-side multiplier M_u, the open platform system outperforms vertical integration if and only if $N_dM_d \geq \overline{NM_d}$.*

Proof. By observing that π_{open}/M_u in Eqn (8) is the generic π_p in Eqn (3) with $\beta = (N_dM_d)^{\alpha}$, the proof follows Proposition 2 for all $M_u > 0$. ■

In the absence of network effects, the platform sponsor should own all means of production. Opening the platform to outside developers, however, becomes more attractive (i) as network effects rise (or the sizes of user or developer pools grow), (ii) as developer output rises, and (iii) content becomes more reusable. Negotiated access/vertical integration becomes more attractive as platform value itself grows. Note that the decentralized innovation is achieved without bargaining costs. A default contract with $\langle \sigma > 0, t > 0 \rangle$ gives developers an option to enter the market without disclosure to the platform sponsor. Open innovation, with a guarantee of lead time, preserves the information asymmetry that protects the innovator and prevents a powerful monopoly platform from stealing the full value of the innovation. The importance of third party contributions also becomes clearer as we observe that price effects, which are one-time gains, yield lower returns than production effects, which are recursive gains.

5 Discussion & Conclusions

Using a formal model of sequential innovation with code spillovers, our contribution is to show why developers might cause a shift in organizational form and to provide a theory of how platform firms optimize their own intellectual property regimes in order to maximize growth. This extends the sequential innovation literature (Green and Scotchmer, 1995; Chang, 1995; Parker and Van Alstyne, 2015) to add developer competition, spillovers, and network effects. From this baseline, we add three new results on optimal openness (σ), optimal IP duration (t), and effects of competition among developers (N_d).

1. We show how a rising number of developers can invert the firm. That is, firms will choose to innovate using open external contracts in preference to closed vertical integration or subcontracts. The locus of value creation moves from inside the firm to outside. Distinct from physical goods, digital goods afford firms the chance to optimize spillovers. If the number of developers is small or network effects are modest, firms prefer vertical integration or closed sub-contracts. However, once a threshold developer base N_d is reached, firms prefer to offer an open default contract to any developer who wishes to build upon the platform. Distinct from traditional buyer-supplier networks, this attracts resources from third parties that the platform firm does not even know.

2. Competition has different implications depending upon whether it occurs between platforms or among developers. Platform-to-platform competition strictly increases the level of openness. Because the platform makes less direct profit, openness costs less and the firm prefers to subsidize developer spillovers. By contrast, developer-to-developer competition has a non-monotonic effect. Openness first rises in the number of developers to promote R&D spillovers but then falls due to developer price competition. The result that openness has an invert-U relationship to innovation is consistent with empirical literature (Boudreau, 2010; Laursen and Salter, 2014).

3. Firms that pursue high risk innovations with more developers can be more profitable than firms that pursue low risk innovations with fewer developers. More developers give platform firms more chances at success. Platforms will increase their openness (σ) as the likelihood of technical success increases until a threshold level of N_d after which the platform reduces openness. Further, the more developers, the shorter is the proprietary period (t) offered under an optimal IP policy. The reason is that more developers increase the value of spillovers. Thus it makes sense to subsidize N-1 other developers by making the code of a given developer public in addition to the open code of the platform itself.

5.1 Limitations and Research Implications

The model analyzed above requires a number of assumptions for tractability. Key among these are (1) a shared consumer value for the platform V and developer additions, v, (2) use of a Cobb-Douglas formulation for developer output, and (3) no developer entry between periods one and two. A shared value is clearly a simplification since consumer valuations are more likely to follow an exponential distribution. However, Bakos and Brynjolfsson (1998) observe that, based on the central limit theorem, the average value converges rapidly for any bounded distribution as the population of consumers grows or the number of items in a bundle grows.

The practical impact of the point-mass valuation is likely to be limited because the focus of the analysis is on the behavior of the platform with respect to technical risk, the number of developers, and network effects. If the markets were made up of heterogeneous consumers, then some consumers would be priced out and the served market would be smaller. It would be interesting to examine the impact of the distribution of consumer values on the choices that platforms make. We leave that analysis to future researchers who might need to use simulation tools given the complexity of the analysis.

The Cobb-Douglas output assumption was also made in order that the model be solvable using formal analytic techniques. However, the formulation is widely used and, importantly, enjoys empirical support in work by Eilhard and Ménière (2009), who found the translog generalization fits the data for open source projects in real applications.

Our model of technical risk assumes that developers who fail are assumed to exit. If developers were to enter between period one and two, the impact on the platform's choices of σ and t should be the same as if the number of developers were simply larger in period one. However, the issue of when and why developers join platforms merits further study.

More generally, we note that results in the sequential innovation literature have not, until now, begun to account for recursive R&D spillovers that are feasible with digital goods. By not accounting for digital reuse, prior literature has recommended a patent period that is too long (Gilbert and Shapiro, 1990; Green and Scotchmer, 1995; Chang, 1995). Further, the prior works do not account for the variety of possible subsequent uses, which conditions and shortens these baseline predictions. Each of the results derived from the analysis presented above can also be formulated as a testable hypothesis, which we hope to explore in follow-on empirical research.

5.2 Managerial and policy implications

There are several managerial and policy conclusions. First, consider a classic M&A policy that would recommend acquiring complementary assets. We show that this can be suboptimal in a platform context. More precisely, we show that "permissionless innovation" can dominate vertical integration in cases where the number of developers becomes large because openness promotes R&D spillovers, which do not occur when the firm internalizes all production. Moreover, the platform owner does not always know which developers will succeed in the market and therefore which assets to acquire. This result implies that a platform strategy has a longer term likelihood of success than a purchasing/subcontracting strategy so long as the developer base reaches a sufficient size. This inverts the firm; the platform can wait longer to observe and profit from external developers before (if ever) acquiring them.

Second, as noted after Proposition 1, suppose that changing the level of openness is not frictionless. This might be the case due to technological or cultural constraints. Then firms prefer to set openness higher than is initially optimal whenever they anticipate growth of the developer base. Firms can also restrict network growth beyond a given size in order to control for poor developers.

Third, the core platform value can become so great that the owner no longer needs to give it away to stimulate growth. In that case the owner prefers to monetize the platform by reasserting control and further limiting openness. We can observe this in practice based on two examples. MakerBot, a 3D printing company, that gave away designs as well as design specs, was more open at first but has since moved to a more closed strategy by pursuing patents and creating applications that are not governed by open source licenses (Brown, 2012). Similarly, Android was more open at first in order to foster growth but has since moved to close the platform by exerting control over application programming interfaces (APIs) and critical applications such as Google maps (Amadeo, 2013).

Fourth, the manager's role must change in a platform context. Rather than optimizing the profits of the firm's own product in isolation, the manager needs to optimize the value created by an ecosystem, even if it cannibalizes a core product. In the context of large numbers of developers, this "platform" model is more profitable in the long run. In a real world context, considering developer profit is consistent with the policies of SalesForce and SAP as these firms specifically measure themselves by how much value they create for ecosystem partners. Indeed, addressing the cannibalization problem via a platform strategy is a significant topic addressed in the book Platform Leadership (Gawer and Cusumano, 2002). Here we show this result formally and prove that it can be more profitable.

Fifth, managing the ecosystem can also be interpreted as setting the optimal growth policy for an intellectual property (IP) regime where code may be reused. This is a unique property of digital and information goods. The period (t) during which a developer can sell an app parallels the duration of patent protection. The end of this period parallels when developer code becomes "public" and useful for R&D spillovers that help other developers. How the reuse of digital code affects optimal IP policy, and in turn is affected by competition, is not analyzed in other literature.

6 Appendix

Proof of Proposition 1

Recall from the model setup (Eqn. (5)) that

$$\pi_p = V(1-\sigma) + \frac{1}{2}v(1-\delta)k(\sigma V)^\alpha + \frac{1}{2}\delta v(1-\delta)k^{1+\alpha}N_r^\alpha(\sigma V)^{\alpha^2}. \tag{9}$$

The corresponding first-order condition w.r.t. δ and σ becomes

$$\begin{aligned} 0 = \frac{\partial \pi_p}{\partial \sigma} &= -V + \frac{1}{2}v(1-\delta)[k\alpha\sigma^{\alpha-1}V^\alpha + \delta\alpha^2 k^{1+\alpha}N_r^\alpha \sigma^{\alpha^2-1}V^{\alpha^2}] & (10) \\ 0 = \frac{\partial \pi_p}{\partial \delta} &= -\frac{1}{2}vk(\sigma V)^\alpha + \frac{1}{2}v(1-\delta)k^{1+\alpha}(\sigma V)^{\alpha^2} - \frac{1}{2}\delta v k^{1+\alpha}N_r^\alpha(\sigma V)^{\alpha^2}. & (11) \end{aligned}$$

Var		*Parameter Definition*
σ	–	Share of platform (%) opened to developers
t, δ	–	Time until exclusionary period expires (discount $\delta = e^{-rt}$)
α	–	Technology in Cobb Douglas production
k	–	Coefficient of reuse
M_d, M_u	–	Market spillovers from developers & users, index sizes of network effects
N_d, N_u	–	Numbers of developers and users respectively
p	–	Price of individual developer applications $p = v(1-\delta)$
ρ	–	Technological uncertainty; equal to $1-\omega$
v	–	Value, per unit, of developer output
V	–	Standalone value of sponsor's platform
y_i	–	Output of a single developer in period i and input to developers in period $i+1$ with $y_i = ky_{i-1}^{\alpha}$ and $y_0 = S$
ω	–	Probability of success for a given innovation; equal to $1-\rho$

Table 1: Parameter Definitions

Multiply Eqn. (10) by σ to get

$$0 = -\sigma V + \frac{1}{2}k\alpha v(1-\delta)[(\sigma V)^{\alpha} + \delta\alpha k^{\alpha} N_r^{\alpha}(\sigma V)^{\alpha^2}]. \tag{12}$$

Denote

$$S := \sigma V. \tag{13}$$

Then, Eqn. (12) becomes $S = \frac{1}{2}k\alpha v(1-\delta)[S^{\alpha} + \delta\alpha k^{\alpha} N_r^{\alpha} S^{\alpha^2}]$, or

$$1 = (k\alpha S^{\alpha-1})\frac{v}{2}(1-\delta)[1 + \delta\alpha(kN_r S^{\alpha-1})^{\alpha}]. \tag{14}$$

Similarly, Eqn. (11) becomes $0 = -\frac{1}{2}vkS^{\alpha} + \frac{1}{2}v(1-\delta)k^{1+\alpha}S^{\alpha^2} - \frac{1}{2}\delta vk^{1+\alpha}N_r^{\alpha}S^{\alpha^2}$. Equivalently,

$$\delta = \frac{1}{2}[1 - (kN_r S^{\alpha-1})^{-\alpha}]. \tag{15}$$

Let

$$M := kS^{\alpha-1}. \tag{16}$$

Then

$$\delta = \frac{1}{2}(1 - \frac{1}{(N_r M)^{\alpha}}) \tag{17}$$

Then Eqns (14,15) become

$$1 = \frac{\alpha v}{2}(1-\delta)M[1 + \delta\alpha(N_r M)^{\alpha}] \tag{18}$$

$$\delta = \frac{1}{2}[1 - \frac{1}{(N_r M)^{\alpha}}]. \tag{19}$$

Substituting (19) into (18), we obtain

$$1 = \frac{\alpha v}{4}\big(1+(N_r M)^{-\alpha}\big)M\big[1+\frac{1}{2}(1-(N_r M)^{-\alpha})\alpha(N_r M)^{\alpha}\big]. \tag{20}$$

Eqn. (20) serves as the basis for our analysis of δ and σ.

First, about δ as claimed in (i). Denote

$$X := N_r M, \tag{21}$$

and view the right-hand side of (20) as a function of X and N_r, $f(X, N_r)$, i.e.,

$$\begin{array}{rcl} 1 & = & \frac{\alpha v}{4N_r}\big(1+X^{-\alpha}\big)X\big[1+\frac{1}{2}(1-X^{-\alpha})\alpha X^{\alpha}\big] \\ & = & \frac{\alpha v}{4N_r}\big(X+X^{1-\alpha}\big)\big[(1-\frac{1}{2}\alpha)+\frac{1}{2}\alpha X^{\alpha}\big] := f(X;N_r). \end{array} \tag{22}$$

Recall $0 < \alpha < 1$, which implies $1-\alpha > 0$ and $1-\alpha/2 > 0$. Therefore, all the terms in the expression of $f(X;N_r)$ are both positive and monotonically nondecreasing. We have the follow properties of $f(X;N_r)$:

(1) $f(0;N_r) = 0$; $f(\infty;N_r) = \infty$ for all $v, N_r > 0$.

(2) $f(X;N_r)$ increases strictly in X and decreases strictly in N_r.

Consequently, there exists a unique $X(N_r) > 0$ such that $f(X(N_r);N_r) = 1$. Clearly $X(N_r)$ monotonically increases in N_r due to the monotonicity of $f(X;N_r)$ w.r.t X and N_r. By further expressing δ in terms of X via (19) and (21), $\delta = \frac{1}{2}[1-X^{-\alpha}]$, we see δ increases in X, thus in N_r. Moreover, the natural bound for an interior $\delta > 0$ requires $X > 1$, which is equivalent to $f(1;N_r) < 1$ due to the monotonicity of f in X. By straightforward rearrangement, $f(1;N_r) < 1$ becomes Condition $R = (\alpha v/2)/N_r < 1$. This completes the proof of Part (i).

Now, consider σ. The uniqueness of $X > 1$ satisfying $f(X;N_r) = 1$ implies the uniqueness of σ. Indeed, by definitions of X, M, and S, we have $X = N_r M = N_r k S^{\alpha-1} = N_r k(\sigma V)^{\alpha-1}$. Under condition $N_r, k > 0$ and $X > 0$ according to argument above, we have

$$\sigma = \Big(\frac{N_r k}{X}\Big)^{\frac{1}{1-\alpha}}/V > 0. \tag{23}$$

Therefore, it is never optimal for the platform to be completely close, $\sigma = 0$ as long as $v, N_r, k > 0$. We now demonstrate the monotonicity property of σ with respect to N_r, or equivalently, to δ, to complete the proof of Part (ii).

Noticing (23) can be re-written as

$$\sigma = \Big(\frac{k}{M}\Big)^{\frac{1}{1-\alpha}}/V, \tag{24}$$

we now convert $f(X;N_r)$ into a function of M and N_d. To be more precise, for

$$Q := N_r^{\alpha}, \tag{25}$$

define function

$$g(M;Q) := f(X;N_r) = \frac{\alpha v}{4}\big(M + M^{1-\alpha}/Q\big)\big[(1-\frac{1}{2}\alpha) + \frac{1}{2}\alpha Q M^{\alpha}\big]. \tag{26}$$

Parallel to previous arguments, we have $g(0;Q) = 0$, $g(\infty;Q) = \infty$; thus, for all $Q > 0$, there exists a unique $M(Q) > 0$ such that $g(M(Q);Q) = 1$. The monotonicity property of $M(Q)$ w.r.t. Q is thus implied in the monotonicity of $g(M;Q)$ w.r.t. both M and Q.

As for the monotonicity of g, it is clear $g(M;Q)$ increases strictly in M. With respect to Q, consider the first-order partial derivative

$$\begin{aligned}\frac{\partial g}{\partial Q} &= \tfrac{\alpha v}{4}\big(-M^{1-\alpha}/Q^2\big)\big[(1-\tfrac{1}{2}\alpha) + \tfrac{1}{2}\alpha Q M^{\alpha}\big] + \tfrac{\alpha v}{4}\big(M + M^{1-\alpha}/Q\big)\tfrac{1}{2}\alpha M^{\alpha} \\ &= \tfrac{\alpha v}{4}\big(-M^{1-\alpha}/Q^2\big)(1-\tfrac{1}{2}\alpha) + \tfrac{\alpha v}{4}\tfrac{1}{2}\alpha M^{1+\alpha} \\ &= \tfrac{\alpha v M}{4}\Big[-\tfrac{(1-\frac{1}{2}\alpha)}{M^{\alpha}Q^2} + \tfrac{1}{2}\alpha M^{\alpha}\Big].\end{aligned} \tag{27}$$

Clearly,

$$\begin{aligned}\Big\{\tfrac{\partial g}{\partial Q} > 0\Big\} &\iff (QM^{\alpha})^2 > \tfrac{1-\alpha/2}{\alpha/2} \\ &\iff (QM^{\alpha}) > \sqrt{\tfrac{1-\alpha/2}{\alpha/2}} \\ &\iff (1-2\delta)^{-1} > \sqrt{\tfrac{1-\alpha/2}{\alpha/2}}\ [by\ (19)] \\ &\iff \delta < \tfrac{1-\sqrt{\frac{\alpha}{2-\alpha}}}{2} = \overline{\delta}\end{aligned} \tag{28}$$

Combining equations $f(X, N_r) = 1$ and $\delta = \frac{1}{2}(1 - \frac{1}{X^{\alpha}})$, $\overline{\delta}$ uniquely determines an $\overline{N_d}$. The monotonicity of δ w.r.t. N_r in Part (i) further yields

$$\Big\{\frac{\partial g}{\partial Q} > 0\Big\} \iff N_r < \overline{N_d}. \tag{29}$$

Therefore, we conclude on $\{N_r < \overline{N_d}\}$ or $\{\delta < \overline{\delta}\}$,

$$\begin{aligned} g(M;Q) = 1 &\implies M \searrow Q[g \text{ increases in } M \text{ and in } Q] \\ &\iff \sigma \nearrow Q\ [\text{by } (24)] \\ &\iff \sigma \nearrow N_r\ [\text{by } (25)] \\ &\iff \sigma \nearrow \delta\ [\text{monotonicity of } \delta \text{ w.r.t. } N_r \text{ in Part (i)}].\end{aligned} \tag{30}$$

In parallel, on $\{N_r \geq \overline{N_d}\}$ or $\{\delta \geq \overline{\delta}\}$, $\sigma \searrow \delta, N_r$. Consequently, σ achieves its maximum at $\delta = \overline{\delta}$, $N_r = \overline{N_d}$. This completes the proof of Part (iii).

By combining Eqns (19, 21, 23) under condition $R < 1$, we can further express σ as function of δ.

$$\sigma = \Big(N_r k\big(1-2\delta\big)^{1/\alpha}\Big)^{\frac{1}{1-\alpha}}/V \tag{31}$$

Clearly, $\sigma < 1$ is guaranteed by $\Big(N_r k\Big)^{\frac{1}{1-\alpha}}/V < 1$, or equivalently, $(N_r k)/V^{1-\alpha} = U < 1$. This confirms Part (ii) of the proposition. Finally, it is easy to see N_r monotonically increases in N_d and $\omega = 1 - \rho$, and the proof is complete.

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