A Resource-based Theory of Hyperspecialization and Hyperscaling in Post-Chandlerian Digital Firms

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ABSTRACT

Compared to enterprises of the past, digital firms tend to be simultaneously narrower in their vertical scope and larger in their scale. We explain this phenomenon through a theory about how attributes of a firm's resource bundle impact its scale and specialization. In particular, we highlight that the high *scalability* of digital firms' resource bundles may drive "hyperspecialization" and "hyperscaling" due to the opportunity costs of not intensively deploying these resources. We use descriptive theory and a formal model to develop a number of propositions that are consistent with observed features of digital businesses. Our research provides a parsimonious modeling framework for future resource-based theorizing about digital firms, and sheds light on the far-reaching ways that technology-enabled resources are reshaping firms in the digital economy.

Keywords: digital firms, scalability, opportunity costs, scale and scope, resource-based view

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INTRODUCTION

The resource-based view (RBV) originally emerged to explain how unique firm-specific assets — conceptualized as resources or capabilities — lead to sustained competitive advantage (Barney, 1991; Mahoney & Pandian, 1992; Peteraf, 1993; Wernerfelt, 1984), but the theory has since been extended to explain firm boundaries. Scholarship in the RBV has long held that firms should integrate into activities for which they have superior resources (Argyres, 1996; Barney, 1999; Madhok, 1996, 1997, 2002). This initial rationale has been refined, and its boundary conditions identified, by combining it with transaction-costs and property-rights theories (e.g., Argyres & Zenger, 2012; Bel, 2018; Kang, Mahoney, & Tan, 2009; Kaul, 2013; Mayer & Salomon, 2006; Mayer, Somaya, & Williamson, 2012). Broadly these conceptualizations fit with Chandler's (1977, 1990) descriptions of how successful firms in the second industrial revolution were organized. Chandler highlighted how firms increased in both scale and scope through the development and redeployment of resources and capabilities, and the internalization of parts of the value chain by adopting new communication and logistics technologies to take advantage of these capabilities and to reduce transaction costs.

Recently, the digital revolution has profoundly reshaped the way we do and organize business (Brynjolfsson & McAfee, 2014; Cusumano, Gawer, & Yoffie, 2019; Siebel, 2019), highlighting a need to reassess our understanding of economic organization and its drivers. In this paper, we seek to shed light on the "post-Chandlerian" digital firm by examining how the digital revolution — and in particular the attributes of firm-level resources that it has enabled — affects firms' decisions about which value adding activities to perform within their boundaries and which ones to outsource to other firms.[1] The answer to this question is generally referred to as *the* theory of the firm (Demsetz, 1988; Rumelt, 1984), underscoring its importance in explaining why firms exist and the role they play in the economy. The theory we propose

[1] To keep things simple, we consistently use the term "integration" to mean the firm's expansion into activities that add value to its focal offering, and "specialization" and "outsourcing" to mean the opposite. In digital businesses, value addition does not necessarily take place in a linear fashion as is typical in industrial firms, therefore the traditional label of "vertical integration" may not always fit.

and develop, both descriptively and through a formal model (Makadok, Burton, & Barney, 2018), builds on scalability and fungibility, two key resource attributes highlighted in prior work (Levinthal & Wu, 2010; Wu, 2013), and on the idea that firms face non-linear adjustment costs in augmenting their resources (Knudsen, Levinthal & Winter, 2014; Pacheco-de-Almeida, 2010; Pacheco-de-Almeida & Zemsky, 2007; Penrose, 1959). We characterize firms' critical tradeoffs when allocating resources across alternative value-adding activities (Helfat, 2015; Helfat & Campo-Rembado, 2016) and generate a set of propositions consistent with observable features of modern digital firms (Adner, Puranam, & Zhu, 2019; Cennamo & Santaló, 2019).

Scaling is a key feature often highlighted about digital firms (Adner, Puranam, & Zhu, 2019; Autor et al., 2020; Hoffman & Yeh, 2018). The degree to which a firm's resource bundle is scalable directly affects the relative profitability of deploying resources more intensively within the focal activity versus redeploying them by integrating into other value-adding activities (Giarratana & Santaló, 2020; Helfat & Eisenhardt, 2004; Madhok, Li, & Priem, 2010; Levinthal 2017; Levinthal & Wu, 2010). Consider Scale AI, a startup creating labeled datasets for artificial intelligence (AI) applications, such as datasets of street scenes used to train algorithms for automated driving. The company uses a platform of human gig-workers and algorithms to create labeled datasets, and in theory could integrate into developing AI for end user markets (by using its strengths in AI algorithms). However, such integration entails significant opportunity costs of not developing its highly scalable digital platform to expand further within AI dataset creation. Thus, when a firm's resource bundle is highly *scalable*, concentrating all resources on the focal activity may be preferable to distributing them across multiple activities, making not integrating into them an optimal choice. Moreover, high scalability of the resource bundle also creates a substantial push for the firm's growth, despite specialization within its focal business. This core intuition highlights how digital firms' resource attributes may foster both high specialization and high scale, which consultants have called "hyperspecialization" and "hyperscaling" (e.g., McKinsey Global Institute, 2015), labels that we adopt and later define in this paper.

Chandler (1977, 1990) characterized the leading firms of the second industrial revolution as being large in both scale and scope, which we contrast with our theory of digital firms with high scale but narrow (vertical) scope. Although Chandler's industrial firms also often used scalable technological resources, their scaling properties hit diminishing returns relatively quickly as production increased; to wit, their minimum efficient scale was much smaller than the total size of the market. As expanding within these firms' core value-adding activities became less attractive, pressures grew to redeploy resources and expand into other parts of the value chain. In modern post-Chandlerian digital businesses, however, the employed resources exhibit significant scalability that does not quickly encounter diminishing returns. For example, in cloud-based SaaS (software as a service) businesses, the marginal costs of serving additional customers are small, and remain small (or even decline) for very large sales volumes. Thus digital firms often pour resources into their focal activities and outsource many others. Even a firm as successful and well-resourced as Netflix outsourced its data warehousing and streaming requirements (to Amazon Web Services) until very recently.

We formalize these arguments with a parsimonious analytical model, which yields a number of key results regarding economic organization in modern digital firms. For simplicity, and in line with Chandler's work described above, we consistently use the label "Chandlerian" to refer to traditional industrial firms whose resources are sublinearly scalable (i.e., exhibit diminishing returns), and use the label "post-Chandlerian" to refer to digital firms whose resources are superlinearly scalable (i.e., exhibit increasing returns).[2] Also, we consistently use the label "complementors" because it is more general, and can conceptually include "suppliers", although we acknowledge there might be meaningful distinctions between these terms in other research contexts.[3] Based on these definitions, our model contrasts the

[2] Ultimately, the availability of increasing or decreasing returns from resources depends on the combination of scaling effects on both the supply side and the demand side. For example, digital firms may also benefit from increasing returns on the demand side due to network externalities, or may at least enjoy elastic demand from access to global markets and virtually costless distribution through the internet. Conversely, traditional Chandlerian firms might have achieved economies of scale in production, but likely faced downward sloping demand curves and less global markets. We return to this issue later in the paper.

[3] Suppliers also perform activities that are complementary to the focal firm's (Balakrishnan and Wernerfelt, 1986; Jacobides, Knudsen, & Augier, 2006; Richardson, 1972): if a downstream stage *a* generates value only with an upstream stage *b*, and vice versa, then the upstream stage and downstream stage are complementary in the sense "*a* doesn't 'function' without *b*" (Adner, 2017; Jacobides et al., 2018).

differences between Chandlerian and post-Chandlerian firms in their integration choices, investments in scaling, and sharing of value with complementors. In the following section we first describe the overall structure and intuition underlying our theory, and then summarize the key results of the model. In so doing, we seek to make our ideas accessible in a non-technical manner.

Taken together, our theory and results extend the RBV by highlighting and explaining a new form of business organization that is high-scale but also highly specialized despite traditional motivations to integrate. Indeed, the digital economy has been characterized by the growth of ecosystem forms of organization that have the capacity to reach a very large number of customers and whose workings are inherently based on the premise of non-integration. Our theory explains these phenomena as the result of an internal dynamic for the continuing growth of the enterprise in which less (scope) is an enabling agent for more (scale). More broadly, our theory also contributes to a deeper understanding of the role of resources in vertical integration. It adds to the RBV by underscoring a powerful, but often neglected, force: the shadow of the opportunity costs of scaling within a specialized activity. In some cases, this force can be so strong as to eclipse the benefits of leveraging superior resources in multiple value-adding activities. At the limit, it can induce firms to become highly specialized and profit from relatively small margins for a large number of customers. Inter alia, our framework advances an approach to formal modeling in the RBV by parameterizing resource attributes such as their scalability and fungibility across uses, which can be valuable for investigating research questions regarding corporate strategy and performance implications in modern economies.

THEORETICAL FOUNDATIONS

The research literature in the RBV has theorized, almost from its inception, that firms should integrate into activities whose resource requirements match the profile of their existing valuable, rare, inimitable, and non-substitutable (VRIN) resources (e.g., Argyres, 1996; Barney, 1999; Madhok, 1996, 1997, 2002). Subsequent work has examined the interdependence between integration decisions and the development of resources and capabilities (Argyres & Zenger, 2012; Kang, Mahoney, & Tan, 2009; Mayer et al., 2012;

Wan & Wu, 2017), and more generally sought to combine the RBV with other theories of vertical integration such as transaction-cost economics and property-rights (e.g., Bel, 2018; Kaul, 2013; Mahoney & Qian, 2013; Mayer & Salomon, 2006). Research has also expanded the scope of the analysis to incorporate continuous governance modes, such as partial integration (Makadok & Coff, 2009; Parmigiani, 2007; Parmigiani & Mitchell, 2009; Puranam, Gulati, & Bhattacharya, 2013), and developed several important insights at the crossroads of the RBV, evolutionary economics, and the modularity literature (Baldwin & Clark, 2000, 2008; Jacobides & Winter, 2005; Helfat, 2015; Helfat & Campo-Rembado, 2016). The key insight from these cumulative RBV contributions to the theory of vertical integration remains essentially the same, which can be summarized as follows: In a value chain (or value system) of complementary activities, a firm will integrate into a value adding activity if its resources are superior to (more productive than) those of potential outsourcing partners.

A potential limitation of this received wisdom is that it does not explicitly consider an important alternative use of the firm's resources, which is to expand in scale within the firm's focal activity, while outsourcing others. In the context of traditional industrial firms and their pipeline business models, where RBV ideas about vertical integration originated, the opportunity costs of not using resources to grow within the firm's focal activity may have been less relevant because such growth quickly hit diminishing returns in productive resources (by reaching minimum efficient scale) or in demand (by exhausting local or regional markets). However, these conditions may no longer hold in the modern digital economy, and it would be valuable to reexamine the RBV's predictions for integration choices in digital firms that have emerged in the third and fourth industrial revolution. Drawing on several descriptions of the digital transformation of the economy (Adner et al., 2019; Agrawal et al.; 2018; Brynjolfsson & McAfee, 2014; Siebel, 2019), our conception of digital firms focuses on two central features. First, these firms employ, to a significant degree, digital resources such as data, software, and artificial intelligence (AI) that are essentially scale-free, such that the resources' marginal costs are near zero for essentially any production quantity (Adner et al., 2019;

Levinthal & Wu, 2010).[4] Second, digital firms distribute their offerings largely through the internet and cloud platforms (Siebel, 2019), and thus have access to a very large market with a large range of highly elastic demand. Moreover, since many digital firms are organized as digital platforms or intermediaries (Cennamo & Santaló, 2019; Parker et al., 2016), they can even experience demand-side positive feedback from network effects, which may also create demand-based increasing returns to scale.

Thus, digital firms provide an interesting (and important, due to their rapid proliferation) context for advancing the RBV theory on vertical integration, while also exhibiting distinctive features indicating that such advances might indeed be necessary. Digital resources are often considered fungible to a variety of value-adding activities (Adner et al., 2019; Agrawal et al., 2018; Brynjolfsson & McAfee, 2014), which should in theory lead to more integration. However, this proposition is in contrast to the very nature of many digital intermediaries and platforms, whose business model is based on the premise of non-integration (Cennamo & Santaló, 2019; Kretschmer et al., 2020; Parker et al., 2016).[5] Compared to traditional firms, they seem to shrink on the vertical dimension, but at the same time grow very large in scale (Adner et al., 2019; Hoffman & Yeh, 2018), often surpassing their counterparts in terms of revenues and market capitalization. Research has also noted that digital resources do not operate on their own and typically need complementary intangible resources, often manifested in specialized human capital, in order to create value (Tambe et al., 2020). In turn, these human and managerial resources are generally very difficult (or equivalently very costly) for firms to augment quickly (Knudsen et al., 2014; Penrose, 1959). As a recent

[4] Increasing sales and use of digital offerings by customers may also increase the value provided by the offering, because data is essentially self-generating and data analytics may enjoy positive feedback loops in these contexts (Adner et al., 2019; Agrawal et al., 2018).
[5] For a more detailed discussion on ecosystems and platforms, please see: Adner (2017), Jacobides, Cennamo, and Gawer (2018), Parker et al. (2016), and Cusumano, Gawer, and Yoffie (2019), and Kretschmer et al. (2020). Although platforms (and ecosystems) appear at first glance to be different from traditional business models (and value chains), recent theoretical work has underscored important similarities (Adner, 2017; Hannah & Eisenhardt; 2018; Ganco et al., 2019; Jacobides et al., 2018). Like value chains, ecosystems are organized around a final product such that their components are complementary (Adner, 2017; Baldwin & Clark, 2008; Casadesus-Masanell & Yoffie, 2007), and emerge from the division of labor among co-specialized firms sharing the value they jointly help create (Jacobides et al., 2018; Jacobides, Knudsen, & Augier, 2006; Panico, 2017). As discussed later in this paper, demand-side positive feedback effects in platform markets (Arthur, 1989, 1996; Hagiu & Yoffie, 2016; Lobel, 2018; Wessel, Levie, & Siegel, 2017) can be modeled using scaling laws in the same way as resources, and yields analogous insights.

article from The Economist points out (2020), top talent capable to work with scalable technologies such as artificial intelligence (AI) is quite scarce: "AI experts are scarce, and command luxuriant salary."

To shed light on these apparent contradictions, we draw on insights from recent developments in the RBV, which has looked to resource attributes — such as scalability and fungibility — as critical parameters that drive the impacts of resources on corporate strategies (Anand & Singh, 1997; Helfat & Eisenhardt, 2004; Levinthal & Wu, 2010; Sakhartov & Folta, 2014, 2015; Wu, 2013). Of particular interest is the distinction between scale-free and non-scale-free resources (Levinthal & Wu, 2010; Sakhartov & Folta, 2014, 2015), which we extend to a continuous parameter: "scalability." We integrate these concepts with related ideas from the world of technology, where practicing experts often discuss firms' strategies in terms of scaling laws (Hoffman & Yeh, 2018; Levie & London, 2018; Wessel et al., 2017). Scaling laws are exponential functions of the type $f(x) = kx^{\sigma}$ which, despite their simplicity, can describe the scaling properties of a variety of complex adaptive systems ranging from organisms (e.g., animals and plants) to organizations (e.g., cities and firms) (Fu et al., 2005; Gabaix, 2016; West, 2017). Using an expression popular in Silicon Valley, we say that resources are superlinearly scalable (or just scalable, for simplicity) if their performance increases (or does not deteriorate) when the size of the firm increases (i.e., they exhibit increasing or constant returns to scale); else, resources are sublinearly scalable (i.e., they exhibit decreasing returns to scale).

In order to develop a firm-level theory of integration decisions, we build on the conception of a firm as a bundle of resources and capabilities (Amit & Schoemaker, 1993; Penrose, 1959) and focus on the attributes of a firm's entire resource bundle. Among a firm's variety of resources, technological production resources—such as factories, IT systems, cloud platforms, and AI systems—play a critical role in the scalability of the bundle as a whole, and are critical for illustrating differences between industrial (Chandlerian) and digital (post-Chandlerian) firms. In industrial firms, the production resources such as plants or production lines often hit diminishing returns relatively quickly (e.g., at minimum efficient scale). By contrast, digital production resources such as cloud software, IT platforms, and AI algorithms can almost be infinitely scaled by virtue of (almost) costless and error-free replication, combined with global connectivity and improvements in cost and performance as more users adopt and contribute data to them (Adner, Puranam, & Zhu, 2019; Agrawal et al., 2018; Brynjolfsson & McAfee, 2014).[6] In turn, when such digital resources are a significant fraction of a firm's resource bundle, it is likely to render the resource bundle as a whole to be scalable.

The other resource type to consider are "Penrosean" resources that essentially consist of the firm-specific human and managerial capital used in conjunction with the firm's technological resources (Castanias & Helfat, 1991). These resources typically consist of the tacit knowledge and skills of the firm's employees, and include managerial human capital and attention (Ocasio, 1997; Penrose, 1959). In turn, these Penrosean resources don't easily scale due to the inherent limits of human attention and abilities, and are also difficult-to-augment (as we explain below). The share of Penrosean resources employed by a firm naturally affects the degree to which the firm's resource bundle is scalable, by essentially dampening its scaling properties. For example, the resource bundle of an accounting firm that uses some digital technologies, but whose resource base consists mostly of accountants, is unlikely to exhibit high scalability. Moreover, Penrosean resources affect the ease (or cost) with which the resource bundle can be augmented. Because these resources are typically firm-specific, they need to be developed over time through a process of generating resource slack by socializing employees, developing or adopting common routines, and training them within the firm (Knudsen et al., 2014; Penrose, 1959). Attempting to rapidly augment these resources escalates costs both directly through time compression diseconomies (Dierickx & Kool, 1989; Pacheco-de-Almeida & Zemsky, 2003, 2007; Teece, 1986) and indirectly through the costs of errors such as poor replication of the firm's tacit knowledge and routines (Levinthal, 1997; Rivkin, 2001).

Based on these attributes of the firm's resource bundle, we develop our formal model to explain the firm's integration choices and degree of scaling. At the heart of our theory is the intuition that a scalable

[6] The scaling properties contributed by digital technologies does not mean that digital firms have no size limit to which they can scale; this limit might simply be quite large and comparable to global demand. The literature on scaling laws also suggests that real world processes are only typically scalable within range (West, 2017).

resource bundle can lead to vertical specialization due to the opportunity cost of not focusing on the focal value-adding activity as intensively as possible—even if the resource bundle is somewhat fungible to other activities. Figure 1 is a graphical representation of the intuition. Let τ be the percentage of the resource bundle, r, allocated to a given application and $V(\tau \times r)$ be the value produced as a function of $\tau \times r$. When the resource bundle is sublinearly scalable, the opportunity cost of withdrawing resources from the focal activity is relatively low; reducing τ has only a small impact on performance. When the resource bundle is scalable, however, the opportunity cost of redeploying the same amount away from the focal activity is high and can result in a significant deterioration in performance.

[Insert Figure 1 approximately here]

We present five propositions derived from our model. Our first proposition lays out the contrasts in the overall integration patterns between Chandlerian and post-Chandlerian firms. Specifically, while in a Chandlerian firm, changes in the cost of outsourcing lead to gradual changes in integration, with various degrees of partial integration as intermediate modes between full specialization and full integration (Puranam, Gulati, Makadok, & Coff, 2009; Parmigiani, 2007; Parmigiani & Mitchell, 2009), in a post-Chandlerian firm, such a change can trigger a discontinuous shift from full specialization to full integration. Our second set of results, in Propositions 2 and 3 respectively, examine the contrasting roles of scalability and fungibility of the firm's resource bundle for Chandlerian and post-Chandlerian firms. Our results show that the propensity to vertically integrate increases with both scalability and fungibility in a Chandlerian firm, but they have opposite effects in a post-Chandlerian one. Scalability induces post-Chandlerian firms to remain specialized even at higher costs of using the market, whereas fungibility increases the propensity to integrate.

Having examined vertical scope decisions, our model turns in Proposition 4 to investigate the interrelationship between scale and scope choices of the firm. The result shows that, unlike in Chandlerian firms where scale and scope go hand in hand (Chandler, 1990), scale and specialization are mutually reinforcing in post-Chandlerian firms. In other words, post-Chandlerian firms would be of smaller scale if they did not specialize, and the fact that they can grow significantly within their focal activity is a key motivation to specialize. In Proposition 5, we further extend our model by endogenizing value capture and coopetition with the complementor firm(s). Our results paint a stark contrast between our theory and one of the canonical results of the RBV literature: that firms will vertically integrate if their resources are more productive than those of their complementors. We show that under post-Chandlerian conditions, resource superiority may not necessarily lead to integration. Instead, up to a point, resource superiority leads the superior firm to forego a greater share of value created so as to incentivize supply of the complementary product or service, thus increasing its own returns by specializing and scaling within its focal activity.

FORMAL MODEL

We formalize our arguments via a parsimonious decision-theoretic model that casts vertical expansion strategies as the solution to a resource-allocation problem involving two complementary value-adding activities.[7] The model borrows elements from the literature on non-scale free resources and resource redeployment (Levinthal & Wu, 2010; Sakhartov & Folta, 2013) as well as from the value-based literature in strategic management (Chatain & Zemsky, 2007, 2011; Chatain, 2014; Jia, 2013; Postrel, 2018; Wan & Wu, 2017). By design, the model does not incorporate coordination costs, technological interdependencies, or supermodular complementarities. Therefore, if vertical integration occurs, it does so due to resource characteristics, despite the absence of these often-cited drivers of vertical integration (Alchian & Demsetz, 1972; Garicano & Wu, 2012; Helfat & Campo-Rembado, 2016; Postrel, 2009).

In what follows, we focus on implications of scalability of resources on the supply-side, without explicitly incorporating the effects of demand-side scale economies. While this modelling choice has the advantage of exemplifying the exposition, we note that our findings are robust to richer characterizations of the demand environment, as we later discuss.

[7] A decision-theoretic model allows us to highlight the core results around the internal resources of the focal firm. We later study a game-theoretic model endogenizing competition and value capture, both showing the robustness of our main results and generating additional insights.

Resource Attributes and Production

To illustrate the basic mechanisms at play, consider an economy with a simple demand environment where the final customer pays a constant amount V for the final product $a \wedge b$,[8] consisting of two components, a and b, in one-to-one proportion, with the value of the components in isolation being normalized to zero. The bundle $a \wedge b$ can be thought of as a final good (e.g., car) requiring a set of inputs (e.g., drivetrain and chassis) in fixed proportions, as the output of an ecosystem whose components exhibit strict complementarities of the type that "a doesn't 'function' without b" (Adner, 2017; Jacobides et. al, 2018) as in the case of processing units and operating systems for personal computers (Casadesus-Masanell & Yoffie, 2007); or of an ecosystem whose components exhibit complementarities of the type that "a functions better with b" as in the case of smartphones and compatible applications (in this latter case, the value of a smartphone without applications is non-zero, but it can be normalized to zero for analytical convenience so that V represents the value added by the applications (Postrel, 2018)).

To produce a and b, the focal firm (firm i) allocates its resource bundle, r, to the two activities by allocating $\tau \in [0,1]$ to activity a and $(1-\tau)$ to b, generating outputs $Q_{ia}(\tau r)$ and $Q_{ib}((1-\tau)r)$, respectively. As described earlier, r may consist of a variety of resources bundled within the firm, ranging from technological production resources (such as digital technologies) to co-specialized Penrosean (human and managerial) resources, and takes on the combined properties of these underlying components. This conceptualization lets us consider a firm-level theory of the opportunity costs of resources that would not emerge if we examined individual resources by themselves. Opportunity cost considerations, in particular, are likely to be driven by the adjustment costs of the Penrosean resources used alongside technological

[8] Thus, technically, the demand for the bundle $a \wedge b$=min{a,b} is perfectly elastic, meaning that V is constant and independent of the quantity of $a \wedge b$ supplied to the market. Later, we suggest how this assumption can be relaxed to model a rich set of demand conditions that include both decreasing and increasing returns. Furthermore, we make the case that the results we derive here can be extended to such a model by incorporating the combined effects of resource-driven and demand-side scaling through a single parameter.

production resources, which are very costly to increase in a short period of time (Giustiziero, 2020; Knudsen et al., 2014; Penrose, 1959).

The production functions Q_{ia} and Q_{ib} follow scaling laws with scaling exponent $\sigma > 0$, thus characterized by the scaling relation $Q_{ia}(tr) = t^{\sigma} Q_{ia}(r)$ and $Q_{ib}(tr) = t^{\sigma} Q_{ib}(r)$ for any scalar *t*.[9] The scaling exponent, σ, determines the scalability of the firm's resources, that is, how the performance of the firm's resource bundle changes with its size. As is standard, σ greater than or equal to one delineates superlinear scaling, with σ less than one sublinear scaling, As we later demonstrate, σ can be interpreted as a reduced form of the combined effects of supply-side and demand-side returns to scale on the firm's resources. If σ > 1, the focal firm can be thought of as a post-Chandlerian firm, in which returns to scale due to economies in software development (Arthur, 1996) and positive feedback loops in data analytics (Agrawal, Gans, & Goldfarb, 2018) are supercharged by network effects on the demand side (Adner et al., 2019; Arthur, 1989, 1996; Sutton, 1991; Wessel, Levie, & Siegel, 2017). Conversely, σ ≤ 1 is consistent, among others, with a Chandlerian firm for which a downward sloping demand curve imposes decreasing returns on an increasing returns technology.

The focal firm's resources are assumed to have a greater baseline productivity in *a,* the main activity, than in the complementary activity *b*, so that $\frac{\partial V Q_{ia}(1)}{\partial r} = \varsigma(1) \geq \frac{\partial V Q_{ib}(1)}{\partial r} = \varphi(1) > 0$. As in prior work (Levinthal & Wu, 2010), the relative magnitude of the constants $\varsigma(1)$ and $\varphi(1)$ defines the fungibility of the firm's resources, that is, the degree to which one unit of the firm's resources performs worse when redeployed from the main activity to the complementary one (Anand & Singh, 1997; Montgomery & Wernerfelt, 1988). Our parameter space also contains the limit case $\varsigma(1) = \varphi(1)$, allowing for resources to perform equally well in both applications (i.e., resources can be perfectly fungible).

[9] The functions Q_{ia} and Q_{ib} are homogeneous of degree *σ*. Homogeneity is a property of a large family of production functions, including the standard Cobb-Douglas production function. Via dimensional analysis (Jong, 1967), it is possible to reduce two-input Cobb-Douglas production functions to the one-input scaling laws.

The cost of acquiring resources is given by $C(r)$. The function $C(\cdot)$ goes through the origin, is twice differentiable, monotonically increasing, and convex, and satisfies the condition $\frac{\partial C(r)}{\partial r} \leq \varsigma(r)$ for $r \leq r'$ and $\frac{\partial C(r)}{\partial r} > \varsigma(r)$ for $r > r'$, where $\varsigma(r) = \frac{\partial V_{ia}(r)}{\partial r}$. The latter condition ensures that the firm will not hoard an infinite amount of resources, because at some point the productivity of the firm's resource bundle at the margin does not justify additional investments (Viner, 1932; West, 2017). Indeed, the use of a highly scalable production technology does not mean that the firm will automatically want to make unlimited investments to grow its resource bundle, as that depends on the other resources deployed alongside these technological resources (Knudsen et al., 2014). In this regard, the co-specialized Penrosean resources create scale adjustment costs both directly through time compression diseconomies (Dierickx & Kool, 1989; Giustiziero, Kaul, & Wu, 2019; Pacheco-de-Almeida & Zemsky, 2003, 2007; Teece, 1986) and indirectly through the costs of errors such as poor replication of the firm's tacit knowledge and routines (Levinthal, 1997; Rivkin, 2001). The increasing adjustment cost of augmenting the resource bundle due to the Penrosean resources contained therein is captured by the convexity of the resource cost function, $C(r)$.[10]

Integration and Outsourcing Regimes

The allocation of the resource bundle to value-adding activities maps onto three regimes: full integration (perform both *a* and *b* in-house); partial integration (perform *a* and some *b* in-house and source additional *b* from complementors); and specialization (perform only *a* in-house and fully source *b* from complementors). Formally, given the focal firm's resource allocation τ_I such that equal quantities of both

[10] The convexity of cost function can also be ascribed to strategic factor market imperfections, which can hamper the firm's ability to procure resources externally by disproportionately increasing acquisition costs (Chatain, 2014). Our approach is consistent with the idea that applying a resource to one application reduces its availability to other applications, which increases prices in the strategic factor market. This type of pecuniary diseconomies reflect market processes and the opportunity costs of allocating scarce resources as perceived by external constituents. The opportunity cost considerations that affect the allocation of resources inside the firm—the focus of this study—relate to the firm's best use of its own resources and they cannot be reflected by prices in the strategic factor market (for a discussion, see Buchanan, 2008; Levinthal, 2017; and Madhok et al., 2010).

components are produced in-house, $Q_{ia}(\tau_I r) = Q_{ib}((1-\tau_I)\, r)$, then: (i) full integration is equivalent to choosing $\tau = \tau_I$, (ii) partial integration to $\tau = \tau_C \in (\tau_I, 1\,)$, and (iii) vertical specialization to $\tau = \tau_S = 1$.

If the focal firm outsources b, then αV, with $\alpha \in (0,1)$, is the "share of value" captured by the complementor(s) for each unit of b. The parameter α measures the per unit value foregone by the focal firm by outsourcing, and thus represents the cost of using the market. It can be thought of as representing an *ad valorem* contract (Hagiu & Wright, 2019; Wang & Wright, 2017) typical of platform intermediaries (e.g., Amazon, Uber) and licensing deals (e.g., Netflix, Spotify), but also as a parameter proportional to the price paid by a buyer to a supplier (Bennett, 2013). For now, we consider α as exogenous to the firm decision, which lets us focus on the core insights about the role of internal resources in the focal firm's choices and outcomes. We later relax this restriction and develop a more general model where the "realized α" is the result of a bargaining process between the focal firm and one or more complementors.

The complementor in the model can be thought of as a "representative agent," representing either one firm or *N* complementors whose aggregate behavior is mathematically equivalent to that of one complementor (Postrel, 2018). Hence, our model can incorporate two possible scenarios often found in winner-takes-all, increasing-returns environments: First, a bilateral monopoly with two dominant firms, as in the case of Intel and Microsoft in the personal computer industry; second, a dominant firm cooperating with a mass of complementary agents, as in the case of Uber or Airbnb hosting a large number of partners on their platforms. We later discuss explicitly how different market structures, *N,* might affect α and the focal firm's strategies.

Together with the allocation of resources, the firm also determines how much to invest in its resource bundle according to the cost function $C(r)$, thus facing a two-variable optimization problem in τ and r. Because the order of the maximization does not affect the outcome (e.g., Athey, Milgrom, & Roberts, 1998), we consider a two-stage maximization where the firm first decides how much to invest in its resource bundle and then how to apportion its resource bundle between the two activities a and b (e.g., Levinthal & Wu, 2010; Kretschmer & Puranam, 2008). Working backward, the optimal resource allocation in the second stage maximizes the objective function $\pi(\tau, r) = VQ_{ia}(\tau r) - \alpha V(Q_{ia}(\tau r) - Q_{ib}((1 - \tau)r))$, where $VQ_{ia}(\tau r)$ corresponds to the revenues from the final good and $\alpha V(Q_{ia}(\tau r) - Q_{ib}((1 - \tau)r))$ to the costs of outsourcing component b. After rearranging, the objective function can be written as:

$$\pi(\tau, r) = \underbrace{(1 - \alpha)VQ_{ia}(\tau r)}_{\text{Benefits of Specialization}} + \underbrace{\alpha VQ_{ib}((1 - \tau)r)}_{\text{Opportunity Cost of Specialization}}. \quad (1)$$

The two terms on the right-hand side of equation (1) highlight the tradeoff faced by the firm when allocating its resources. When $\tau = 1$, the firm specializes in a and generates revenues equivalent to the first term, which corresponds to the benefits of specialization. However, if $\tau = 1$ then $(1 - \tau) = 0$, and the firm foregoes the share of value equal to the second term, which is the opportunity cost of specialization. If the benefits of specialization always outweigh the opportunity cost of not capturing all the value, the firm will allocate all of its resources to a. If not, the firm will opt to capture more (partial integration) or all (full integration) of the value created by allocating some of its resources to the complementary activity b.

Solution Space

Figure 2 describes the solution space of our model, delineating the relationship among the scalability of the resource bundle, the value distribution, and sourcing regimes. (An analytical solution to the firm's maximization problem is provided in the Appendix). Darker colors correspond to lower values of τ, and consequently to more integration. The black solid line traces the value of α beyond which collaborating with the complementor is too costly, triggering full integration. We label the maximum value share the focal firm will forego before integrating as "critical α" or α*. The critical α is a function of the value of the firm's outside option, integration, relative to outsourcing. As such, the critical α can asymptotically get close to 1, but cannot reach or exceed 1; otherwise, the focal firm would incur a loss or make no profits, an outcome inferior to what it would attain under integration. As Figure 2 demonstrates, when α is below the critical threshold, the firm benefits from outsourcing, but in different ways for Chandlerian and post-Chandlerian firms. This contrast is summarized in the following proposition.

> ***Proposition 1 (Discontinuous integration)**: For Chandlerian firms, an incremental change in the cost of outsourcing triggers a gradual change in integration; that is, integration choices are evaluated at the intensive margin. In contrast, for post-Chandlerian firms, an incremental change in the cost of outsourcing can trigger a discontinuous change between full integration and full specialization; that is, integration choices are evaluated at the extensive margin.* (Proof in Appendix.)

[Insert Figure 2 approximately here]

Proposition 1 demonstrates that the optimal strategy follows different logics depending on whether the firm's resource bundle is sublinearly scalable ($\sigma < 1$) or superlinearly scalable ($\sigma \geq 1$). With sublinear scaling (Chandlerian firms), productivity in the firm's main activity eventually plateaus and the firm can improve resource utilization by redeploying some resources from the main activity to the complementary. So, profits increase along the intensive margin via a partial integration strategy that equates the (marginal) performance of the firm's resources in a to that in b. Partial integration generates the distinctive "fan-shaped" region on the left side of Figure 2, which is the result of tradeoffs between two underlying mechanisms: scalability facilitates the use of the firm's resource bundle in multiple applications, which leads to more integration, but it also makes some specialization attractive because performance in the main application deteriorates more slowly.

As in prior RBV research (Parmigiani, 2007; Parmigiani & Mitchell, 2009), partial integration in our model requires resources to be fungible. However, even perfect fungibility is insufficient; the resource bundle also needs to be sublinearly scalable. Thus, we expect partial integration to be more frequent in Chandlerian settings, a result consistent with both within-industry studies (Parmigiani, 2007; Parmigiani & Mitchell, 2009) and cross-industry ones (Atalay, Hortaçsu, and Syverson, 2014). In contrast to the equilibration logic that drives partial integration for sublinearly scalable resources, the resource allocation of scalable resource bundles ($\sigma \geq 1$, as in the right panel of Figure 1) leads to "bang-bang" outcomes that rule out intermediate concurrent sourcing. Because the performance of scalable resources never plateaus, the firm cannot maximize along the intensive margin. It must examine alternatives at the extensive margin, comparing the overall profits of the two corner solutions: (full) integration and (full) specialization. If the value captured by the complementor is not high enough to negate the benefits of growth in the main activity, the firm specializes by going "all-in" in pursuit of superlinear returns in the main activity.

Interestingly, Proposition 1 is consistent with the Silicon Valley mantra for early-stage ventures: "to scale, do things that don't scale" (Hoffman & Yeh, 2018). Consider the case of Airbnb. When Airbnb was a tiny startup, much before it became a digitally scaled firm, its founders realized that the chances of renting a room on Airbnb depended greatly on the quality of photographs. Because Airbnb was operating with a rudimentary website and had not yet invested much in scalable digital technology, the founders did this activity in-house for a significant portion of their hosts (those in New York). Brian Chesky (2017), CEO and co-founder of Airbnb, recounts: "We literally would knock on the doors of all of our hosts [in New York]. We had their addresses and [...] we'd show up at their door and they're like 'Wow. This company is pretty small.'" However, once the company reached a critical mass and invested heavily in its digital platform, the company's strategy progressively shifted to the founders managing a short list of freelance photographers, to an employee managing many freelance photographers, to an automated system for a global network of freelance photographers (Hoffman & Yeh, 2018), all driven by Airbnb's increasing opportunity costs of allocating resources to the complementary activity of photography. As this example indicates, even highly scalable digital firms often begin with less scalable non-digital resources, and this transition over time provides a nice illustration of how integration choices change as the firm moves from the sublinear scaling region (left side) of Figure 2 to the superlinear scaling region (right side).

Resource Attributes and Hyperspecialization

Our second result outlines the relationship between the scalability of resources and the "critical α." In so doing, it provides a rationale for referring to outsourcing in post-Chandlerian firms as *hyperspecialization*, which we define to mean the firm's propensity to specialize and not integrate even when the cost of "using the market" (captured here by the value shared with the complementor) is quite high. Thus, hyperspecialization is very different from ordinary specialization when resources are sublinearly scalable, which can be sustained only when the cost of using the market (or the value shared with the complementor) is low.

> ***Proposition 2 (Scalability and hyperspecialization):*** *Denote as "critical α" the maximum value share the focal firm is willing to forego by outsourcing (and not fully integrating). Then, the critical α is increasing in scalability for post-Chandlerian firms and decreasing in scalability for Chandlerian firms.* (Proof in Appendix.)

Proposition 2 demonstrates how the effect of scalability differs in Chandlerian ($\sigma < 1$) and post-Chandlerian ($\sigma \geq 1$) firms. Consistent with Chandler's ideas, scalability improves the attractiveness of full integration relative to outsourcing when $\sigma < 1$, causing the critical α line on the left side of Figure 2 to slope downward. This happens because higher scalability creates "excess capacity" and facilitates the leveraging of the firm's resources in multiple applications: the more scalable the firm's resource bundle is, the easier it is for the focal firm to scale operations into both activities. In post-Chandlerian firms, however, scalability has the opposite effect. In this region, even if resources are perfectly fungible, the firm can achieve greater productivity by focusing on just one activity because the firm avoids fracturing its resource bundle, and sustains growth along the superlinear trajectory. Furthermore, because the firm can offset the revenues foregone when splitting the pie by significantly increasing output volume, the more scalable the firm's resource bundle, the lower the minimum share of value the firm is willing to accept in order to specialize rather than integrate. In Figure 2, this is reflected in the upward sloping line for critical α for post-Chandlerian firms ($\sigma \geq 1$). This result is akin to Airbnb collecting small (3%) commissions for a larger number of transactions on its scalable online platform, whereas traditional hotel chains like Hilton and Marriott receive 8-12% of sales from third parties who, like Airbnb hosts, own the property and manage operations (McNew, 2016).

Next we examine the fungibility of the firm's resource bundle and its relationship with integration choices. Fungibility has been the resource attribute that prior RBV literature primarily focused on when examining corporate scope (Levinthal & Wu, 2010; Montgomery & Wernerfelt, 1988). To more completely understand its role, we examine how fungibility works in Chandlerian (sublinearly scalable) and post-Chandlerian (superlinearly scalable) contexts, and especially how it compares with scalability.

Proposition 3 (Fungibility and hyperspecialization): *For both Chandlerian and post-Chandlerian firms, the critical α is decreasing in the fungibility of the firm's resource bundle.* (Proof in Appendix.)

[Insert Figure 3 approximately here]

Proposition 3 demonstrates that, unlike with scalability, the critical α always decreases with fungibility, whether resources are sublinearly scalable or superlinearly scalable (see Figure 3). This is because fungibility boosts the productivity of the firm's resources in the complementary activity, thus favoring the sourcing regime that uses resources in both applications, namely, integration. Proposition 1 and Proposition 2 together reveal an interesting contrast between Chandlerian (sublinearly scalable) and post-Chandlerian (superlinearly scalable) environments. In traditional Chandlerian firms, the two resource attributes commonly associated with the "value" of a resource, scalability and fungibility (Schmidt & Keil, 2013), have the same implications for the firm: Both facilitate leveraging the firm's resources in multiple applications, allowing the firm to take its competitive advantage from one stage to create value in others. In post-Chandlerian firms, however, scalability and fungibility have *opposite* implications. While higher fungibility improves the relative attractiveness of the outside option, integration, higher scalability favors specialization even when the cost of using the market is substantial.

The evolution of the vertical scope of Netflix can help illustrate our theory. Netflix started in 1997 with a DVD rental-by-mail business model, and from the outset it relentlessly invested in digitization and software-driven automation. The company's datasets, back-end software, and recommendation algorithms were key highly-scalable digital resources that likely put the company in the superlinear region of our model

($\sigma \geq 1$).[11] Consistent with our model, Netflix remained focused on taking advantage of the scaling-up opportunities in its DVD rentals platform, and not integrating into upstream content production. Indeed, "Singular focus" were the first two words of the company's second-ever annual report, in 2003. In the late-2000s, as it switched to online streaming, Netflix faced a significant increase in its content costs. In its DVD rental business, Netflix bought DVDs and — under the first sale doctrine of copyright law — simply rented them out without further payments to the movie studios. In its streaming business model, without the first sale doctrine to rely on, Netflix needed to take licenses for content from the studios, who began demanding higher prices, thus increasing the value share (α) that Netflix was forced to forego. Netflix's content costs reportedly went from $229 million in 2010 to more than $1 billion in 2011 (Kafka, 2010, 2011a). In response, Netflix vertically integrated into commissioning and owning original content. Ted Sarandos, Netflix chief content officer, explained (Kafka, 2011b): "[W]ould [I] prefer to license previous seasons of HBO, Showtime, Starz shows? Sure. And if those shows are not going to be made widely available in decent [price] windows, then my other alternative would be to compete with those guys for those shows." Netflix's fungible digital resources, which provided insights into customer preferences, facilitated its vertical integration by providing the company with an information advantage in the factor markets for content (Barney, 1986; Makadok, 2001). When acquiring the rights to *House of Cards*, Netflix outbid networks including HBO, Showtime, and AMC, and even made a two-season commitment (instead of the typical commitment to a pilot), due to customer insights from its proprietary data and algorithms. Thus, Netflix's vertical integration decisions into content can be explained by the scalability and fungibility of its resource bundle, and by changes in the value share it had to forego to content owners.

[11] Included in these scaling advantages were the low marginal costs of providing a wide DVD assortment in an internet retailing model, relative to a bricks and mortar movie rental company like Blockbuster. Netflix's software, including its algorithms and customer DVD queue feature, also enabled efficient management of its inventory and distribution, which further improved with scale. On the demand side, the scalability of Netflix resources was further enhanced by highly elastic demand due to the rapid adoption of DVD players among U.S. households.

Hyperscaling and hyperspecialization

When the resource bundle exhibits superlinear scaling ($\sigma \geq 1$), the additional application of resources to a given activity can increase output exponentially and incentivize firms to grow large, an outcome we refer to as *hyperscaling*. Here, we examine how such hyperscaling is in turn influenced by hyperspecialization. To do so, we move back to the first stage of the model, turning our attention to the firm's optimal investment in its resource bundle, which depends on the sourcing regime chosen. Formally, the firm's optimal resource investment satisfies the first order condition $\frac{\partial \pi(\tau_j, r)}{\partial r} = \frac{\partial C(r)}{\partial r}$ for $j \in \{S, C, I\}$, which is reached when the cost of additional investment equals the (marginal) productivity of the firm's resource bundle. Similar to Chandler's (1990) focus on assets as a measure of firm size, we focus on the size of the firm's resource bundle (which in turn also directly translates to the size of revenues and profits in our model) as the representative measure of the firm's size.[12] As demonstrated by the following proposition, firm size is only partly explained by returns to scale; it is also significantly explained by hyperspecialization.

> ***Proposition 4 (Hyperscaling and hyperspecialization):*** *Specialized post-Chandlerian firms are larger than integrated post-Chandlerian firms as well as fully or partly integrated Chandlerian firms; however, the relative scale difference between specialized and integrated post-Chandlerian firms decreases with the fungibility of the integrated firms' resource bundle.* (Proof in Appendix.)

This proposition highlights that, unlike industrial firms in which — to borrow from Chandler's famous book title — scale and scope went hand in hand, modern post-Chandlerian firms have a propensity toward greater scale that is instead supported by their *specialization*. Our comparison in Proposition 4 pits specialized firms against both integrated firms with the same scalable resource bundles and fully or partly integrated firms with sublinearly scalable resource bundles. If two firms utilize the same scalable resources (with the same scalability and fungibility), but one is specialized and the other is not, the specialized firm

[12] Because the extent of labor employed in production can be lower when digital resources are used, our results cannot be extended to make predictions about employment.

is larger. If two firms utilize resource bundles with different degrees of scalability, the firm whose resource bundle is more scalable will be larger, ceteris paribus. These reflections suggest that post-Chandlerian firms not only have a propensity for hyperscaling, but also that hyperspecialization and hyperscaling are mutually reinforcing. Further, Proposition 4 compares two integrated firms with resource bundles that have different levels of fungibility with a specialized one, positing that the integrated firm with a more fungible resource bundle has a smaller relative size penalty from integration. This follows from the fact that the firm with more fungible resources is more efficient *on average* in its secondary activities, which justifies investment in greater scale (more resources). Thus, our model predicts that the size penalty associated with integration may be smaller for firms like Netflix, whose vertical integration is facilitated by fungible resources. That said, the scaling penalty due to integration never converges to zero.

The above arguments reveal an important strategic trade-off inherent in the allocation of scalable resources: to grow more in size, post-Chandlerian firms need to shrink their range of activities. The combination of economies of specialization and superlinear scaling boosts the overall productivity of resources, driving greater profits and attracting more capital for large-scale investments. When resources are sublinearly scalable, however, we revert to the organizational landscape of traditional Chandlerian industries, with integrated firms growing larger than their specialized counterparts. Figure 4 illustrates this result. It shows the relationship between returns and scale at the two ends of the sourcing continuum. When resources are sublinearly scalable, the solid line corresponding to integration dominates the dashed one corresponding to specialization. This changes when resources are scalable, with the difference between the two lines corresponding to a *specialization effect* — that is, extra scaling due to the complementarity between scalability and specialization.[13]

[13]As an interesting subtlety, an increase in the scalability exponent increases scale (as shown in Figure 4) only if the optimal *r* exceeds a certain threshold. This cut-off value for *r* identifies a point whose surpassing can lead to sustained growth and can be interpreted as a tipping point, a critical mass or minimum resource base that must be attained in order to trigger hyperscaling. This is often the case with digital goods, which typically require a substantial upfront investment, but then scale at almost no cost. As noted by Arthur (1996: 103) “the first disc of Windows to go out the door costs Microsoft $50 million; the second and subsequent disks costs $3.”

[Insert Figure 4 approximately here]

Proposition 4 is consistent with the observation that the largest companies by market capitalization in the 1950s and '60s, such as GM, AT&T, DuPont, and Standard Oil, are all classic examples of vertically integrated corporations, some of which featured in Chandler's historical accounts. By contrast, many of the largest companies by market capitalization today made their fortunes as super-intermediaries, whose business models consist in mediating the thin layer that separates specialized complementors in the ecosystem they created. These firms often surpass their Chandlerian counterparts in terms of output volumes, market capitalization, and asset values, despite being more specialized.

Proposition 4 is also consistent with changes over time in the semiconductor industry. The impact of Moore's Law on the semiconductor industry—exponentially increasing miniaturization and reducing costs per unit—is well known. However, the industry has also been shaped by "Moore's Second Law", which asserts that the cost of an integrated circuit (IC) fabrication plant (fab) will double every four years (Moore, 1995), which has rapidly increased the minimum efficient scale of IC fabs. Over time, these changes have sharply increased the degree of scaling in IC fabrication, and in turn led to more consolidation among firms (scale) and the emergence of dedicated fabs (specialization) as the dominant type of IC firm.[14] This example illustrates the applicability of our theory (in some cases) to industries beyond digital businesses, so long as scalable resources (and conducive demand conditions) are present.

Endogenizing the Firm's Value Share

Our main model sets the fraction of value shared by the focal firm with complementors (α) to be exogenous. We thus focus attention on the attributes of internal resources, in line with the theme of the current special issue. We now endogenize α by incorporating the role of the complementor market. This extension not only ensures the robustness of our main model, but also enriches our analysis by offering additional insights.

[14] Prior research has primarily emphasized the role of transaction costs and their decline through modularization in explaining the vertical disintegration of the industry (Linden & Somaya, 2003; Macher & Mowery, 2005); however, declining transaction costs alone would not explain the increasing consolidation among IC fabrication firms.

Following prior literature, we model two key aspects of the complementor market: the number of complementors (Brandenburger & Nalebuff, 1996; Porter, 1980) and the productivity of the complementors (Barney, 1999; Jacobides & Winter, 2005). While stylized, this model setup allows us to capture the essence of complementor market structure, as in prior work (Argyres, 1996; Barney, 1999; Jacobides & Winter, 2005; Kaul, 2013). Specifically, we consider the complementor market as consisting of *N* identical firms. Each complementor generates outputs $Q_{ja}(\tau_j r_j)$ and $Q_{jb}((1-\tau_j)r_j)$, where Q_{ja} and Q_{jb} are scaling laws with scaling exponent $\sigma_j > 0$. Complementor productivity is measured analogously to firm *i*'s, with complementors assumed to have a greater baseline productivity in *b,* the complementary activity such that $\frac{\partial VQ_{jb}(1)}{\partial r_j} = \varphi_j(1) \geq \frac{\partial VQ_{ja}(1)}{\partial r_j} = \varsigma_j(1) > 0$.[15]

Our model extension shows that the value share captured by complementors increases when the number of complementors shrinks. The intuition behind this is simple: When competition among complementors decreases, their relative bargaining power with respect to the focal firm increases, resulting in the remaining complementors receiving a larger share of the value pie (formally, $\frac{\partial \alpha}{\partial(-N)} > 0$). This confirms a key finding of the IO-based strategy literature (e.g., Brandenburger & Nalebuff, 1996; Porter, 1980), which suggests that outsourcing tends to be more favorable in more competitive complementor markets (Hecker and Kretschmer, 2010). This baseline result serves as a "reality check" for our model.

Perhaps more counterintuitive is the result that the value share captured by complementors increases when their productivity decreases (formally, $\frac{\partial \alpha}{\partial(-\varphi_j(1))} > 0$). Metaphorically speaking, this result indicates that the focal firm is willing to "reward" the complementors in a manner proportional to their

[15]The costs of acquiring resources for the complementors is given by *C(r)*, defined analogously to firm *i*'s cost function. For added realism, we also parametrize transaction costs, denoted by and measured as the value lost in coordinating market exchanges (e.g., Coase, 1937; Williamson, 1975) such that whenever the component *b* is outsourced to the complementors, the complementors only receive $\theta\alpha$, with $\theta \in (0,1)$. Although we assume that the transaction costs are directly borne by the complementor (and indirectly borne by the focal firm *i*, since, as we demonstrate in the Appendix, α, is increasing in $-\theta$), the results would be qualitatively similar had transaction costs been borne by the focal firm or spread equally between the two sides of the market.

"incompetence." It is worth pausing briefly to explain why this result is not trivial. In the model, a complementor's outside option is determined by the profits the complementor can achieve doing its own integration. These profits are increasing in complementor productivity. Therefore, one would expect a positive relationship between complementors' productivity (which augments their outside option) and the value share they capture. The fact that the opposite holds true reveals a subtle theoretical relation between α and the incentives to scale, a point we now elaborate further.

In a system of complementary activities, one side benefits from the scale of the other side, and vice versa. For this reason, the focal firm is willing to concede a larger share to less-productive complementors to enhance the returns on their resources. The higher returns compensate for the complementors' inferior productivity and augment the complementors' incentives to invest in capacity (resources). There is, however, a fundamental difference that distinguishes Chandlerian and post-Chandlerian firms. In Chandlerian firms, any increase in α due to a decrease in complementor productivity also induces the focal firm to expand its vertical scope incrementally through partial integration (as illustrated on the left-hand side of Figure 2). Because this effect is stronger the more fungible and productive the firm's resources, a decrease in complementor productivity ultimately generates a dynamic akin to the canonical results of the RBV literature, which posits that firms will expand their vertical scope if their resources are fungible and more productive than those of the complementors. For post-Chandlerian firms, however, the classic RBV result does not hold. For this type of firm, resource superiority may not lead to more integration because an increase in α has no impact on scope unless α reaches the proximity of the critical α line (as illustrated on the right-hand side of Figure 2). Rather, specialization can be optimal even when the cost of outsourcing is substantial and this leads the focal firm to forego increasing shares of the value created as a way to incentivize more inferior complementors to increase the supply of complementary products and services.[16] These tradeoffs for post-Chandlerian firms are illustrated in Figure 5.

[16] This happens despite the absence of administrative and bureaucratic costs, which would tilt the firm calculus towards outsourcing (e.g., Coase, 1937; Williamson, 1975). Indeed, the existence of increasing returns at the technological level is equivalent to assuming that administrative and bureaucratic costs are not substantial (Coase, 1937).

[Insert Figure 5 approximately here]

Figure 5 reveals how the complementor's value share changes with its relative productivity (on the horizontal axis). While a decrease in complementor productivity initially leads to a continuous increase in its value share, once the realized α reaches the critical α, outsourcing becomes too costly compared to internal production (it would require $\alpha > \alpha^*$), and the focal firm switches to integration.[17] The share given to the complementor drops to zero as the regime changes. The switch in regimes delineates the non-linear effect of complementor productivity on the realized α, which is the result of two conceptual drivers. One driver is the continuous change of value split within the outsourcing regime; the other is the discontinuous transition to integration in which low levels of complementor productivity can force the focal firm to cut out complementors and switch regimes. We summarize the above insights with the following proposition.

Proposition 5 (Realized α): *In post-Chandlerian firms, the value share captured by complementors, α, increases when complementor productivity decreases up to the critical threshold. If the complementor's productivity declines further, post-Chandlerian firms will integrate and make the input in-house.*

One interesting implication of Proposition 5 emerges from looking at different parts of the "scalable" region in Figure 2. For post-Chandlerian firms, integration is more likely to be triggered when margins are thinner (the value share foregone is larger) because a sudden switch to integration occurs only in the proximity of the critical α, which is in turn increasing in scalability. This implication can be illustrated with Amazon's different strategies between its two key businesses, e-commerce (retail) and cloud (AWS). Amazon's margins are thinner in e-commerce, consistent with its retailing complementors being arguably less competent. Consistent with our theory, Amazon has demonstrated an appetite for internalizing adjacent activities in e-commerce, such as logistics (trucking and air freight investments to disintermediate UPS and

[17] For completeness, we note that integration also occurs when the endogenous α falls below the complementors' critical α, that is, the minimum share of the value pie the complementors are willing to accept in order to collaborate with the focal firm.

FedEx) and product development (reportedly shutting down third-party sellers to introduce its own private labels) (Schreiber, 2016; Zhu & Liu, 2018). By comparison, Amazon has consistently refrained from integrating into complementors' businesses in cloud computing (Hoffman & Yeh, 2018). The relationship between AWS and Twilio, a business-to-business cloud communication platform hosting its services on AWS, is an illustrative example. As one commentator observed around the time of Twilio's IPO in 2016 (Seward, 2016): "Twilio customers, in other words, are outsourcing messaging to Twilio, which in turn outsources to Amazon. […] You could argue this is a precarious position to be in because Amazon could always decide to make messaging a feature of AWS." Consistent with our theory, however, "the two companies are better described as partners rather than competitors" (Sun, 2017).

FUTURE RESEARCH

As with any formal theory, our model makes a number of assumptions in order to highlight the main theoretical mechanisms and derive key insights. We acknowledge the limitations associated with these assumptions and discuss their implications, below. Relaxing these boundary conditions to our theory may represent significant opportunities for future research.

Demand Considerations

To focus our paper on insights for the RBV, we assume a perfectly elastic demand environment, which allows the firm to sell unlimited quantities for a fixed price in the final product market. However, decreasing returns on the demand side, arising from a downward sloping demand curve, can diminish the scaling effects of firms' resource bundles discussed above. Demand-side considerations matter because a firm's impetus to specialize and grow in scale derives ultimately from the "inducements" provided by rents created from a combination of supply and demand (Helfat & Eisenhardt, 2004; Madhok et al., 2010; Makadok, 1999; Penrose, 1959; Sakhartov & Folta, 2015; Sakhartov, 2017). However, our model can be extended to incorporate a rich set of demand conditions from the Dixit-Stiglitz system of monopolistic competition (Alfaro et al., 2019; Dixit & Stiglitz, 1977; Helpman, 1985), in which the demand side can be modeled by using a scaling parameter ρ. In this approach, a downward sloping demand corresponds to $\rho > 1$, perfectly elastic demand to $\rho = 1$, and increasing returns on the demand side to $\rho < 1$. These demand side scaling parameters can be easily incorporated in our model to yield a profit equation similar to (1), wherein production quantities follow scaling laws of degree σ/ρ rather than σ.[18] All of the results described above can be generalized to a range of demand conditions by simply substituting σ/ρ as the scaling parameter. Thus hyperspecialization and hyperscaling will occur only if $\sigma/\rho > 1$.[19]

Put differently, a complete theory of scalability at the firm level requires that the combination of supply side (resource-driven) and demand side characteristics exhibit increasing returns. However, digital firms often distribute their offerings through the internet and cloud platforms (Siebel, 2019), and thus may have access to a very large global market with highly elastic demand ($\rho \to 1$). For these firms, resource-driven scalability will play a primary role in driving our theoretical propositions. Moreover, in digital firms that are organized as platforms or intermediaries, increasing returns (scalability) on the demand side can occur through positive feedback from network effects (Cabral, Salant, & Woroch, 1999; Cennamo & Santaló, 2019; Grajek & Kretschmer, 2012; Parker et al., 2016), capturing the sentiment that "[i]n the world of technology, the more of something you make, the more valuable it can become" (Wessel et al., 2017). For these firms, resource-driven and demand-driven scaling effects can be mutually reinforcing in our

[18] In the Dixit-Stiglitz system, the (inverse) demand function corresponds to the scaling law $V = AQ_{ia}{}^{(1-\rho)/\rho}$, where V is the value for the final consumer and $A > 0$ is a given term for the firm. Assuming the focal firm captures the full surplus from customers (as in the main model), the resource allocation problem described in equation (1) generalizes to the maximization of $\pi(\tau, r) = (1-\alpha)\, A\rho\, Q_{ia}(\tau r)^{1/\rho} + \alpha A\rho\, Q_{ib}((1-\tau)r)^{1/\rho}$, wherein $Q_{ia}(\tau r)^{1/\rho}$and $Q_{ib}((1-\tau)r)^{1/\rho}$ follow scaling laws of degree σ/ρ.

[19] The model extension leading to Proposition 5 is robust to the Dixit-Stiglitz demand system of monopolistic competition, in which for every product produced in-house, each complementor faces an (inverse) demand curve corresponding to the scaling law $V_j = A_j Q_{jb}{}^{(1-\rho_j)/\rho_j}$, with $A_j, \rho_j > 0$. If A_j is treated as exogenous, the Dixit-Stiglitz demand system will lead to results that are qualitatively similar to Proposition 5. Alternatively, if A_j is endogenized as a decreasing function of the number of firms producing differentiated goods, as in in some iterations of the Dixit-Stiglitz model (e.g., Yang & Heijdra, 1993, d'Aspremont et al., 1995), both the complementors and the focal firm would be more inclined to cooperate because the monopolistic competition outcome would reduce the baseline level of demand for their products.

proposed theory.[20] Nonetheless, in contexts where digital firms face conventional downward sloping demand, demand side diminishing returns generate a boundary condition for our scalability-driven propositions.

Transaction Costs

Another set of boundary conditions arise from various transaction cost considerations, which have long been a centerpiece of vertical integration theory (Coase, 1937; Williamson, 1975; 1999). Since this paper focuses on the role of internal resources, transaction cost is considered an exogenous shift parameter that is largely outside our theory. We model such a parameter in Proposition 4 and find that in the presence of scalable resources transaction costs play a very similar role to capability differences, another cost of "using the market" (Mahoney & Qian, 2013). Thus, our theory does depend on transaction costs not being too high in the intermediate product market, in which case of course no specialization will occur. Transaction costs are also implicated in other boundary conditions of our theory. Consistent with the RBV theory of the firm (Argyres & Zenger, 2012; Barney, 1999; Madhok, 2002; Teece, 1982) we assume that transaction costs in the market for resources and their services, and in the market for corporate control, are sufficiently high as to preempt transactions in them. Thus, the firm cannot simply sell the services of its resources and must instead produce intermediate and/or final products (Penrose, 1959), and it cannot simply buy up complementor firms or their resources. When these boundary conditions are not present, future work may identify and examine novel extensions of our theory, such as scalable resource acquisition as a motivation for acquisitions or the emergence of novel markets that trade in the services of highly scalable resources.

[20] Despite the availability of network effects for some Chandlerian firms, operational scalability (or the lack thereof) may perhaps explain why they were largely vertically integrated. AT&T, which pioneered telephone services in the United States, is an illustrative example. Although telephone use is associated with network effects, its adoption took several decades (Fischer & Carroll, 1988), due to the substantial costs of expanding landline networks and the labor-intensive nature of the service (which initially relied on hundreds of thousands of trained telephone operators) (Lipartito, 1994). Thus, while AT&T enjoyed some scalability on the demand side, its resources were evidently less scalable, and as a whole the company operated like a Chandlerian firm, as our theory would predict. In contrast, today's digital firms enjoy access to ready-made networks (like the internet) on the demand side and tend to employ more scalable resource bundles (with a smaller complement of co-specialized human capital).

Importantly, our theory highlights the point that transaction cost reduction might not be necessary for the emergence of platforms and the dissolution of value chains into ecosystems. Instead scalable resources (combined with demand-side scaling effects) can drive digital (and especially platform) firms towards greater specialization even in the presence of significant transaction costs and coordination needs with complementors. It is therefore possible that, at least in some sectors of the economy, ecosystems have arisen not because of lower transaction costs but to manage higher transaction and coordination costs (Baldwin & Clark, 2008; Dosi et al., 2008). Thus the coordination that firms undertake within ecosystems may be seen, and studied in future work, as solutions to manage the unresolved transaction costs between hyperspecialized complementary digital firms. These ideas are consistent with the observation that ecosystems entail more significant interdependence and organizational interactions between complementors than traditional arm's length relationships (Ganco et al., 2019; Postrel, 2009).

DISCUSSION

The aim of this paper was to describe some of the key forces that shape the allocation of resources, vertical integration, and scale of digital firms. To do so, we combined insights from recent developments in the RBV with insights and examples from the world of technology, and derived a stylized representation of the resource-driven production characteristics and integration choices of digital firms. Drawing on the idea that digital technologies lead to firms having highly scalable resource bundles, our theory posits that scalability enhances the opportunity cost of expanding into related activities, and thus leads to vertical specialization. Our formalization of these intuitions led to a set of additional results; namely, that the scalability of resource bundles will induce specialized firms to focus on volumes rather than value capture, to out-scale integrated firms, and to switch discontinuously from specialization to integration, whereas the fungibility of resource bundles will mitigate some of these effects of scalability. These findings are consistent with a number of examples and trends that we discuss, suggesting that our overall framework may capture a broad set of empirical regularities in the digital economy. In the discussion below, we highlight a number of potential contributions of the theory developed in this paper.

Theories of the Post-Chandlerian Firm

Ever since Chandler's (1977, 1990) rich descriptions of how the pursuit of scale and scope was integral to the success of large corporations that were emblematic of the second industrial revolution, research has sought to understand how and why more modern firms might be organized in different ways than these Chandlerian firms. Prior conceptions of post-Chandlerian economic organization have suggested a decline in the size and vertical integration of firms—thus a decrease in both scale and scope—driven by a reduction in transaction costs—due to greater modularity and more relational contracting—in the high technology industries of the 1990s and early 2000s (Lamoreaux, Raff, & Temin, 2004; Langlois, 2003; 2004). Similarly, scholars researching the early internet actively debated the so-called "disintermediation hypothesis" (e.g., Benjamin & Wigand, 1995; Parker et al., 2016; Sarkar, Butler, & Steinfield, 1995), which argued that the internet would reduce transaction costs to sell directly to customers and thus diminish or end the role of traditional intermediaries (Hackett, 1992; Lobel, 2018; Spulber, 1996; Yavas, 1994). Those against the hypothesis conjectured that technology would lower the costs of market coordination and thus lead to vertical "dis-integration" and smaller firms (Brynjolfsson et al., 1994). It is notable that all of these ideas about how new digital technologies would impact economic organization are rooted in transaction cost logic, which has historically had a significant impact on theorizing about vertical integration (Williamson, 1975; 1999).

By contrast, our paper points to the RBV, and especially the constructs of *scalability* and *fungibility* in resources (Levinthal & Wu, 2010; Schimdt & Keil, 2013), as a promising lens through which examine the impact of digital technologies on economic organization. Through this lens, we posit a novel theory about how digital technology-enabled highly-scalable resources are likely to lead to firms that are *both* highly specialized (hyperspecialization) and very large (hyperscaling). Thus, in contrast to prior conceptions of the post-Chandlerian firm, which generally predict reductions in both firm scale and firm scope, we propose a theory of the digital firm that is high in scale but lower in scope (more specialized). This theory appears to be consistent with descriptions of significant scaling in digital firms (Adner et al., 2019; Hoffman & Yeh, 2018), and the emergence of super-intermediaries on the internet (Parker et al., 2016). Moreover, as noted above, our theory builds explicitly on the RBV and relies on resource attributes, rather than transaction costs, as drivers of scale and scope.

Much of our understanding about economic organization and vertical integration is influenced by scholars such as Coase (1937), Chandler (1977, 1990) and Williamson (1975, 1999), whose work was rooted in the study of industrial firms. Digital firms break from the diminishing returns assumptions that industrial firms' resources and/or demand conditions were traditionally subject to, giving our research the potential to break new ground on post-Chandlerian forms of organization. Despite this appeal, however, the theory we propose may represent an incomplete picture of modern digital firms, leaving room for a number of extensions in future research. For example, digital technologies also appear to have a variety of impacts on both transaction costs in markets and bureaucratic costs within firms, which may combine with resource characteristics in shaping the organizational form of these firms. Following the robust tradition of theoretical integration between governance and resource-based perspectives (Argyres & Zenger, 2012; Kang et al., 2009; Mayer et al., 2012; Wan & Wu, 2017), future research can more comprehensively examine the interaction between resource scalability and transaction costs to develop a richer understanding of post-Chandlerian digital firms.

Modeling Platform for Future Research

Although we also articulate our theory verbally, we seek to contribute to the literature through the modeling framework we develop, which we hope will be a platform for cumulative research on resource attributes and their effects on firm-level outcomes. Our model is parsimonious, but builds on critical prior research on resource attributes, such as scalability, fungibility, and resource adjustment costs (Knudsen et al., 2014; Levinthal & Wu, 2010; Schimdt & Keil, 2013). In turn, using such a model to advance theory has the advantage of laying bare the underlying assumptions and theoretical mechanisms that lead to the theory's predictions, which can in turn be empirically tested and revised if they are not supported. In turn, our model has yielded a number of nuanced results, whose logics we have explained throughout the paper, even though they were not evident ex ante. In particular, we refer here to the contrast between Chandlerian and post-Chandlerian firms in the types of integration, the marginal effects of scaling, and the mutual reinforcement between hyperspecialization and hyperscaling, which we describe in Propositions 1, 2 and 4. In addition, Proposition 5's prediction that less capable complementors would capture a greater share of value from the focal firm was another result that was largely unanticipated.

Despite these provocative results, our modeling framework has the potential to explore a number of other questions, which provide a rich set of opportunities for future research. For example, firms may be able to exercise some choice in the degree of scalability and fungibility of their resources, and endogenizing this choice and their interdependence (for example, more fungible resources may be less scalable within any particular use) may yield interesting insights into the complex strategies available to digital firms. Our model focuses on the general case where both complementary activities employ similarly scalable resources, and that the demand conditions in the product market are supportive (in the post-Chandlerian case, diminishing returns are assumed to be either non-existent or at a minimum too small to counteract resource-driven scaling). However, that leaves open a number of combinations of resource and demand conditions that can be modeled in future work, such as a combination of highly scalable and less scalable resources in the complementary activities (potentially using different resource bundles), and increasing or decreasing returns demand environments. These models could generate a complex set of integration outcomes that can further enrich the theory we have developed.

Our modeling framework can also be fruitfully extended to examine the dynamics of scaling. First, both resource and demand attributes may change over the firm or industry life cycle (e.g., Klepper, 1996; Agarwal & Gort, 1996), as we have seen in the examples of firms like Netflix and AirBnb. In particular early-stage firms may begin with less scalable resources, and only gradually invest in more scalable digital resources after first exploring and learning more about their markets and business models. At the other end of the life-cycle, even highly scalable businesses are likely to eventually saturate their market, and at this stage demand-side diminishing returns are likely to reduce their scaling advantages and impetus to specialize. Our model may also be extended to situations where firms anticipate the opportunities to scale and make resource investments accordingly. In their book *Blitzscaling* (2018), Silicon Valley VC investor Reid Hoffman and his coauthor, Chris Yeh, posit two "growth limiters" that firms must anticipate in order to scale rapidly: the lack of product/market fit and the lack of operational scalability. The authors explain (2018: 75-76) that "both can still kill your company" and that "the wisest innovators design operational scalability into their models." Seen in this light, the stylized pattern of product innovation followed by process innovation highlighted in the literature on technology management (Utterback & Abernathy, 1975; Clark, 1985; Klepper; 1996) may need to be revised for digital firms. Future extensions of our model can examine if and when early-stage process and operational improvements are essential for digital firms to achieve a "first-scaler advantage," which accrues not to the first firm that enters a market but the first firm that serves that market at scale (Hoffman & Yeh, 2018; Lee, 2019; Levie & London, 2018).

Finally, although this paper has examined competition between the focal firm and its (potential) complementor, a number of other competitive scenarios may be explored in future work. For example, the final product may face explicit competition from other firms, who may also compete to attract away the complementor(s) and thus deny the scaling advantages the focal firm may access through specialization. In their book *Blitzscaling* (2018), Hoffman & Yeh (2018) suggest that competitive pressures only heighten the pressures to scale rapidly, and to hyperspecialize in support of scaling; considering such competition (including the case of complementors who can multi-home) may provide a rich landscape within which to extend our model. Another dimension of competition to consider in future work is new entry, which can be affected by both traditional isolating mechanisms (Barney, 1991; Peteraf, 1993; Wernerfelt, 1984) and the preemption of entry through investments in highly scalable resources. Future work can also model the dynamic competition between firms and complementors when relative resource advantages are not stable but dependent on prior integration choices (Argyres & Zenger, 2012; Mayer et al., 2012), and both firms can compete the final product market (Wan & Wu, 2017) or the focal firm can compete with the complementor in its main market (Zhu & Liu, 2018). The many potential extensions we highlight illustrate the significant potential of our modeling framework for a rich body of future work.

Implications for RBV Research

The RBV has long held that relative resource strengths are an important determinant of vertical integration (Argyres, 1996; Madhok, 1996, 2002), a prediction that also comports with managerial experience (Barney, 1999). This prediction has also held up very well in the context of industrial firms characterized by diminishing returns on both the resource (supply) and demand sides. However, recent advances in the RBV that explicitly incorporate resource attributes like scalability and fungibility (Levinthal & Wu, 2010; Schimdt & Keil, 2013) and the emergence of digital firms as a significant new business context (Adner et al., 2019; Siebel, 2019) present exciting opportunities to examine and extend this theory. In this paper, we provide such an extension by focusing attention on the opportunity costs of highly scalable resources that are more productive when intensively deployed within a focal activity, rather than being spread across other activities in pursuit of integration. We further elaborate this theory by examining the role played by resource fungibility, accounting for resource adjustment costs and demand conditions, and incorporating competition with the firm's complementor(s). We have already highlighted the contributions of our theoretical results and modeling framework, above, which are also relevant to the RBV.

In addition, we suggest that our theory and model are also of value for elaborating and extending the implications of the RBV by dimensionalizing resources according to their attributes and developing formal approaches that examine the impacts of these resource attributes in conjunction with economic models of firms and markets. Prior research has emphasized the importance of resource attributes such as scalability, fungibility, resource accumulation costs, and redeployability (Knudsen et al., 2014; Levinthal & Wu, 2010; Schimdt & Keil, 2013; Sakhartov & Folta, 2014, 2015; Wu, 2013) in explaining how resources affect important questions for strategic management. Although much of this research has focused on questions related to firm boundaries such as vertical integration and diversification, a tradition that the current paper follows, uncovering the implications of resource attributes for firm performance and competitive advantage also presents valuable opportunities. Indeed, the modeling approach taken in this paper is based on a profit maximization premise, and the propositions we derive may also have implications for firm performance. As an illustration, our theory highlights the potential value of even weak resources for a complementor firm, who can potentially garner rents by partnering with firms that have highly scalable resources. Future work that builds on our theory and model may more explicitly focus on the implications of resource attributes for firm performance, which is of central interest to the RBV literature.

In conclusion, we suggest that our modeling framework and proposed theory are of enduring value to the RBV, the evolving science of economic organization, and our understanding of digital firms that are integral to the modern knowledge-based economy. As an initial step towards the characterization of such complex phenomena, our theory is necessarily conjectural and incomplete, and invites further investigations using complementary approaches and methodologies.

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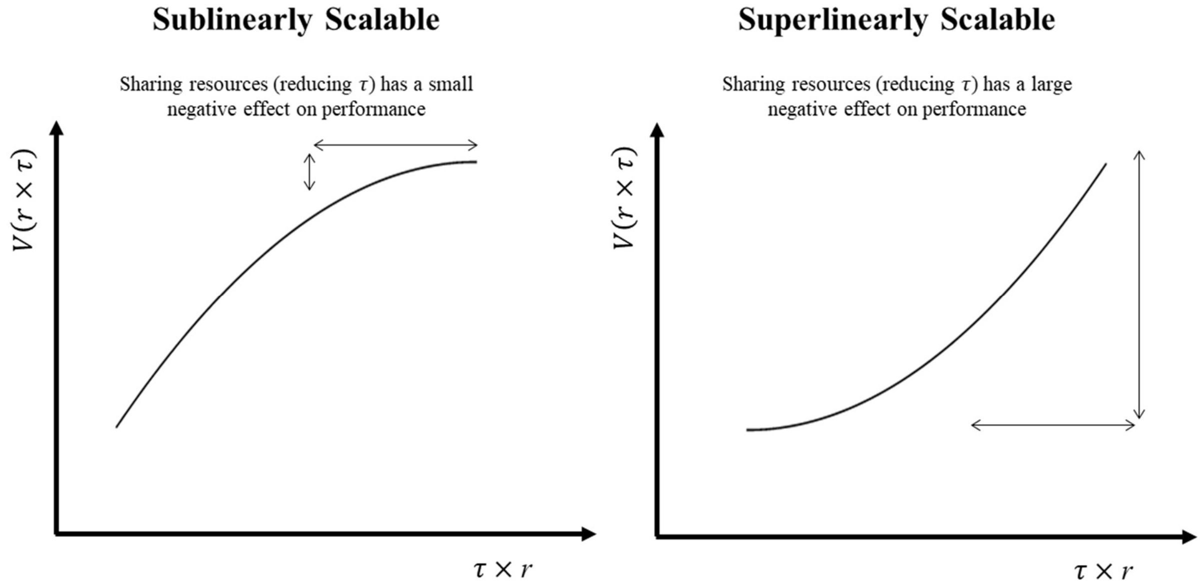
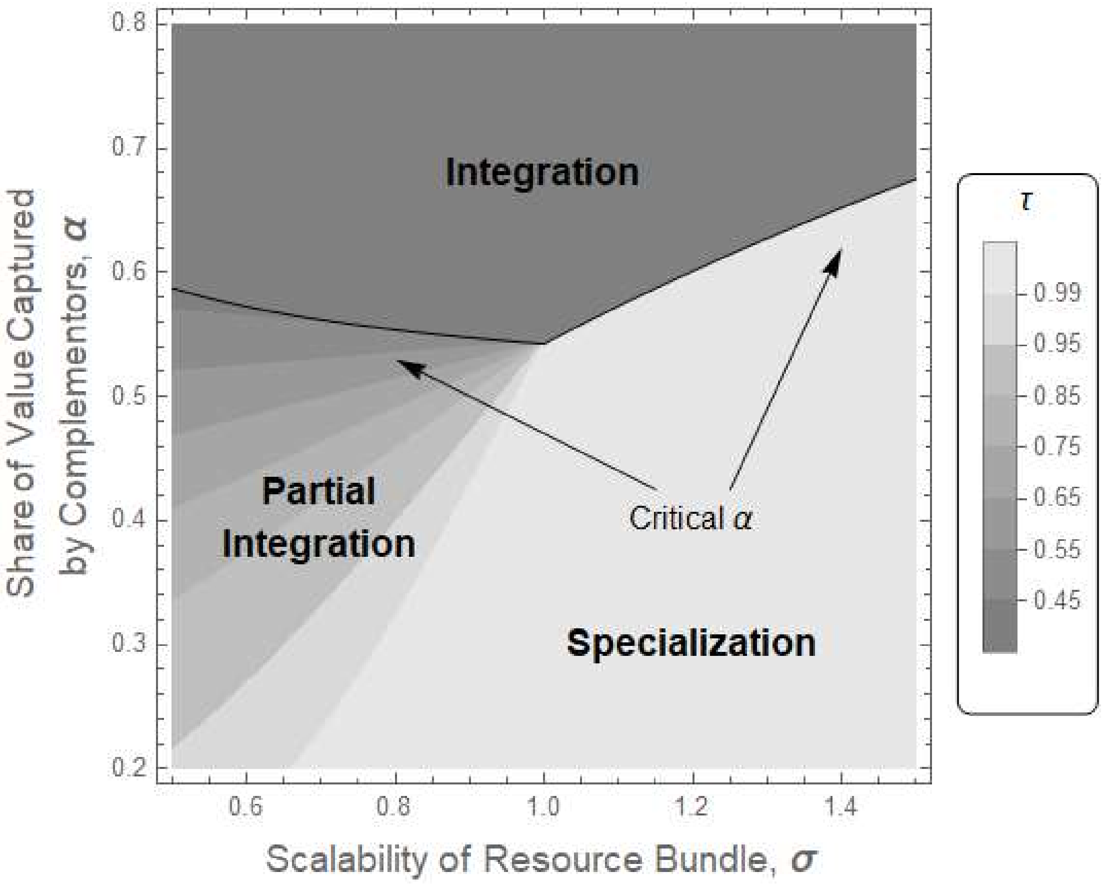
FIGURES

Figure 1: Sublinearly scalable vs. Superlinearly scalable Resources



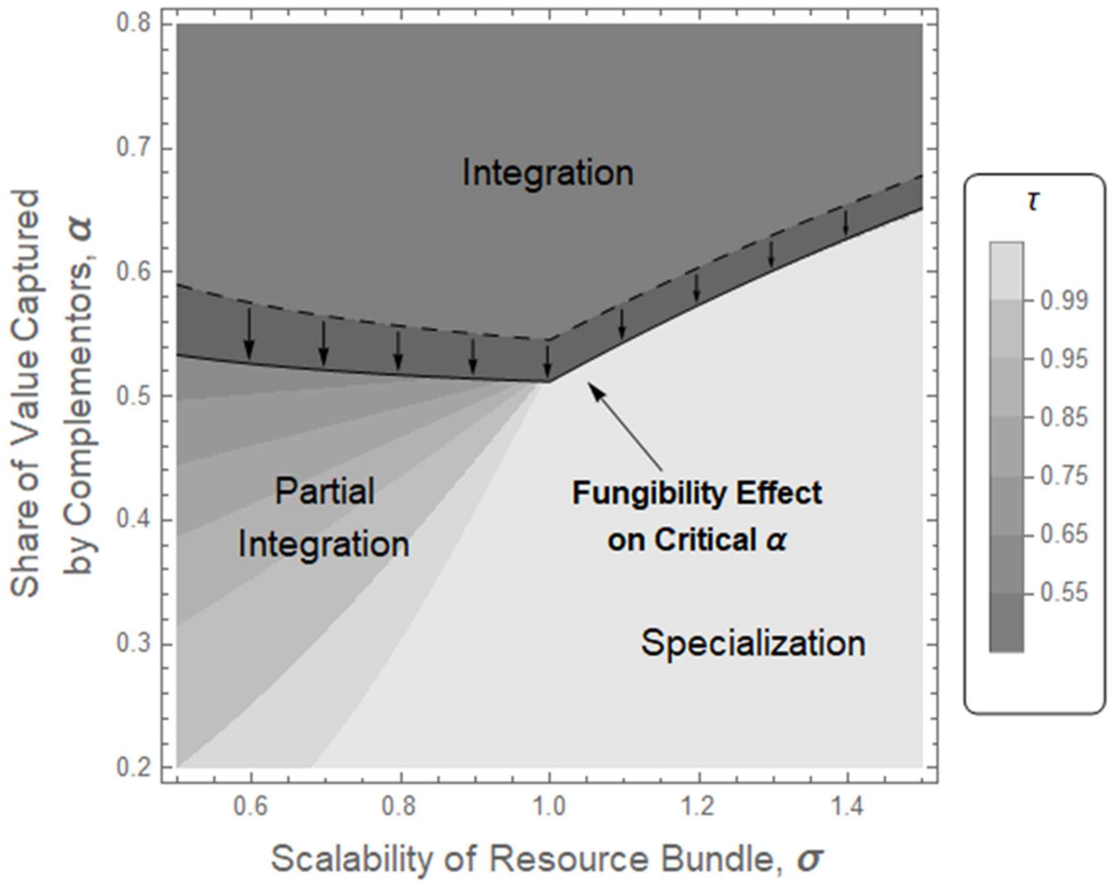
Notes: The above figure is a stylized representation of opportunity cost of redeploying resources when they are sublinearly scalable (left side) and superlinearly scalable (right side). When resources are sublinearly scalable, the opportunity cost of withdrawing resources from one application is relatively low because reducing τ (i.e., the percentage of resources allocated to a given application) has a minor impact on performance. When resources are superlinearly scalable, the opportunity cost of redeploying the same amount is higher and can result in a significant penalty.

Figure 2: Scalability, Value Distribution, and Sourcing Regimes



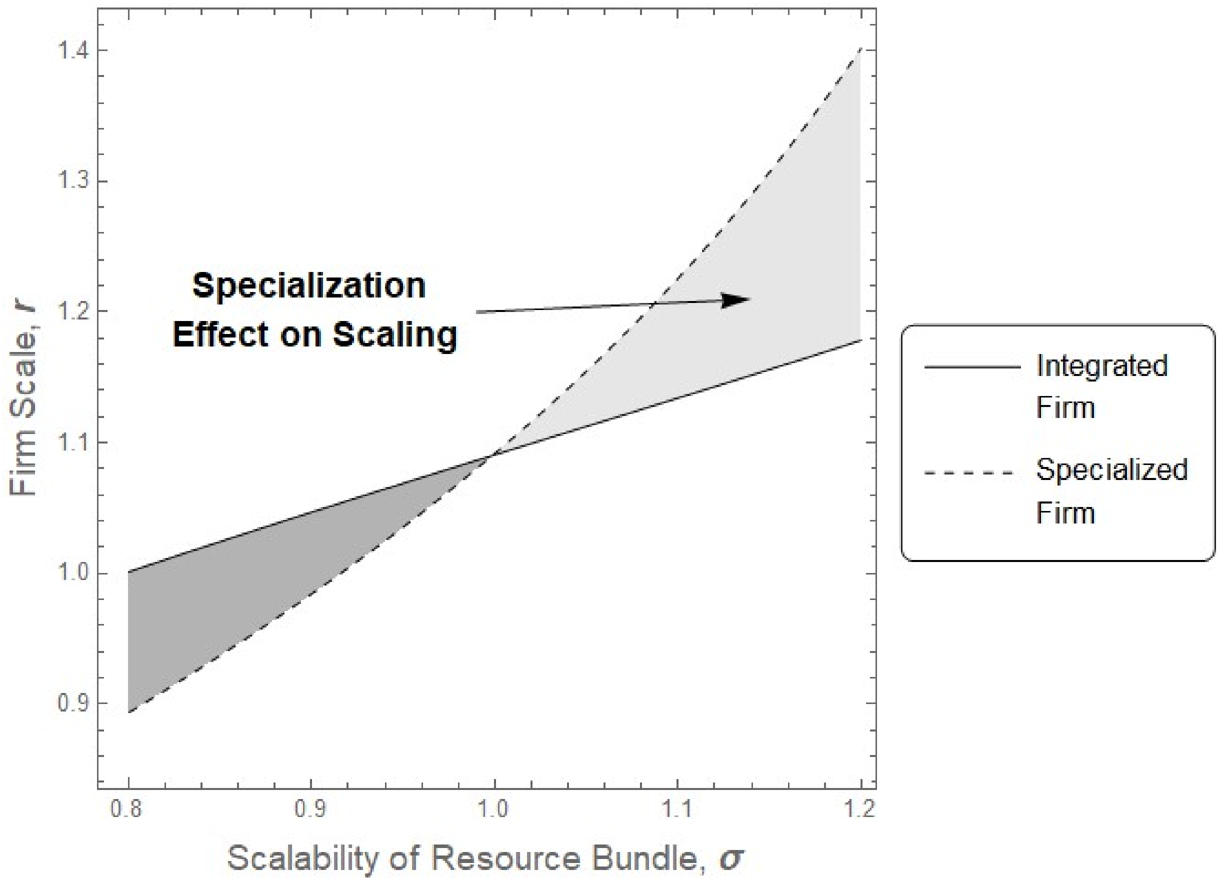
Notes: The above figure reports the results of a numerical simulation of the relationship between the scalability of resources, the value distribution, and sourcing regimes, represented by the parameters σ, α, and τ, respectively. Darker colors correspond to more integration. The black solid line traces the critical value of α beyond which collaborating with the complementor is too costly, triggering full integration. The optimal strategy follows different logics depending on whether resources are sublinearly scalable (left side, $\sigma < 1$) or scalable (right side, $\sigma \geq 1$).

Figure 3: Fungibility Effect on Critical α



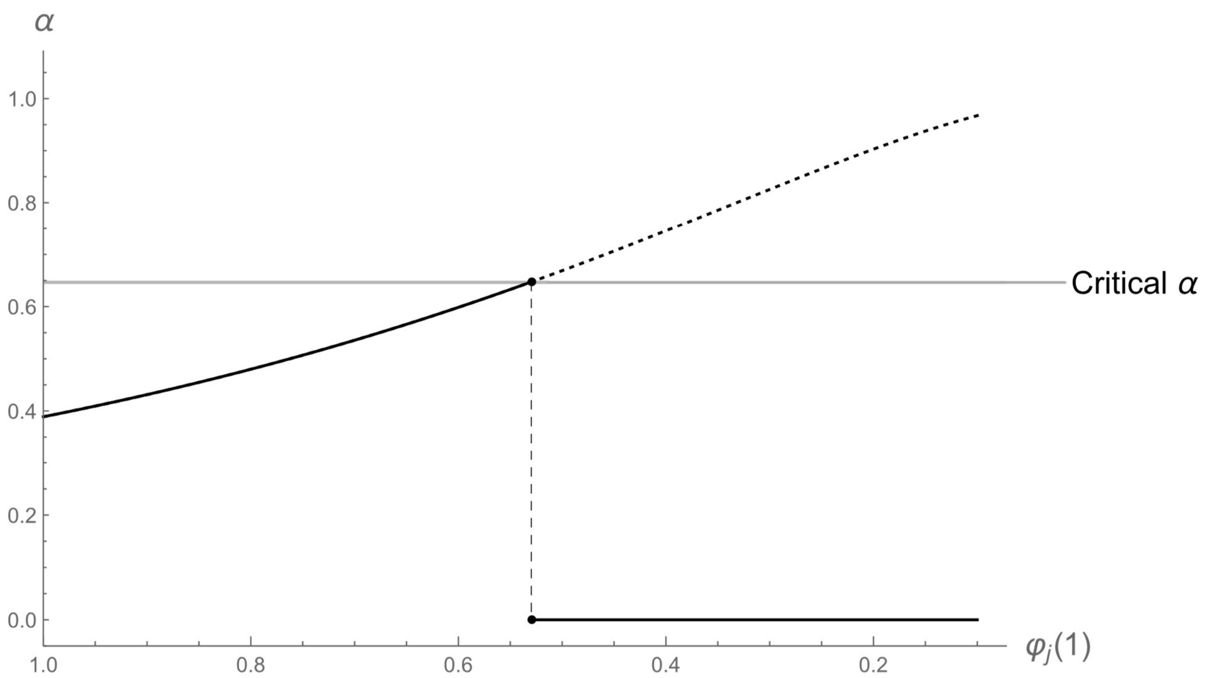
Notes: The above figure illustrates the downward shift in critical α with an increase in fungibility. Fungibility also changes the degree of outsourcing undertaken in the Partial Integration region, which is not illustrated in the figure (and is difficult to discern in a single graph). The boundary between the Partial Integration region and the Full Specialization region remains unchanged.

Figure 4: Specialization Effect on Scaling



Notes: The above figure shows the relationship between the scalability of the firm's resource bundle σ and the scale (size) of the firm (captured by the optimal size of the firm's resource bundle r) at the two ends of the sourcing continuum, integration and specialization. When the firm's resource bundle is sublinearly scalable (left side, $\sigma < 1$), the solid line corresponding to integration dominates in size over the dashed one corresponding to specialization (as in a Chandlerian firm). This changes when resources are scalable (right side, $\sigma \geq 1$), with the difference between the two lines corresponding to an enhancement of the hyperscaling effect — that is, the optimal scale of the firm is larger due to the complementarity between scalability and specialization (in post-Chandlerian firms).

Figure 5: Complementor Productivity and Value Capture



Notes: The above figure illustrates how the value share that a post-Chandlerian firm is willing to forego (α) changes as the relative capability of the complementors ($\varphi_j(1)$) decreases. The focal firm's resources are set to be perfectly fungible, with productivity in both applications normalized to 1. There is a region on the horizontal axis (from 1 to approximately 0.54) in which the focal firm is more competent than the complementors, but does not integrate. As the complementors become less productive, not only does the focal firm continue to outsource to them but the value share it is willing to forego also increases. Once this value share reaches critical α, the firm finds it optimal to integrate and no longer shares any value with the complementors. We note that a complementor cannot profitably undercut the competition. If a complementor offered a lower α to the focal firm, such complementor would not capture the whole market. On the contrary, it would scale less because a lower α would reduce the returns of its resources and its incentives to invest in capacity.

APPENDIX

Proof of Proposition 1

Given the constraint $\tau \in [\tau_I, 1]$, the Lagrangian of firm *i*'s objective function is

$$VQ_{ia}(\tau r) - \alpha V(Q_{ia}(\tau r) - Q_{ib}((1-\tau)r)) + \lambda_1(\tau - \tau_I) + \lambda_2(1-\tau), \quad \text{(A1)}$$

with first order condition

$$\frac{\partial L(\tau,\lambda_1,\lambda_2)}{\partial \tau} = \varsigma(\tau r)r - \alpha(\varsigma(\tau r)r + \varphi((1-\tau)r)r) + \lambda_1 - \lambda_2 = 0, \quad \text{(A2)}$$

where $\varsigma(r) = \frac{\partial VQ_{ia}}{\partial r}$ and $\varphi(r) = \frac{\partial VQ_{ib}}{\partial r}$ and complementary slackness conditions:

$$\lambda_1(\tau - \tau_I) = 0, \quad \text{(A3)}$$

$$\lambda_2(1-\tau) = 0. \quad \text{(A4)}$$

The firm integrates if $\lambda_1 > 0$ and $\lambda_2 = 0$. The first order condition and the complementary slackness conditions imply $\lambda_1 = \alpha(\varsigma(\tau_I r)r + \varphi((1-\tau_I)r)r) - \varsigma(\tau_I r)r > 0$, which is true if $\alpha > \frac{\varsigma(\tau_I r)}{\varsigma(\tau_I r)+\varphi((1-\tau_I)r)} \geq \frac{1}{2}$. Because $Q_{ia} = Q_{ib}$ implies $\varsigma(1)(\tau_I r)^\sigma = \varphi(1)\big((1-\tau_I)r\big)^\sigma \rightarrow \varsigma(\tau_I r)\tau_I r = \varphi\big((1-\tau_I)r\big)(1-\tau_I)r$. Solving for τ_I, we derive $\tau_I = \frac{\varphi((1-\tau_I)r)}{\varsigma(\tau_I r)+\varphi((1-\tau_I)r)}$, so that the critical α can be rewritten as:

$$\alpha > 1 - \tau_I \geq \frac{1}{2}. \quad \text{(A5)}$$

For all feasible directions ϵ such that $\tau_I + \epsilon > \tau_I$, the product $\pi'(\tau_I, r)\epsilon$ is negative because (A2) and $\lambda_1 > 0$ imply $\pi'(\tau_I, r)$ is negative while ϵ is positive by definition. This ensures that $\tau = \tau_I$, $\lambda_1 = \alpha V(\varsigma(\tau_I r)r + \varphi\big((1-\tau_I)r\big) - V\varsigma(\tau_I r)r$, and $\lambda_2 = 0$ is a local maximum because $\pi(\tau, r)$ cannot increase in the proximity of the constraint. When $\sigma < 1$, because π is strictly concave down, the point identifies a global maximum.

When $\sigma \geq 1, \tau = \tau_I$, $\lambda_1 = \alpha(\varsigma(\tau_I r)r + \varphi((1-\tau_I)r)r) - \varsigma(\tau_I r)r$, and $\lambda_2 = 0$ identifies a global maximum if:

$$\alpha > 1 - \tau_I{}^\sigma \geq \frac{1}{2}. \quad \text{(A6)}$$

The condition in (A6) is derived by comparing profits at the endpoints $\tau = \tau_I$ and $\tau = \tau_S = 1$.

Partial integration corresponds to an interior solution $\tau_C \in (\tau_I, 1)$, requiring $\lambda_1 = 0$ and $\lambda_2 = 0$. The first order condition implies:

$$(1-\alpha)\varsigma(\tau_C r) = \alpha\varphi((1-\tau_C)r) = \eta. \quad \text{(A7)}$$

Using Euler's homogenous function theorem and (A7), the second order condition for a maximum is $\tau_C^{-1}(\sigma - 1)\,\eta + (1-\tau_C)^{-1}(\sigma-1)\eta < 0$, which holds only if $\sigma < 1$. When $\sigma < 1$, π is strictly concave down and $\tau = \tau_C, \lambda_1 = 0$, and $\lambda_2 = 0$ identifies a global maximum when $\alpha \leq 1 - \tau_I$. Because the characterization $Q_{ia}(\tau_I r) = Q_{ib}((1-\tau_I)\, r)$ implies that $1 > \tau_I > 0$—if $\tau_I = 0$, for example, then $Q_{ia}(\tau_I r) \neq Q_{ib}\big((1-\tau_I)r\big)$ because $Q_{ia}(\tau_I r) = 0$ and $Q_{ib}\big((1-\tau_I)r\big) > 0$—we have that $1 > 1 - \tau_I > 0$.

From the above arguments, it follows $\sigma \geq 1$ never leads to an interior solution. If $\alpha \leq 1 - {\tau_I}^{\sigma}$ and $\sigma \geq 1$, it must be $\lambda_1 = 0$ and $\lambda_2 > 0$. Then, $\tau_s = 1$ and $\lambda_2 = (1-\alpha)\varsigma(r)r$. Moving along all feasible directions, ϵ', such that $\tau_s + \epsilon' < \tau_s = 1, \pi'(\tau_s, r)\epsilon'$ is negative because (A2) and $\lambda_2 > 0$ imply $\pi'(\tau_s, r)$ is positive while ϵ' is negative by definition. This ensures $\tau = \tau_S, \lambda_1 = 0$, and $\lambda_2 = (1-\alpha)V\varsigma(r)r$ identifies a global maximum when $\sigma \geq 1$ and $\alpha \leq 1 - {\tau_I}^{\sigma}$. Therefore, when resources are scalable, the critical α is $1 - {\tau_I}^{\sigma}$. Because $1 > \tau_I > 0$, we have $1 > 1 - {\tau_I}^{\sigma} > 0$ since $0 < {\tau_I}^{\sigma} < 1$ for any $\sigma > 0$.

Assume $\sigma < 1$. If $\alpha \leq 1 - \tau_I \rightarrow \tau = \tau_C$ and if $\alpha > 1 - \tau_I \rightarrow \tau = \tau_I$. Then, τ can be characterized as $\tau = \tau_I + (\tau_C - \tau_I)H(1 - \tau_I - \alpha)$, where $H(x) = \begin{cases} 1 & x \geq 0 \\ 0 & x < 0 \end{cases}$ is the Heaviside step function. Noting that τ_C is an implicit function of α defined by the first order condition (A7), differentiating τ_C with respect to α gives:

$$\frac{\partial \tau_C}{\partial \alpha} = \frac{1}{\sigma - 1} \frac{\tau_C(1-\tau_C)}{\alpha(1-\alpha)}. \tag{A8}$$

Because $\frac{1}{\sigma-1}$ is negative and the other factors are positive, $\frac{\partial \tau_C}{\partial \alpha}$ is negative. We can then express $\frac{\partial \tau}{\partial \alpha}$ as:

$$\frac{\partial \tau}{\partial \alpha} = \frac{\partial \tau_C}{\partial \alpha} H(1 - \tau_I - \alpha) + (\tau_C - \tau_I)\delta(1 - \tau_I - \alpha). \tag{A9}$$

The function $\delta(x) = \begin{cases} 0 & x \neq 0 \\ +\infty & x = 0 \end{cases}$ is Dirac delta function, also called pulse function, which corresponds to the derivative of the Heaviside step function. Since $\tau_C = \tau_I$ when $1 - \tau_I = \alpha$, $(\tau_C - \tau_I)\delta(1 - \tau_I - \alpha) = 0$ for all $\alpha \in (0,1)$.[21] The derivative $\frac{\partial \tau}{\partial \alpha}$ is then negative and equal to $\frac{\partial \tau_C}{\partial \alpha}$ when $\alpha \leq 1 - \tau_I$, and equal to zero when $\alpha > 1 - \tau_I$. Because $\frac{\partial \tau}{\partial \alpha}$ is defined for every $\alpha \in (0,1)$, τ continuous in α. We deduce that the nature of the firm's response to (infinitesimal) changes in the parameter α is continuous, with adjustments to vertical scope occurring at the margin.

Now assume $\sigma \geq 1$. If $\alpha \leq 1 - {\tau_I}^{\sigma} \rightarrow \tau = \tau_S$ and $\alpha > 1 - {\tau_I}^{\sigma} \rightarrow \tau = \tau_I$. Then, $\tau = \tau_I + (\tau_S - \tau_I)H((1 - {\tau_I}^{\sigma}) - \alpha)$, which is discontinuous because $\lim_{\alpha \to 1 - {\tau_I}^{\sigma} -} \tau = \tau_S \neq \lim_{\alpha \to 1 - {\tau_I}^{\sigma} +} \tau = \tau_I$. By the chain rule, the derivative $\frac{\partial \tau}{\partial \alpha}$ can be expressed as:

$$\frac{\partial \tau}{\partial \alpha} = -(\tau_S - \tau_I)\delta((1 - {\tau_I}^{\sigma}) - \alpha). \tag{A10}$$

From the properties of Dirac delta function, it follows that $\frac{\partial \tau}{\partial \alpha}$ is zero everywhere except at $\alpha = 1 - {\tau_I}^{\sigma}$, where it pulses and spike to $-\infty$. We infer that, when resources scale superlinearly, (infinitesimal) positive changes in the parameter α can to vertical expansion only in the proximity of the critical α line, altering vertical scope discontinuously from specialization to integration. Q.E.D.

[21] $\delta(0)0 = 0$ because, by the algebraic properties of the Dirac delta function, $\delta(x)x = 0$ for all $x \in \mathbb{R}$.

Proof of Proposition 2

For $\sigma < 1$, the effect of scalability on the critical α is $\frac{\partial(1-\tau_I)}{\partial\sigma} = -\frac{\partial\tau_I}{\partial\sigma}$. Using $Q_{ia}(\tau_I r) = Q_{ib}((1-\tau_I)\, r)$ to implicitly differentiate τ_I with respect to σ gives $\frac{\partial\tau_I}{\partial\sigma} = \frac{(1-\tau_I)\tau_I(ln(1-\tau_I)-ln(\tau_I))}{\sigma}$. Therefore, $\frac{\partial(1-\tau_I)}{\partial\sigma} = -\frac{\partial\tau_I}{\partial\sigma} = -\frac{(1-\tau_I)\tau_I(ln(1-\tau_I)-ln(\tau_I))}{\sigma}$, which is less than or equal to zero because (A5) implies $1-\tau_I \geq \tau_I \rightarrow ln(1-\tau_I) \geq ln(\tau_I)$. For $\sigma \geq 1$, the effect of scalability on the critical α is $\frac{\partial(1-\tau_I{}^{\sigma})}{\partial\sigma} = -\frac{\partial\tau_I}{\partial\sigma}\sigma\tau_I{}^{\sigma-1} - \tau_I{}^{\sigma}(\tau_I)$. Given that $\frac{\partial\tau_I}{\partial\sigma} = \frac{(1-\tau_I)\tau_I(ln(1-\tau_I)-ln(\tau_I))}{\sigma}$, $\frac{\partial(1-\tau_I{}^{\sigma})}{\partial\sigma}$ can be rewritten as $-\tau_I{}^{\sigma}(\tau_I ln(\tau_I) + (1-\tau_I)ln(1-\tau_I))$, which is positive because $1 > \tau_I > 0$ implies $ln(\tau_I), ln(1-\tau_I) < 0$. Q.E.D.

Proof of Proposition 3

When resources are sublinearly scalable, the critical α is $1-\tau_I$. The effect of fungibility on the critical α is then $\frac{\partial(1-\tau_I)}{\partial\,\varphi(1)} = -\frac{\partial\tau_I}{\partial\varphi(1)}$. Using $Q_{ia}(\tau_I r) = Q_{ib}((1-\tau_I)\, r)$, implicitly differentiating τ_I with respect to $\varphi(1)$ gives $\frac{\partial\tau_I}{\partial\varphi(1)} = \frac{(1-\tau_I)\tau_I}{\sigma}$, which is positive because both τ_I and $(1-\tau_I)$are positive. Therefore $-\frac{\partial\tau_I}{\partial\varphi(1)}$ is negative. When resources are scalable, the critical α is $1-\tau_I{}^{\sigma}$. The effect of fungibility of the critical $\alpha$is then given by the derivative $\frac{\partial(1-\tau_I{}^{\sigma})}{\partial\,\varphi(1)} = -\frac{\partial\tau_I}{\partial\varphi(1)}\sigma\tau_I{}^{\sigma-1}$. Since $\frac{\partial\tau_I}{\partial\varphi(1)} = \frac{(1-\tau_I)\tau_I}{\sigma}$, $\frac{\partial(1-\tau_I{}^{\sigma})}{\partial\,\varphi(1)} = -(1-\tau_I)\tau_I{}^{\sigma}$, which is negative because $(1-\tau_I), \tau_I{}^{\sigma} > 0$. Q.E.D

Proof of Proposition 4

Because the optimal scaling rule satisfies $\frac{\partial\pi(\tau_j,r)}{\partial r} = \frac{\partial C(r)}{\partial r}$ for $j \in \{S, C, I\}$ and $C(\cdot)$ is monotonically increasing, a firm opting for sourcing regime j is as large as or larger than a firm opting for sourcing regime $i \neq j$ if $\frac{\partial\pi(\tau_j,r)}{\partial r} \geq \frac{\partial\pi(\tau_i,r)}{\partial r}$for all $r > 0$.

Consider a post-Chandlerian whose scaling exponent is $\sigma \geq 1$. By (A6), the firm will specialize if $\alpha \leq 1-\tau_I{}^{\sigma}$, else it will integrate. When it specializes, the marginal productivity of its resources is $\frac{\partial\pi(\tau_S,r)}{\partial r} = (1-\alpha)\varsigma(r)$, when it integrates, $\varsigma(\tau_I r)\tau_I$. By Euler's theorem, $\varsigma(\tau_I r)\tau_I$ is equivalent to $\tau_I{}^{\sigma}\varsigma(r)$. Using (A6), we have $(1-\alpha)\varsigma(r) \geq \big(1-(1-\tau_I{}^{\sigma})\big)\varsigma(r) = \tau_I{}^{\sigma}\varsigma(r)$.

However, because $\frac{\partial(\tau_I{}^{\sigma})}{\partial\,\varphi(1)} = \frac{\partial\tau_I}{\partial\varphi(1)}\sigma\tau_I{}^{\sigma-1} = (1-\tau_I)\tau_I{}^{\sigma} > 0$ (with $\frac{\partial\tau_I}{\partial\varphi(1)} = \frac{(1-\tau_I)\tau_I}{\sigma}$ being the derivative of τ_I with respect to $\varphi(1)$ implied by $Q_{ia}(\tau_I r) = Q_{ib}((1-\tau_I)\, r)$), the difference $\frac{\partial\pi(\tau_S,r)}{\partial r} - \frac{\partial\pi(\tau_I,r)}{\partial r} = (1-\alpha)\varsigma(r) - \tau_I{}^{\sigma}\varsigma(r)$is decreasing in the fungibility of firm i's resources.

Next, we compare a specialized post-Chandlerian firm with scaling exponent $\sigma \geq 1$ to a partially integrated Chandlerian firm with scaling exponent $\sigma' < 1$ so that $\frac{\partial VQ_{ia}(1)}{\partial r} = \varsigma'(1) \geq \frac{\partial VQ_{ib}(1)}{\partial r} = \varphi'(1) > 0$. The marginal productivity of the specialized post-Chandlerian firm's resources is $(1-\alpha)\varsigma(r)$. The marginal productivity of the resources of the partially integrated firm is $(1-\alpha)\varsigma'(\tau'_C r)\tau'_C + \alpha\varphi'\big((1-\tau'_C)r\big)(1-\tau'_C)$, which, by (A7), can be expressed as $\frac{\partial\pi(\tau'_C,r)}{\partial r} = (1-\alpha)\varsigma'(\tau'_C r)$. The marginal productivity of the specialized firm is greater than that of the partially integrated firm because $\varsigma(r) > \varsigma'(\tau'_C r)$ if $r \geq r'$. Whether this threshold is met depends on the specifics of the cost function. The cut-off value for *r* identifies a point whose surpassing can lead to sustained growth and can be interpreted as a tipping point or critical mass that must be attained in order to trigger hyperscaling.

Finally, we compare a specialized post-Chandlerian firm with scaling exponent $\sigma \geq 1$ to an integrated Chandlerian firm with scaling exponent $\sigma' < 1$. The productivity of the integrated firm given by $\tau'_I\varsigma'(\tau'_I r)$. The productivity of the specialized firm is $(1-\alpha)\varsigma(r) \geq \left(1-(1-\tau_I{}^{\sigma})\right)\varsigma(r) = \tau_I{}^{\sigma}\varsigma(r)$. We have that $\tau_I\varsigma(\tau_I r) > \tau'_I\varsigma'(\tau'_I r)$ if $r \geq r''$. Also in this case, the cut-off value for *r* can be interpreted as a tipping point or critical mass.

It is interesting to note that, if the specialized firm's resources had scaled sublinearly with scaling exponent $\sigma' < 1$, the productivity under integration would have dominated the productivity under specialization for $\alpha > 1 - {\tau'_I}^{\sigma'}$. Given that integration requires $\alpha > 1 - \tau'_I > 1 - {\tau'_I}^{\sigma'}$, the integrated firm would have been larger than specialized firm. Q.E.D**.**

Model Extension: N-firm Game-theoretic Model and Proof of Proposition 5

The "threat points" within which α leads to trade between firm *i* and firm *j*s are fully determined by the second-stage maximization programs delineating the optimal allocation of resources. For firm i, this corresponds to the Lagrangian in (A1). Therefore, when firm i's resources scale superlinearly, firm i will specialize if α is below the threat point $(1 - \tau_I{}^{\sigma})$, else it will integrate. When resources scale sublinearly, firm *i* will opt for concurrent sourcing if α is below the threat point $1 - \tau_I$, else it will integrate.

For any firm j, the second-stage maximization program can be converted to the Lagrangian:

$$(1-\theta\alpha)VQ_{ja}(\tau_j r_j) + \theta\alpha VQ_{jb}((1-\tau_j)r_j) + \lambda_{j1}(\tau_{jI} - \tau_j) + \lambda_{j2}(\tau_j - 0). \qquad \text{(A11)}$$

This maximization problem mirrors firm *i*'s. When the complementors' resources are scalable, the complementors will specialize in *b* if α is above the "threat point" $\theta^{-1}\left(1-\tau_{jI}\right)^{\sigma_j}$, else they will integrate (where $\theta \in (0,1)$ is the transaction cost parameter defined in footnote 15).[22] When the scalability of their resources is sublinear, the complementors will perform concurrent sourcing if α is above the threat point $\theta^{-1}\left(1-\tau_{jI}\right)$, else they will integrate.[23]

The equilibrium value of α is determined by the market clearing constraint requiring that *a*s and *b*s are produced in one-to-one proportions,

$$g = Q_{ia}(\tau r) - Q_{ib}\left((1-\tau)r\right) - N\left(Q_{jb}\left((1-\tau_j)r_j\right) - Q_{ja}(\tau_j r_j)\right) = 0, \qquad \text{(A12)}$$

where $\tau, r, \tau_j,$ and r_j are a function of α. The market clearing constraint must always be satisfied in equilibrium. If it were not, because, for instance, firm *i* produced an excess supply of *a*s, then firm *i* would deviate by reducing its resource stock, r, so as to match the complementors' supply. In doing so, firm *i* would reduce its costs and, consequently, increase its profits. We also note that when $N > 1$, none of the complementors can profitably undercut the "realized α." If a complementor deviated by offering a lower α to firm *i,* such complementor would not capture the whole market. On the contrary, it would scale less

[22] As in the case of firm *i*, when resources scale superlinearly, the threat point is determined by comparing profits at the corner solutions $\tau_j = \tau_{jI}$ and $\tau_j = 0$.

[23] When resources scale sublinearly, the threat point is reached when the shadow price of integration, captured by the Lagrange multiplier λ_{j1}, becomes positive.

because a lower α would reduce the marginal revenue product of its resources and, ultimately, its incentives to invest in r_j.[24]

Then, for α clearing the market, the profile of actions $(\{1, r_S(\alpha)\}, \{0, r_{jS}(\alpha)\})$ is a Nash equilibrium if $\sigma, \sigma_j \geq 1$ and $(1-\tau_I{}^{\sigma}) \geq \alpha \geq \theta^{-1}(1-\tau_{jI})^{\sigma_j}$; $(\{\tau_C(\alpha), r_C(\alpha)\}, \{\tau_{jC}(\alpha), r_{jC}(\alpha)\})$ is a Nash equilibrium if $\sigma, \sigma_j < 1$ and $1-\tau_I \geq \alpha \geq \theta^{-1}\theta^{-1}(1-\tau_{jI})$; and $(\{1, r_S(\alpha)\}, \{\tau_{jC}(\alpha), r_{jC}(\alpha)\})$ is a Nash equilibrium if $\sigma_i \geq 1, \sigma_j < 1$ and $(1-\tau_I{}^{\sigma_i}) \geq \alpha \geq \theta^{-1}(1-\tau_{jI})$.

Using (A15) to implicitly differentiate α with respect to $-\varphi_j(1), -N,$ and $-\theta$, it follows:

$$\frac{\partial \alpha}{\partial(-\varphi_j(1))} = -\left(\frac{\partial g}{\partial \tau_i}\frac{\partial \tau_i}{\partial \alpha} + \frac{\partial g}{\partial r_i}\left(\frac{\partial r_i}{\partial \tau_i}\frac{\partial \tau_i}{\partial \alpha} + \frac{\partial r_i}{\partial \alpha}\right) + \frac{\partial g}{\partial \tau_j}\frac{\partial \tau_j}{\partial \alpha} + \frac{\partial g}{\partial r_j}\left(\frac{\partial r_j}{\partial \tau_j}\frac{\partial \tau_j}{\partial \alpha} + \frac{\partial r_j}{\partial \alpha}\right)\right)^{-1}\left(\frac{\partial g}{\partial(-\varphi_j(1))}\right) > 0 \quad \text{(A13)}$$

$$\frac{\partial \alpha}{\partial(-N)} = -\left(\frac{\partial g}{\partial \tau_i}\frac{\partial \tau_i}{\partial \alpha} + \frac{\partial g}{\partial r_i}\left(\frac{\partial r_i}{\partial \tau_i}\frac{\partial \tau_i}{\partial \alpha} + \frac{\partial r_i}{\partial \alpha}\right) + \frac{\partial g}{\partial \tau_j}\frac{\partial \tau_j}{\partial \alpha} + \frac{\partial g}{\partial r_j}\left(\frac{\partial r_j}{\partial \tau_j}\frac{\partial \tau_j}{\partial \alpha} + \frac{\partial r_j}{\partial \alpha}\right)\right)^{-1}\left(\frac{\partial g}{\partial(-N)}\right) > 0 \quad \text{(A14)}$$

$$\frac{\partial \alpha}{\partial(-\theta)} = -\left(\frac{\partial g}{\partial \tau_i}\frac{\partial \tau_i}{\partial \alpha} + \frac{\partial g}{\partial r_i}\left(\frac{\partial r_i}{\partial \tau_i}\frac{\partial \tau_i}{\partial \alpha} + \frac{\partial r_i}{\partial \alpha}\right) + \frac{\partial g}{\partial \tau_j}\frac{\partial \tau_j}{\partial \alpha} + \frac{\partial g}{\partial r_j}\left(\frac{\partial r_j}{\partial \tau_j}\frac{\partial \tau_j}{\partial \alpha} + \frac{\partial r_j}{\partial \alpha}\right)\right)^{-1}\left(\frac{\partial g}{\partial(-\theta)}\right) > 0 \quad \text{(A15)}$$

The sign of the above derivatives is fully determined by their numerators, since the denominator is always negative (intuitively, a positive change in α, which is the share of the pie apportioned to activity *b*, leads to a migration of resources towards that activity, thus having a negative impact on the difference between *a*s and *b*s measured by *g*). In (A13), the numerator is positive because a negative change in the complementors' baseline capability reduces the output of the complementors' main activity, depleting the *b*s in the market. For the market to clear, this reduction in supply needs to be counterbalanced by an increase in α. In (A14), the numerator is negative because a decrease in the number of complementors in the market results, ceteris paribus, in a reduction in the supply of *b*s, which must be met by a greater α. In (A15), an increase in transaction costs reduces the complementors willingness to trade, diluting the supply of *b*s in the market. This effect must then be offset by an increase in α so as to rebalance the supply of *b*s.

Noting that *g* in (A12) is continuous in α, that for every action profile, that α can get arbitrarily close to one (e.g., for θ arbitrarily small) or arbitrarily close to zero (e.g., for $\varphi_j(1)$ arbitrarily large), we can deduce that $\alpha(\cdot)$ is a function with image $(0,1)$, is differentiable, and monotonic in each variable $\varphi_j(1), N,$ and θ. Because α can fall outside the threat points (e.g., for θ arbitrarily small), if $\sigma < 1$ there exist initial values $\varphi_j(1)$, *N*, and θ, and increments $\Delta\varphi_j(1) < 0$, $\Delta N < 0$, and $\Delta\theta < 0$ such that $\alpha(\varphi_j(1), N, \theta) \leq 1-\tau_I \rightarrow \tau = \tau_C$ and $\alpha(\varphi_j(1) + \Delta\varphi_j(1), N, \theta), \alpha(\varphi_j(1), N + \Delta N, \theta), \alpha(\varphi_j(1), N, \theta + \Delta\theta) > 1-\tau_I \rightarrow \tau = \tau_I$. If $\sigma \geq 1$, there are values $\varphi_j(1)', N'$, and θ', and increments $\Delta N' < 0$, $\Delta\varphi_j(1)' < 0$, and $\Delta\theta' < 0$ such that $\alpha(\varphi_j(1)', N', \theta') \leq 1-\tau_I{}^{\sigma} \rightarrow \tau = \tau_S$ and $\alpha(\varphi_j(1)' + \Delta\varphi_j(1)', N', \theta')$, $\alpha(\varphi_j(1)', N' + \Delta N', \theta')$, $\alpha(\varphi_j(1)', N, \theta' + \Delta\theta') > 1-\tau_I{}^{\sigma} \rightarrow \tau = \tau_I$. Q.E.D.

[24] The marginal revenue product of firm *j*'s resources is $\frac{\partial \pi(\tau_j, r_j)}{\partial r_j} = \frac{\partial\left(VQ_{jb}((1-\tau_j)r_j) - (1-\theta\alpha)V(Q_{jb}(\tau_j r_j) - Q_{ja}((1-\tau_j)r_j))\right)}{\partial r_j}$. This expression determines firm *j*'s scale via the first order condition $\frac{\partial \pi(\tau_j, r_j)}{\partial r_j} = \frac{\partial C(r_j)}{\partial r_j}$.