The Ecosystem Penalty: Value Creation Technologies and Incentive Misalignment

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Abstract

When are the incentives of a business ecosystem's participants aligned with its growth? How is the type of complementarities between ecosystem components affecting this alignment? Developing a formal model of value creation and value capture in an ecosystem, we find that alignment is typically imperfect compared to an integrated benchmark, highlighting an "ecosystem penalty" whereby participants' returns to value creation are lower than that of the ecosystem. Contrary to conventional wisdom, ecosystems with strong synergies between components can exhibit increasing misalignment when its participants have strong *ex ante* capabilities, while those with weaker synergies can be well-aligned when the orchestrator is strong and complementors are close substitutes. Ecosystems where value creation is constrained by its weakest component exhibit both the best and the worst alignment.

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1 INTRODUCTION

In the past several years, ecosystems (Adner, 2017; Jacobides, Cennamo, and Gawer, 2018; Kapoor, 2018) have become the focus of intense research as an organizational form permitting to stimulate innovation and value creation (Adner, 2017; Adner and Kapoor, 2010; Hannah and Eisenhardt, 2018). As such, investments in value creation are key to ecosystem development and survival (Ethiraj, 2007; Hannah and Eisenhardt, 2018; Kapoor and Agarwal, 2017), yet the incentives of ecosystem participants need to be aligned to make these investments (Adner, 2012, 2017; Baldwin, 2020; Ozcan and Hannah, 2020). While the literature suggests that returns to investments in value creation may vary across ecosystems participants (Chu and Wu, 2021; Jacobides and Tae, 2015; Miller and Toh, 2022), we lack a structured account of the mechanisms underlying such incentive alignment. Extant literature suggests some behavioral explanations (e.g., Adner, 2017, 2022; Adner and Feiler, 2019) or moral hazard (Baldwin, 2020), yet the question remains as to how the fundamental features of the ecosystems, such as the technology of value creation and competition over value capture, may permit incentive alignment or cause misalignment.

Furthermore, while complementarity is recognized as a defining feature of an ecosystem (Adner, 2017; Baldwin, 2018; Jacobides et al., 2018; Kapoor, 2018), there are few attempts to systematically explore its impact on value creation and value capture for ecosystem participants. Ecosystems may feature different types of complementarities, for instance, displaying weaker synergies ("A does not work without B" (Baldwin, 2018; Jacobides et al., 2018)[1], strong synergies between complements ("more of A makes B more valuable" (Baldwin, 2018; Jacobides et al., 2018)), or constraints (total value creation is constrained by the weakest between A and B (Ethiraj, 2007)). Yet, while there is a general understanding that the underlying type of complementarities among ecosystem components will affect the total value created (Adner and Kapoor, 2010; Ethiraj, 2007), we lack a comprehensive account of how it may affect *individual* value capture of ecosystem participants and, consequently, their incentives to invest in increasing value creation.

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[1] This is the case where the value of the products (services) together is higher than the sum of their separate values (Baldwin, 2018). This is what Jacobides et al. (2018) call "unique" complementarities: an orchestrator's product doesn't function without a complementor's product, and vice versa (Hart and Moore, 1990).

Taken together, this reveals a lacuna that we seek to address in this paper: *How do different types of complementarities, or technologies of value creation, shape ecosystem participants' incentives to improve value creation in an ecosystem?* To answer this question, we develop a formal model of value creation and value capture in a business ecosystem accounting for different types of complementarities. Specifically, our model maps firms' individual capabilities to create value and the type of complementarity between them (how these individual capabilities combine in an ecosystem) into the total value creation by the ecosystem, and then into firms' individual value capture, which, in turn, translates into incentives to improve their value-creating capabilities (see Figure 1).

We model an archetypical ecosystem including an orchestrator, competing complementors, and a final customer. For a practical illustration consider, for instance, Airbus as an orchestrator, Pratt & Whitney and CFM as competing engine producers, and an airline company who chooses which engine to install on the Airbus aircraft. Competitive asymmetry between ecosystem components – a one-of-a-kind orchestrator vs. (partially) substitutable complementors – reflects the dynamic of many real-life ecosystems where there is a powerful platform or an orchestrator (e.g., smartphone OS, game console, aircraft producer) and multiple competing complementors (app developers, game developers, engine producers).[2] We use the value-based framework (Brandenburger and Stuart, 2007) to map value creation into value capture under competition, and rely on Cappelli and Chatain (2023) to ensure a mutually consistent distribution of value. We then compare each actor's level of improvement in its value-creating capability in Nash Equilibrium to the benchmark given by a fully integrated benchmark. We use a costless integration idealized benchmark, where the orchestrator and the complementor act as one actor in perfect alignment, to show how competition for value capture between ecosystem participants shapes their incentives to invest.[3]

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[2] While in real life we may observe several orchestrators in the market (e.g., iOS and Android), we assume that horizontal differentiation between orchestrators is sufficiently strong that the competing orchestrator(s) can only create a minimal value for the buyer, which is consistent with the assumption of a "single-homing" buyer, common in the platform literature (Armstrong, 2006; Cennamo, Ozalp, and Kretschmer, 2018; Panico and Cennamo, 2022). We thus have a setup of monopolistic orchestrator and competing complementors similar to Casadesus-Masanell, Nalebuff, and Yoffie (2007), which allows us to focus on the key mechanisms of interest, such as the type of complementarity and the alignment among whether or not the ecosystem participants act as one, while leaving the implications of the competition in the orchestrator's component for the future research.

[3] Cognizant of the "nirvana fallacy" (Demsetz, 1969), we do not consider the idealized integrated actor benchmark as feasible in practice. Rather, we use it as a common metric to explore the patterns and the degrees of incentive

(Insert Figure 1 about here.)

We repeat this analysis under three archetypical technologies of value creation, or types of underlying complementarities between ecosystem components. We start with a scenario of weak synergies between ecosystem components, or additive value creation technology, where the total value created is the sum of the individual capabilities of the orchestrator and of the best complementor, yet both are necessary in order to create value (as in messaging apps on a smartphone). We then contrast the results with the scenario of a strong complementarity where the total value created is the product of the individual capabilities of the orchestrator and of the best complementor (Baldwin, 2020), for instance as in virtual reality games. Finally, we examine the scenario where the total value creation is constrained by the least performing ecosystem component (Ethiraj, 2007), which we call the weakest link value creation technology (e.g., as in consoles and video games).[4]

We find that in most cases ecosystem participants can be expected to underinvest in value creation compared to the first best creating an "ecosystem penalty" as individual actor's marginal returns are typically less than the return to the ecosystem as a whole. The size of penalty, or the degree of misalignment, depends on the type of actor (orchestrator vs. complementor) and the level of their *ex ante* capabilities. For instance, complementor exhibits the best alignment when the competing complementor is a close substitute. When it comes to the orchestrator – the actor that is more scarce in an ecosystem as it is one-in-kind – the penalty size and relationship to the orchestrator's capabilities vary sharply across the type of complementarities.

We find that when ecosystem has weak synergies between components (additive value creation) the best incentive alignment is achieved when complementors are close substitutes, and the orchestrator has *ex ante* high capabilities. By contrast, when ecosystem has strong synergies between components (multiplicative value creation), the misalignment is minimized when the orchestrator has low *ex ante* capabilities. The weakest link value creation features the most variance in ecosystem

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misalignment in an ecosystem. We acknowledge that there are other reasons why ecosystem components may not be integrated in the first place (e.g., differences in capabilities, diseconomies of scale and scope, etc.) but we leave them out of the scope of this study as our goal is not to compare ecosystem vs. integration, but instead compare different flavors of underlying value creation in ecosystems.

[4] In all scenarios value creation is supermodular in the capabilities of the orchestrator and the complementors. Note: a function is supermodular if and only if $x > x'$ and $y > y'$ imply $f(x', y') - f(x', y) \geq f(x, y') - f(x, y)$.

penalty leading to both the best and the worst alignment of incentives. When the orchestrator and the complementor start with a similar level of capabilities, then they will make a higher investment in an ecosystem compared to the integrated benchmark, consistent with the idea of the modular architecture benefits (Baldwin and Clark, 2000). In addition, when the orchestrator's starting capabilities are well below both complementors then the orchestrator makes the same improvement as the integrated actor would have. However, when the orchestrator is the least capable actor in an ecosystem but is close to the inferior complementor, it leads to the worst alignment. We show that while the orchestrator remains the constraint on the total value creation, it will limit its improvement to preserve its position as the weakest actor. This happens because in the latter situation complementors are fully substitutable, which allows the orchestrator to appropriate the most from its improvement; improving beyond will allow the best complementor to have a claim on the returns to such improvement, which will severely dampen the orchestrator's incentives. In configurations like these, an ecosystem may get stuck in a situation where individual incentives to invest may be too low for the ecosystem's member who is constraining the overall value the most, creating a vicious circle of low returns and low investments. Table 1 provides a preview of the main findings.

	Additive Value Creation	Multiplicative Value Creation	Weakest link Value Creation
Ecosystem value creation	Weak synergies, weak form of supermodularity	Strong synergies, strong form of supermodularity	Constrained by weaker component, weak form of supermodularity
Function of participants' capabilities	Total value = Orchestrator + Complementor	Total value = Orchestrator x Complementor	Total value = min{Orchestrator, Complementor}
Best ecosystem alignment	Strong orchestrator, complementors close substitutes	Weak orchestrator, complementors close substitutes	Orchestrator and complementor have similar capabilities (higher than benchmark improvement), or very weak orchestrator (same as benchmark)
Worst ecosystem alignment	Weak orchestrator, and high capability gaps among complementors	Misalignment more acute as orchestrator's and complementor's capabilities increase	Weak orchestrator trying to match inferior complementor (value creation levels out – "value trap")

Table 1: Preview of the main findings

To the extent of our knowledge this paper is the first to provide a model linking total value creation, private value capture and private incentives to improve value creation in a comprehensive unified framework. It is also the first to systematically explore heterogeneity in terms of underlying complementarities and its impact on value creation and value capture in an ecosystem. In doing so we are able to address a gap in the ecosystem literature concerning the understanding of the key contingencies and mechanisms relating fundamental features of an ecosystem – the technology of value creation and competition over value capture – to value creation incentives.[5] The insights from our model contribute to the literature in several ways.

First, our analysis helps establish new mechanisms underpinning ecosystem alignment (Adner, 2017) and ecosystem evolution (Hannah and Eisenhardt, 2018; Jacobides et al., 2018). Our results demonstrate that incentive misalignment is an inherent feature of an ecosystem, driven by the competition over value capture. We are able to identify the economic determinants of incentives misalignment in addition to behavioral explanations in the extant literature. This helps establish the baseline in terms of incentive (mis)alignment that we can expect, and that we can act upon through ecosystem governance tools (Kretschmer et al., 2022).

Second, we offer a workable model for the ecosystem analysis that allows to translate individual capabilities of ecosystem participants into value creation, and then value creation into individual value capture, which, in turn, affects incentives to improve individual capabilities and therefore value creation. This model enables understanding the difference between total value creation – by the whole ecosystem (e.g., Adner and Kapoor, 2010) – and actual value capture by an individual actor. We find that higher total value creation does not necessarily translate into a proportionate increase in an individual value capture, which suggests that current ecosystem research, by not sufficiently elaborating on the determinants of the link between value creation and value capture, may be

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[5] John and Ross (2022) develop a formal model of value creation and value capture to look at the complementors' investment as a function of the orchestrator's bargaining power and whether externalities generated are positive or negative. This is somewhat similar to our scenario of multiplicative value creation. In this paper, while finding similar results in the multiplicative scenario, we examine two other types of complementarities in an ecosystem – additive and weakest link – and show that the degree of incentive misalignment follows very different patterns in those scenarios. Our model also has important differences, such as giving equal billing to the orchestrator and the complementors, competition among complementors, and a four-way bargaining over value capture (among the orchestrator, the superior complementor, the inferior complementor, and the buyer) as opposed to bilateral negotiations between the orchestrator and the complementors in John and Ross (2022). Including these features allows us to have a set of different and nuanced findings.

overestimating the incentives of ecosystem participants to invest in value creation and, for instance, resolve ecosystem bottlenecks (Hannah and Eisenhardt, 2018). In doing so, our analysis shows how the formalism of a mathematical model can be helpful in uncovering the mechanisms driving firms' strategies in a context featuring complex interdependencies (Gans and Ryall, 2017; Makadok, Burton, and Barney, 2018). In particular, it shows how value-based framework (Brandenburger and Stuart, 2007; Gans and Ryall, 2017; MacDonald and Ryall, 2004) can be helpful in disentangling the impact on the total value creation and individual value capture.

Third, our findings provide insights as to which ecosystem configurations are more or less conducive to firms' investment in value creation. This has natural managerial implications, as well as a number of empirically testable propositions linking drivers of alignment to the ecosystem's performance and that of its participants. Furthermore, our results demonstrate that it is crucial to recognize the type of complementarities in order to understand incentive (mis)alignment in an ecosystem. The same configuration of an ecosystem actors with the same capabilities may lead to opposite outcomes in terms of incentives to investment in value creation depending on how these capabilities combine. This has implications for the generalizability of empirical findings and for managerial decisions.

Our paper is organized as follows. Section 2 provides a brief theoretical background for the study. Section 3 describes a formal model of ecosystem value creation and value capture. Building on the model, in Section 4 we compare the ideal level of improvement in value creation and ecosystem participants' actual improvement level across three scenarios of value creation technology. Finally, in Section 5 we discuss the results and conclude.

2 THEORETICAL BACKGROUND

A business ecosystem can be defined as "a set of actors that contribute to the focal offer's user value proposition" (Kapoor, 2018). To successfully compete in such contexts the focal firm needs to "align" complementors – producers of complementary products/services – to ensure the availability and quality of complements for its focal product (Adner, 2012, 2017; Adner and Kapoor, 2010) lest it risks low adoption and performance of the focal product (Adner and Kapoor, 2010, 2016; Hannah and Eisenhardt, 2018; Kapoor and Furr, 2015; Kapoor and Lee, 2013). Firms are generally understood to be motivated to invest to increase the total value creation in the ecosystem because they anticipate to capture some of that value in return (Adner and Kapoor, 2010; Kapoor and Agarwal, 2017). A lack of investment from the complementors is typically attributed to behavioral reasons (Adner, 2012, 2022; Adner and Feiler, 2019), or exogenous technological shocks (Adner and Kapoor, 2010, 2016; Kapoor and Furr, 2015), while the focal firm is assumed to benefit from investing in complements (Hannah and Eisenhardt, 2018).

To the extent of our knowledge, there is scant research on the economic underpinnings of incentive misalignment in an ecosystem. Ethiraj (2007) explicitly takes the issue and examines firms' investments into a component that constrains the performance of an ecosystem and theorizes about the relationship between ecosystem value creation and private returns to investment. Baldwin (2020) analyzes the impact of complementarity between ecosystem participants and incentives to improve value creation through the lens of transaction cost economics and property rights theory. John and Ross (2022) develop a formal model of value creation and value capture to examine complementors' investment under multiplicative value creation, depending on the impact of the bargaining power of the orchestrator firm, and whether externalities are positive or negative.

However, the nuances of competition over value capture as determinants of the firms' incentives to invest are rarely explicitly addressed or examined in detail. In Ethiraj (2007) firms are assumed to benefit from their investments in value creation. Baldwin (2020) does look at the effect of the fear of holdup, however, the effect of competitive asymmetry between ecosystem components – when one ecosystem participant is a monopolist while its complementor has substitutes – is not explicitly considered; as a result firms are assumed to exhibit the same investment behavior regardless of their competitive scarcity. In John and Ross (2022) complementors are not directly competing with each other for the buyer, making orchestrator's bargaining power largely exogenous.[6]

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[6] In addition, our paper models a four-way negotiation over value capture between the orchestrator, the superior complementor, the inferior complementor, and the buyer, in contrast to bilateral negotiations between the orchestrator and the complementors in John and Ross (2022). We show that such a four-way negotiation can be a major source of inefficiencies in the disputes over value capture. This setup is also representative of many real-life ecosystems where complementors directly compete with each other for the buyer who assembles the final bundle of the orchestrator's product and the complementor's product, such as smartphone apps, video games.

Yet there is evidence that firms in a component that is in scarce supply may capture a disproportionate amount of value (Baldwin, 2018; Jacobides, Knudsen, and Augier, 2006; Jacobides and MacDuffie, 2013) and thus may benefit more than others from their investment (Jacobides and Tae, 2015; Miller and Toh, 2022).[7] Thus, while we understand that value creation for the overall ecosystem benefits its participants, we know less about how competition over value capture shapes individual firm's return from investing in value creation, even though we can expect this to be one important driver of their investment incentives.

In addition, there is a lack of an integrated account on how variation in the types of underlying complementarities affects both value creation and value capture. Extant research typically focuses on one type of complementarity at a time: constraint type of complementarities in Ethiraj (2007), multiplicative in John and Ross (2022). While Baldwin (2020) provides a crucial contribution by suggesting contingencies of ecosystem effectiveness depending on the strength of synergies between complements (which may increase or decrease the fear of holdup) we have yet to explore the effect of how the differences in the nature of interdependencies between ecosystem components affect ecosystem participants' added value and thereby expected value capture.

The implication is that we need a comprehensive framework that unifies value creation and value capture as antecedents to the firms' incentives to improve value creation in an ecosystem. The task is complicated as value creation and value capture in an ecosystem are usually tightly linked, and difficult to disentangle from each other. To this end we use the formalism of value-based strategy (Brandenburger and Stuart, 2007; Gans and Ryall, 2017; MacDonald and Ryall, 2004) that allows to account at the same time for how total ecosystem value is furthered and how new value is split among participants. We can thus disentangle what drives value creation for the ecosystem versus what drives individual value capture, and analyze how complementarities underlying value creation matter to this question (see Figure 1).

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[7] The literature on platforms and platform-based ecosystems examines tradeoffs between the value creation by the ecosystem and value capture by individual firms. However, value creation is typically conceptualized as driven by network effects (Mantovani and Ruiz-Aliseda, 2016) and not due to the investment in product's quality (as in the business ecosystems literature). In addition, the focus is usually only on one component of the ecosystem – either how platforms may use their position to extract more value (e.g., Gawer and Henderson, 2007; Wen and Zhu, 2019) or how complementors may try to protect their value capture *vis-à-vis* platform (e.g., Wang and Miller, 2020; Zhu and Liu, 2018) – but not on both.

By relying on a formal model that acknowledges how value capture by one type of actor feeds back on value capture by other types we are able to provide a logically consistent account of how incentives to invest in the ecosystem are shaped by interactions between participants to the ecosystem, giving equal billing to the viewpoint of all actors in an ecosystem (e.g., the orchestrator, the complementors, and the buyers). By modeling three different types of complementarities (weak synergies, strong synergies, and constraints) we are able to understand how the nature of interdependencies between ecosystem participants matters to both value creation and value capture.

3 A FORMAL MODEL OF ECOSYSTEM VALUE CREATION AND VALUE CAPTURE

We build a parsimonious model to study competition over value between, and within, the various components of an ecosystem. Components are the building blocks of the technology that forms the ecosystem (Baldwin, 2020). In our model, one component comprises a single firm, the orchestrator (Furr and Shipilov, 2018; Gawer and Cusumano, 2008), while the other component hosts two rival complementors. A buyer, the final user, combines these components to create value. Firms can invest to improve their capabilities which are then combined to create value according to a specific value-creation technology.

The model follows the structure of a biform game (Brandenburger and Stuart, 2007), with an investment stage, solved non-cooperatively, preceding a value creation and value capture stage, where competition over value is modeled according to a coalitional game. As is standard, the model is solved backward, by first deriving bounds on value capture implied by the core stemming from the player's capabilities and the value creation technology. From this, we derive the evaluation of value capture given the shape of the core following Cappelli and Chatain (2023). We then move to the non-cooperative stage and characterize the equilibrium level of improvement in value-creating capabilities, based on the expected value capture and development cost.

We compare equilibrium development to a benchmark where all ecosystem participants act as if they were a single actor, thereby eliminating competition over value capture between the orchestrator and the complementors. Comparisons to the integrated benchmark allows us to understand the drivers of better and worse incentive alignment in an ecosystem. We apply this to analyze three types of complementarities, or three value creation technologies, i.e., stylized ways in which capabilities in each component combine to create value for the ecosystem: the additive case, the multiplicative case, and the weakest link case. We break down the exposition of the model in three steps: value creation, value capture, and incentives alignment.

3.1 Value creation

Our elemental ecosystem comprises two components. In the first component there is only one firm, the orchestrator (O) of the ecosystem. In the second component, the "complementor" component, firms compete with each other to offer a functionality on top of the orchestrator's product. We include two such complementors, C_L and C_H, with C_H having higher value-creating capabilities than C_L.

The structure of this ecosystem captures the situation whereby one leading entity, the orchestrator, creates and exclusively controls an infrastructure (e.g., an operating system) on top of which other firms can contribute a compatible component (e.g., an app) that serves to increase the value for the final user. The orchestrator, however, is in full control of its component and does not admit competition, while it provides the necessary elements (e.g., an API, a certification, standards) for firms in the second component to provide a complement.[8]

Each firm can produce one unit of a product in its respective component. The final user, buyer B, consumes a bundle consisting of one unit from each component. A unit of any component has

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[8] The choice to model an ecosystem where the buyer "single-homes" (i.e., there is is only one viable orchestrator) is consistent with the prior work on platforms (Armstrong, 2006; Cennamo et al., 2018; Panico and Cennamo, 2022). For instance, Cennamo et al. (2018) posit that "when it comes to choosing among functionally similar platforms, they [consumers] tend to single-home, or largely use one of them as their preferred platform of choice, even when consumers affiliate with multiple platforms". Similarly, Armstrong (2006) argues that it is rare to have both consumers and complementors multi-home, and that at least one group should single-home. In line with this work, we assume that, if there is a competing orchestrator, horizontal differentiation is strong enough to consider the buyer as single-homing. Since the buyer single-homes, we set the complementors' outside option to zero assuming that even if the complementors multi-home and are able to create value with a different orchestrator in a different buyer segment (which prefers an alternative orchestrator to the focal one) they are interested in the focal buyer segment. These assumptions are also consistent with our goal to explore the impact of the underlying complementarities and of the competition over value capture on the ecosystem participants' incentives to invest in value creation. Notably, having competitive asymmetry between components (monopolistic orchestrator and competing complementors) allows us to explore the nuances of the competition over value capture in an ecosystem, while leaving the implications of varying the competition on the orchestrator's side to future research.

no value if it is not combined with a unit of the other component. That is, the complement has no value without the orchestrator's product, and the orchestrator's product without the complement is not valuable either. Moreover, we normalize the value of the alternatives available to the buyer outside of the game (e.g., participating to another, competing, ecosystem) to zero.

Formally, all players belong to the set $N = \{O, C_L, C_H, B\}$. Value creation possibilities are described by a characteristic function $v(S)$ that maps a set of players $S \subseteq N$ into the maximum value these players can create together. A set of players S can only create positive value if it comprises the orchestrator, at least one complementor, and the buyer. This means $v(O, C_L, B) \geq 0$, $v(O, C_H, B) \geq 0$, and $v(O, C_L, C_H, B) \geq 0$ while all other combinations of players have a worth equal to zero. Also, the complementors are substitutes to one another, and since C_H enables higher value creation we have $v(O, C_L, B) \leq v(O, C_H, B)$ and $v(O, C_H, B) = v(O, C_L, C_H, B) = v(N)$.

3.2 Value capture: The core

Following the logic of biform games (Brandenburger and Stuart, 2007), we calculate each actor's value capture under competition by first computing the core of the game. The core finds allocations of value such that no subset of players is better off turning down the allocation. The core of the game is given by the following constraints. Let π_i be the value captured by player i. The first constraint is that the sum of the value captured equals to the total value created: $\sum_{i \in N} \pi_i = v(N)$. The other constraints translate the notion that each subset of players captures at least as much as it can guarantee to itself unilaterally. That is: $\sum_{i \in S \subset N} \pi_i \geq v(S), \forall S \subset N$.

In the ecosystem described above, the core is characterized by the following system of constraints on the value captured by each member:

$$\pi_O + \pi_{C_L} + \pi_{C_H} + \pi_B = v(N), \tag{1}$$

$$\pi_{C_L} = 0, \tag{2}$$

$$0 \leq \pi_{C_H} \leq v(N) - v(O, C_L, B), \tag{3}$$

$$0 \leq \pi_O \leq v(N), \tag{4}$$

$$0 \leq \pi_B \leq v(N). \tag{5}$$

The first constraint means that the value created ($v(N)$) is fully distributed among players. The second means that C_L never captures value because it is not needed to create the maximum value in the ecosystem. As a result, the value created is split between the remaining players who are necessary to value creation: orchestrator O, complementor C_H and buyer B. The third constraint says that C_H cannot capture more than its added value to the ecosystem ($v(N) - v(O, C_L, B)$). This is because C_L serves as an imperfect substitute. The last two constraints mean that the ceiling on value capture for both the orchestrator (O) and the buyer (B) is the total value created ($v(N)$).

The key implication of these constraints taken together is that there is a floor on the value captured together by orchestrator O and buyer B. Indeed, since $\pi_{C_H} \leq v(N) - v(O, C_L, B)$ it follows that an amount equal to $v(O, C_L, B)$ (what would be left if C_H captured its maximum value) must be split between the orchestrator (O) and the buyer (B).[9]

3.3 Expected value capture

In this section we provide an overview of how we compute each actor's expected value capture based on the value capture bounds established in the previous section. To translate the bounds on value capture into a single value that represents the expected value capture by each player we

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[9] The reader may wonder why the weaker complementor C_L would bother to show up in our game if it cannot hope to capture any value. This could easily be explained by extending the model to include different segments of horizontally differentiated buyers so that the relative position of each complementor in each segment be reversed and each be able to capture value under the competitive assumptions of the core. For instance, complementor C_L could be the leading complementor in a second consumer segment while complementor C_H would not have added value within that segment. We leave such extension to future research as we are focusing this paper on exploring the interaction between between- and within-component competition and the technology of value creation in the most parsimonious model.

draw on Cappelli and Chatain's (2023) extension of Brandenburger and Stuart's (2007) celebrated biform games framework. This is motivated by the limitation of Brandenburger and Stuart's (2007) framework for modeling value capture in situations where more than two players are necessary for value capture, such as in business ecosystems. We provide a detailed explanation of the method and why it offers a solution to the issues above in Appendix A.

In Brandenburger and Stuart's (2007) original framework, each player evaluates value capture as a linear combination of the lower and upper bound of their value capture in the core, using a parameter (the confidence index α_i) to weight the respective importance they put on each bound. This evaluation represents preferences over the best and the worst cases but is *not* an expected value calculation even though it is often interpreted as such. In our setting, a limitation arises because the existence of a floor on the value captured collectively by O and B does not translate in these player's evaluation of their prospects, which only depends on their minimum and maximum value capture (0 and $v(N)$ respectively for both). Increased substitution by the weaker complementor (C_L), which makes collectively O and B better off, does not have an effect on these players' evaluation of their prospects in this framework, contrary to intuition.

This is remedied in Cappelli and Chatain's (2023) extension, where each actor computes an expected value capture from the core under the assumption that a point in the core is randomly picked under a uniform distribution. This allows to account for all constraints defining the core (for instance, in this model, these constraints are equivalent to inequalities (1-5). This information is then used to assess the actor's value capture prospects, in addition to the values of the upper and lower bounds of the actor's value capture interval. In this paper, we focus on the expected value capture under the uniform distribution of the possible payoffs in the core, and leave aside the behavioral aspects further explored in Cappelli and Chatain (2023).

Using bounds on value capture stemming from inequalities (1-5) we can characterize the core as a geometric shape whose extreme points correspond to the maximum possible value capture by each actor. Since inferior complementor C_L never captures any positive value, we can represent the core in the 3-dimension simplex. The simplex shows all the ways in which value can be split between the three players O, B, and C_H, holding the sum of their value capture constant and equal to the total value created ($v(N)$). A point in the simplex represents a way to split the full value of the game among the three players (coordinates thus sum to $v(N)$). The closer a point is to a summit of the triangle, the more value is allocated to the player whose summit it is. For instance, the summit labelled "Orchestrator" gives the coordinate $v(N)$ to the orchestrator, and 0 to the other players (i.e., the orchestrator captures all value created). The coordinates of the centroid of the core give the expected value capture of each player under a uniform distribution of allocations in the core.

(Insert Figure 2 about here.)

The shape of the core provides an intuitive understanding of the expected value allocation. For instance, consider the situation where inferior complementor C_L is so weak that it does not help create value (i.e., $v(O, C_L, B) = 0$). This means that there is no floor to the orchestrator's and the buyer's combined value capture. In that situation, the core is the full simplex (see Figure 2a), its centroid is at an equal distance from each summit, and the value $v(N)$ will be in expectation split three-ways between the buyer, the orchestrator, and superior complementor C_H.

Consider instead the situation whereby complementor C_L improves and provides a stronger fallback option for C_H to the orchestrator and the buyer (e.g., $v(O, C_L, B) = \frac{2}{3}v(N)$). The core adopts a trapezoidal shape (Figure 2b) with the possible value allocations "pushed" towards the orchestrator and the buyer as the centroid moves concurrently towards the bottom of the simplex. The higher the value that can be created with inferior complementor C_L ($v(O, C_L, B)$), the flatter the trapezoid, and the more value allocation is favoring the orchestrator and the buyer. If weaker complementor C_L is just as good as superior complementor C_H, then $v(O, C_L, B) = v(N)$, and the core reduces to the base of the triangle in Figure 2c, and value is fully split between the orchestrator and the buyer while complementors capture zero.

Clearly, the orchestrator and the buyer are better off collectively in 2c than in 2a. In the latter case, C_H cannot capture any value, and consequently orchestrator O and buyer B must collectively capture more than in the other cases. The key difference between 2a and 2c is that the shape of the core has changed from a triangle to a line. This geometric interpretation is directly translating a simple intuition about ecosystem strategy: when members of a component are less differentiated, the force of competition makes them unable to capture value versus the other components, which results in more value available to the other components.[10]

Lemma 6 in Appendix A provides formulas for the calculation of expected value capture in the core of the orchestrator, the buyer and the superior complementor (since the inferior complementor captures zero) based on value capture bounds established in inequalities (1-5), with the key inputs being the total value created with a superior complementor $v(N)$ and value created with the inferior complementor $v(O, C_L, B)$.

3.4 Incentives to invest in value creation

Thanks to our formal model of value creation in an ecosystem we have determined the relationship between value creation in the ecosystem, characterized at a general level by $v(N)$ and $v(O, C_L, B)$, and the expected value captured by each player. We can now analyze the levels of improvement to the orchestrator's and complementor's value creating capabilities resulting from simultaneous independent development decisions.

At the end of the non-cooperative stage, each actor $i \in \{O, C_L, C_H\}$ has value creating capabilities V_i. We assume that $V_{C_H} \geq V_{C_L}$ and denote $r_H := V_{C_H} - V_{C_L}$ the advantage of superior complementor C_H over inferior C_L. We consider three different value-creation technologies that convert the capabilities into value creation in the characteristic function of the coalitional game.

1. *Additive value creation*, where the total value created is the sum of the orchestrator's and complementor's individual value creation, i.e. $v(N) := V_O + V_{C_H} = V_O + V_{C_L} + r_H$ and $v(O, C_L, B) := V_O + V_{C_L}$.

2. *Multiplicative value creation*, where the total value creation is the product of the orchestrator's and complementor's individual value creation, i.e. $v(N) := V_O \times V_{C_H} = V_O \times (V_{C_L} + r_H)$ and $v(O, C_L, B) := V_O \times V_{C_L}$.

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[10] In Brandenburger and Stuart's (2007) original framework the evaluation of the value captured by the orchestrator and by the buyer in these three cases (2a, 2b, and 2c) would be the same, with $\pi_O = \alpha_O v(N)$ and $\pi_B = \alpha_B v(N)$. The upper and the lower bounds of the core are identical in all three cases (0 and $v(N)$, respectively), even though we see that the orchestrator and the buyer are collectively better off when competition between complementors is stronger.

3. *Weakest link value creation*, where the total value creation is equal to the value creation of the inferior offering in the bundle, i.e. $v(N) := \min(V_O, V_{C_H}) = \min(V_O, V_{C_L} + r_H)$ and $v(O, C_L, B) := \min(V_O, V_{C_L})$.

Now that we can map capabilities (V_O, V_{C_H}, V_{C_L}) and value creation technology into the characteristic function v, we can use Lemma 6 in Appendix A to convert these capabilities into amount of value captured in the coalitional game. Use $p_i(V_O, V_{C_H}, V_{C_L})$ to denote the value captured by player i ($i \in \{B, O, C_H, C_L\}$) in the coalitional game. The context will usually be enough to specify the value creation technology.

Capabilities are the outcome of a simultaneous development game in which each firm, starting from a given level of capability $s_i \geq 0$, has the opportunity to develop further its capability by $x_i \geq 0$, at cost $c(x_i) = \frac{1}{2}x_i^2$. After development, the final capability is $V_i := s_i + x_i$. In the Nash equilibrium, each firm is maximizing its profit taking as given the development decision of the other firms. Abusing notation slightly and denoting by $-i$ the firms other than i, firm i sets x_i to maximize:

$$\Pi_i = p_i(x_i, x_{-i}) - c(x_i). \tag{6}$$

Implicit in this formula are the starting level of capabilities s_i, which are not strategic variables. In case of multiple equilibria, we always focus on the equilibrium, which always exists, in which the complementor with an initial advantage before development (C_H) develops at least as much as the complementor who is initially disadvantaged (C_L), and, if there are many such equilibria, on the one that exhibits the highest level of development. The proof is in the Appendix B.

We can compare the equilibrium development levels to the benchmark of the development decision taken by a unitary integrated actor where the orchestrator and the complementors act as a single unit I, combining O, C_L, and C_H as a unitary actor, who creates and splits value with buyer B. In our analyses, we normalize integration costs, or benefits, to zero, in order to concentrate on the exploration of the joint effect of competition over value on development decisions. Obviously, the very existence of ecosystems as a form of market organization implies that for those that we observe the costs of integration must be superior to its benefits (e.g., see Baldwin 2020). We thus use costless integration as an analytical benchmark allowing consistent comparison between different scenarios of value creation, and do not claim that integration is costless in general.

It can be shown that the integrated actor never has an interest in investing in the less advantaged complementor's capability since it provides no benefit. Moreover, the integrated actor is in a bilateral negotiation with the buyer and gets half of the total value. Thus, in the integrated benchmark, x_O and x_{C_H} are set to maximize:

$$\Pi_I(x_O, x_{C_H}) = \frac{1}{2}v(N) - c(x_O) - c(x_{C_H}), \tag{7}$$

where $v(N)$ is the total value in the game, which depends on initial starting capabilities and investment in O's and C_H's capabilities.

Comparison between equilibrium development levels by the integrated benchmark and by the individual actors in an ecosystem allows us to determine whether and when organizing as an ecosystem creates misalignments in investment incentives independently from integration costs. In particular, we can investigate whether competition over value capture in an ecosystem leads its participants to improve their capabilities below or above the level that would maximize the total value creation by the ecosystem, and explore the role of the value creation technology (additive, multiplicative, weakest link).

4 VALUE CREATION TECHNOLOGY AND RETURNS TO INVESTMENT: MAIN ANALYSES AND RESULTS

In this section, we compare the equilibrium efforts of the orchestrator and the complementor to improve their respective capabilities to the idealized full alignment benchmark, represented by an integrated actor. We find that there is often a divergence versus the full alignment benchmark, and that the degree and the patterns of incentive misalignment vary across value creation scenarios in non-obvious manners. We start with the additive value creation scenario, which features weak synergies between ecosystem components. We then show the results of multiplicative value creation scenario, featuring strong synergies between ecosystem components, and we conclude with the weakest link value creation scenario. All proofs and details of the analysis are in the Appendix B.

4.1 Additive value creation technology: weak synergies between components

We start with examining the additive value creation technology, a case where both components are necessary to create value, and yet synergies between them are weak. In this case the value created by the bundle is the sum of the orchestrator's and the superior complementor's individual value creation. Formally, the value created with an inferior complementor is equal to $v(O, C_L, B) = V_O + V_{C_L}$, and the value created with the superior complementor is $v(N) = v(O, C_H, B) = V_O + V_{C_L} + r_H$. Note that since $v(O) = v(C_L) = v(C_H) = 0$, the additive case is an edge case of supermodularity (see Baldwin, 2020). This type of interdependencies is sometimes referred to as "unique complementarities" (Jacobides et al., 2018).

This scenario is relevant to the study of ecosystems because it is often the case that components are all necessary for value creation, but that besides this, there is no connection between their respective marginal improvements. For instance, in the case of photovoltaic panel installation, both the installation and the financing are parts of the solar energy ecosystem (Hannah and Eisenhardt, 2018). However, once both components are functional, it is hard to see that improvements in one at the margin would lead to superior contribution of the other. This highlights the necessity to disentangle reasoning at the margin of component improvement versus reasoning about whether a component needs to be present. For instance, more convenient financing would increase value for the final customer, but has no bearing on making panel installation higher quality. Similarly a higher quality installation will please the customer, but does not make more convenient financing more valuable in itself. Other examples include simple apps on a smartphone (e.g., messenger apps) that do not depend on advanced hardware features, or content on a streaming platform that does not require special capabilities to be consumed.[11]

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[11] Note that while the total value creation is additive, value capture features complementarity because a single actor cannot create value on its own. As Baldwin (2020) explains, such value creation is an edge case of supermodularity. Formally, following Baldwin (2020), let us have x and y denoting individual performances of the orchestrator and the complementor, and $x = x' > 0$ ($y = y' > 0$) when the orchestrator (complementor) is present, and $x = 0$ ($y = 0$) when it is not. Then, under weak synergies we have $f(0, y') = f(0, 0) = 0$ because the orchestrator is one-in-kind,

Comparing the equilibrium improvement in the orchestrator's and complementor's capabilities to the full alignment benchmark of the integrated actor in the equilibrium we find the following:

Proposition 1 *Under additive value creation, ecosystem participants' investment in value-creating capabilities is equal or below those of the integrated actor benchmark, creating an 'ecosystem penalty'. This ecosystem penalty is less severe when orchestrator's ex ante capabilities are high, and when complementors are close substitutes.*

The intuition for this result can be traced to differences in marginal returns from improving capabilities between the integrated benchmark and the ecosystem. When the integrated benchmark increases the total pie ($v(N)$), it gets $\frac{1}{2}$ of the value in return (see equation 7 and the dashed line in Figures 3a and 3b). However, in an ecosystem, we find that the orchestrator and the complementor always get less than half of their contribution to the increase of the total pie. Each of them develops their capability less than what the integrated benchmark would have done and the resulting value creation in the ecosystem is lower. We call this situation an "ecosystem penalty", in which jockeying about value capture in an ecosystem results in a smaller total pie for the ecosystem compared to the ideal benchmark of costless integration and coordination.[12]

(Insert Figure 3 about here.)

When is this penalty least? Intuition suggests that this will be the case when the difference in marginal returns to development between the ecosystem and the integrated benchmark is lower. Our results show that this depends on the *ex ante* level of capabilities of the orchestrator and the complementors. Looking at the orchestrator's *ex ante* capabilities, we find that the orchestrator makes higher improvement when these capabilities are high (see Figure 3a). The intuition is as follows: because

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$f(x',y') > 0$, and $f(x',0) > 0$ because if the superior complementor is absent then there is a substitute in the form of the inferior complementor, and $f(x',y') - f(x',0) > 0$ since higher value is created when the superior complementor is present. Then we have $f(x',y') - f(x',0) \geq f(0,y') - f(0,0)$, satisfying the definition of supermodularity.

[12] Note that we use the benchmark of the costless integration as an idealistic representation of a fully aligned ecosystem to explore the existence and the degree of potential incentives misalignment within an ecosystem. We do not make claims as to the actual choice of the ecosystem as a governance mode. Our focus in this paper is to explore the economic fundamentals behind incentive misalignment in an ecosystem, while we leave comparison of different governance modes (such as markets, hierarchy and ecosystems) to future research.

the superior complementor has an imperfect substitute, higher *ex ante* value-creating capabilities of the orchestrator mean that the latter has a better ability to fall back on the inferior complementor, and thus have a higher guaranteed value capture. The orchestrator is thus more willing to exert higher effort to improve its capabilities because it knows it can appropriate most of it.

For the superior complementor C_H, the investment is least penalized when it is neck and neck with its competitor, i.e., when the starting superior complementor's advantage over the inferior one is low (see Figure 3b). The explanation for this result is as follows. Suppose both complementor's starting capabilities are identical, and that one complementor start developing its capability above zero. This results in a small relative increment of the total pie and of the range of value the other players (orchestrator and buyer) can capture, but a very large relative increment of the value capture possibilities for the complementor, which were initially nil. Geometrically, this means the core of the game morphs from a line (see Figure 2c) into a trapezoid shape (see Figure 2b). In this case a point taken randomly will in expectation allocate nearly half of the increment to the complementor, resulting in a large marginal return, while the rest will be split equally between the two other players (see Figure 2b for an illustration: the centroid is almost half way between the lower and upper bounds of complementor value capture). However, when the starting advantage over the inferior complementor is already large (i.e., the core is already a trapezoid), then any incremental increase will have to be split three-way between the orchestrator, the superior complementor, and the buyer, and the complementor faces diminishing returns to its investment.

In other words, when complementors are nearly perfect substitutes, the orchestrator can easily play them against each other, which helps it capture the bulk of the value. However, at the margin, it is the better complementor who enjoys the largest returns. When the superior complementor is already much better than its alternative it is less incentivized to improve its capabilities because it has to share any marginal gains from the improvement with the orchestrator who is one-in-kind, and the buyer. While being close to the weaker complementor is detrimental to the value C_H can capture in absolute terms, it turns out to be helpful for value capture at the margin of capability development. This illustrates well that the discrepancy between marginal and absolute value capture is crucial to understand since investment levels are driven by the former, not the latter.

What is the effect of each actor's capabilities on the other actor's investment? From the orchestrator's perspective, complementors being close substitutes means higher value capture as it can play them against each other and is thus willing to make a higher improvement in its capabilities. Figure 3a shows that the orchestrator's equilibrium effort curve is closer to the integrated benchmark when the superior complementor's advantage (r_H) is lower. For the complementor C_H, higher orchestrator's capabilities mean that the latter is the major source of value creation in an ecosystem, making C_H advantage over its inferior substitute smaller in relative terms and thus limiting C_H claim to value capture. This incentivizes C_H to improve its own value-creating capabilities to be able to claim more value. Figure 3b shows that the curve of the complementor's effort is closer to the integrated benchmark when the initial level of the orchestrator's capabilities (s_O) is higher.

These results offer a few immediate implications for the ecosystem literature. First, we show that incentive misalignment is a fundamental feature of an ecosystem, driven by the need to split value created among several actors. At the same time, our results suggest that this misalignment can be mitigated under certain conditions. Notably, the ecosystem penalty is least when there is neck-to-neck competition among complementors while the orchestrator has strong capabilities *ex ante*. This resembles the situation found in many app stores in mature app categories, such as email clients, that provide improvement over basic functionalities. Software complementors are plentiful, with relatively low differentiation, few new features, and none that require specific performance improvement or integration with hardware and operating system.

Our results also suggest that we may need to be cautious when expecting a co-creation of value in an ecosystem. While conventional wisdom suggests that an ecosystem should attract high-performing complementors (e.g., "killer apps") we find that unless there are good substitutes for such complementors this could worsen incentive misalignment, especially in the situations when continuous improvement in value creation is important (e.g., frequent updates). This underscores the importance of explicitly accounting for competition over value capture when considering whether the ecosystem will sufficiently invest to grow value creation.

4.2 Multiplicative value creation: strong synergies between components

We now examine the scenario where the total value creation by the ecosystem is the product of the orchestrator's and the complementor's individual value creation, which is a classic case of supermodularity (Topkis, 1998). Under this scenario the value created with an inferior complementor equals $v(O, C_L, B) = V_O \times V_{C_L}$ and the value created with a superior complementor is $v(N) = v(O, C_H, B) = V_O \times (V_{C_L} + r_H)$. This is the case when there are strong synergies between ecosystem components, and an improvement in one component boosts the performance of the other component. For an illustration consider modern-day computer operating system and microprocessors: a more powerful microprocessor makes performance improvements in an operating system more valuable, and a better-performing operating system makes an improvement in a microprocessor more desirable. Comparing the expected improvement by the orchestrator and the superior complementor of their respective capabilities to the full alignment benchmark of an integrated actor we have the following proposition:

Proposition 2 *Under multiplicative value creation, ecosystem participants' investment in value-creating capabilities is equal or below those of the integrated actor benchmark, creating an "ecosystem penalty". This ecosystem penalty is less severe when the orchestrator's ex ante capabilities are low, and when complementors are close substitutes.*

Similarly to the additive case, we find that the private returns in an ecosystem are typically below those of the integrated benchmark due to the competition over value capture. We also find that, as in the additive scenario, the alignment is worse when the superior complementor's *ex ante* advantage over its inferior substitute is larger. However, in contrast to the additive scenario, we find that incentive misalignment for the orchestrator can be mitigated when the orchestrator's *ex ante* capabilities are low (as opposed to high in the additive scenario). Why do we observe an opposite result? The orchestrator is still able to capture a higher share of value thanks to the existence of the inferior complementor, however, because value creation is multiplicative, rather than additive, any improvement in the orchestrator's value-creating capabilities creates positive externalities (John and Ross, 2022) that have to be split. An integrated actor only needs to split these externalities with the buyer, and will thus get half of them. In an ecosystem the externalities have to be split three-way, and the higher the *ex ante* capabilities of the actors, the higher the externalities created by the improvement, and the larger the divergence in value captured by an ecosystem participant from that by the integrated actor.

While higher *ex ante* capabilities of both the orchestrator and the complementor lead to higher value capture by the ecosystem participants, they lead to an even higher value capture by an integrated actor, who gets to keep half of the positive externalities, creating a larger gap between the equilibrium efforts. Thus, the penalty is reduced when these positive externalities are low, which happens when the *ex ante* capabilities of ecosystem participants are low.[13] We see in Figure 4a that the wedge between the effort by the integrated benchmark (dashed lines) and the orchestrator's equilibrium effort in an ecosystem (solid lines) increases with the orchestrator's *ex ante* capabilities. We also see that the wedge is higher when the complementor's *ex ante* advantage r_H is higher (grey lines) versus when it is lower (black lines). Figure 4b exhibits a similar dynamic for the gap for the superior complementor's equilibrium effort relative to its *ex ante* advantage over the inferior complementor, and shows that the gap is larger when the orchestrator's *ex ante* capabilities are high (grey lines) compared to when they are low (black lines).

(Insert Figure 4 about here.)

Comparing the additive and the multiplicative cases is instructive regarding the interplay of the strength of complementarities and the appropriateness of an ecosystem organization. While they are at both ends of the synergistic spectrum in terms of value creation, we find that they present similar challenges in terms of misalignment of investment incentives. This misalignment stems from the fact that there is no guarantee that the marginal returns to improving capabilities accrued by ecosystem members are aligned with what the ecosystem as a whole would necessitate. More interestingly, the challenge seems the most manageable with *additive* value creation.

This creates a paradox. Ecosystems are theoretically identified with the idea of strong complementarities (e.g., supermodularity as a defining feature of ecosystems as in Jacobides et al. (2018)).

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[13] Note that while the results in terms of the complementor's equilibrium effort are similar to those in Proposition 1, the mechanism behind is different.

Yet we have found so far that an ecosystem, on its own terms, features a better incentives alignment when complementarities are least. These results are consistent with findings in John and Ross (2022) that under positive externalities complementors will invest less than what would maximize value creation for the ecosystem as a whole, and with Baldwin's (2020) insight that in the presence of strong complementarities it might be better to internalize complements due to a classical TCE holdup problem because of co-specialization. Our results suggest that even in the absence of the moral hazard risk, the competition over value capture can severely dampen the incentives to invest in value creation. We also offer contingencies of such misalignment, for instance, when capabilities of the ecosystem participants are already high the misalignment is even more severe.

Our results might also explain why in contexts featuring high complementarities we often observe a shift towards integration, rather than staying in an ecosystem. For instance, Apple switched to developing its own ARM microprocessor rather than continuing to rely on Intel when the latter could not proffer the desirable performance and the integration with Apple's operating system.

4.3 Weakest link value creation: constraints between components

Finally, we turn our attention to the scenario where the total value creation by the ecosystem is constrained by its least performing part.[14] Formally, in the weakest link scenario value created with the inferior complementor is equal to $v(O, C_L, B) = \min(V_O, V_{C_L})$, and value creation with the superior complementor is $v(O, C_H, B) = \min(V_O, V_{C_L} + r_H)$.

This scenario has been featured in one of the most influential early studies of investment in ecosystems (Ethiraj, 2007), set in the computer industry. This is also a scenario common in wearable technology sector, such as smartwatch, where the performance of the operating system is constrained by the characteristics of a device, such as battery life. Similarly, augmented reality or motion capture video games often exhibit this type of complementarity. For instance, performance of video games on the first generation of iPad was severely capped by a weak motion detection technology, and only after the release of the next generation (iPad 2) with a much improved technology, iPad video games

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[14] As in a Leontief production function: $f(x, y) = \min(x, y)$. This function is supermodular (Vives, 2007), representing another edge case of supermodularity (the proof is in the Appendix B).

started to be considered competitive to those on the consoles.

This scenario is the most complex because the existence of the ecosystem penalty depends not only on the *ex ante* level of each ecosystem participant, but also on their positions relative to each other. We first look at the case when the orchestrator and the superior complementor have a similar starting level of capabilities.

Proposition 3 *Under the weakest link value creation technology, when the orchestrator and the superior complementor have similar* ex ante *capabilities, the improvement in their respective capabilities will be above the integrated actor benchmark.*

In contrast to the additive and the multiplicative scenarios, we find that in the weakest link scenario there are configurations of capabilities when an ecosystem features a higher improvement compared to the integrated benchmark. This happens because, unlike in the previous scenarios, where each component could be improved on its own, here there is no point in improving a component beyond the level of the other component (since the total value creation is restricted to that of the weakest component). Therefore, in this scenario, the actors need to match each other's capabilities level. In the integrated benchmark, when the orchestrator and the superior complementor components have the same starting level of capabilities, this means that to improve total value creation by X, the integrated benchmark needs to invest twice that amount, once for each component, while the return it gets is half of the total improvement. As a result, it is as if the integrated benchmark had to develop only one capability, but with a quarter (half of the half) of the value captured. By contrast, in an ecosystem each actor takes as given the development of the other actor, and since there are now three actors vying for value (orchestrator, superior complementor, and buyer), their returns to development are always more than a quarter of the total value created. This is why when the orchestrator and the superior complementor have a similar level of *ex ante* capabilities, in an ecosystem they will be able to make a higher improvement compared to the integrated benchmark.[15]

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[15] We assume that the actor in one component can anticipate the improvement in the other component, and match it. This assumption seems plausible in contexts featuring the weakest link value creation technology, such as tech industries, where firms typically telegraph the changes in their components to complementors (for instance, think of Apple or game console owners communicating technical updates to app or game developers).

What happens when the *ex ante* capabilities of the orchestrator and the complementor are different? We find that the equilibrium level of improvement depends on the relative order of the *ex ante* capabilities of all actors, displaying a complex, and sometimes discontinuous, pattern, featuring both the best and the worst cases of incentive alignment. Let us first look at situation where the orchestrator is the weakest link, and at the equilibrium effort in the orchestrator's component:

Proposition 4 *Under the weakest link value creation technology, when the orchestrator and the superior complementor have different* ex ante *capabilities, and the orchestrator constrains value creation, the ecosystem penalty depends on the relative order of the orchestrator's and complementors' capabilities:*

1. **[No penalty at lower levels of orchestrator's *ex ante capabilities*]** *When the orchestrator's* ex ante *capabilities are low and remain strictly below both complementors' levels after development, the orchestrator's incentives are perfectly aligned with those of the integrated actor benchmark. There is no penalty.*
2. **[Largest penalty at intermediate level ("value trap")]** *When the orchestrator's* ex ante *capabilities constrain both complementors, but are in an intermediate range, then the orchestrator will set its development level below that of the integrated benchmark to avoid exceeding the inferior complementor's capabilities. The equilibrium development level decreases with the orchestrator's capabilities, resulting in the total value creation plateauing, and creating the largest ecosystem penalty.*
3. **[Intermediary penalty at higher levels]** *When the orchestrator's* ex ante *capability constrains only the superior complementor, but not the inferior complementor, then the former sets the development level below that of an integrated actor. The development level increases with the* ex ante *orchestrator's capabilities until the orchestrator matches those of the superior complementor.*

Figure 5 provides the illustration for Proposition 4.[16] The dashed lines show the equilibrium efforts by the integrated actors while the solid lines show the effort in an ecosystem. To provide a comprehensive picture, the black lines show the effort in the orchestrator's component while the grey lines show the effort in the complementor's component. We observe a symmetric pattern for an integrated actor: when the orchestrator's component is lagging behind, it invests $x_O = \frac{1}{2}$, until it starts being close to the complementors component, at which point an integrated actor will invest in both components to have matching capabilities (the X-shaped pattern in the middle of Figure 5). Finally, once the orchestrator's component reaches a high level, it is the complementor's component that becomes the weakest link and an integrated actor will redirect all investment there.

(Insert Figure 5 about here.)

(Insert Figure 6 about here.)

In an ecosystem, when the orchestrator's *ex ante* capabilities are very low, and the post-improvement capabilities' level stays below that of both complementors, then it makes the same improvement in the equilibrium as the integrated actor (Figure 5, between points $s_O = 0$ and (a)). Due to the weakest link technology, in this case complementors are perfect substitutes: if $V_O < V_{C_L} < V_{C_H}$, then $\min(V_O, V_{C_L}) = \min(V_O, V_{C_H}) = V_O$. For an example, think of a situation when a poor motion detection technology renders differences between video games moot. The orchestrator can thus deny both complementors the ability to capture value, which leaves the orchestrator only having to split the value with the buyer, as in the integrated benchmark situation. As a result, there is no incentive misalignment for the orchestrator as it is able to appropriate the returns from improving its capabilities in the same way as the integrated benchmark.

However, as the orchestrator's *ex ante* capabilities become higher (but still constraining both complementors) it starts reducing its improvement (Figure 5, between points (a) and (b)). To un-

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[16] Due to the nature of the weakest link value creation scenario, involving matching investments between components and discontinuous transitions between different levels of returns to investment, a convenient and unified closed-form solution cannot be obtained. Instead, we use the derived value capture functions and cost functions described above (for a detailed description and mathematical formulas see Appendix B), to numerically solve the development game in an ecosystem and in the integrated benchmark. The overall dynamic holds irrespective of which specific values are selected: while the exact amount of investment is determined by the selected values of the actor's *ex ante* capabilities, the breaking points and the curves come from value capture functions, as explained in the Appendix B.

derstand the mechanism behind this we need to closely examine marginal returns of the orchestrator illustrated in Figure 7, where we set $x_O = 0$ and $x_H = 0$. When the orchestrator's *overall* capabilities level V_O surpasses that of the inferior complementor (V_{C_L}), but is still below that of the superior complementor V_{C_H} we observe a discontinuous drop in the orchestrator's marginal returns. This happens because now the superior complementor has a claim on the value created by the orchestrator by deconstraining the orchestrator. Formally, if $V_{C_L} < V_O < V_{C_H}$ then without the superior complementor we have the total value creation equal to $\min(V_O, V_{C_L}) = V_{C_L}$, and with the superior complementor the total value creation is $\min(V_O, V_{C_H}) = V_O > V_{C_L}$. Without the superior complementor, one would have to fall back on the inferior complementor and reduce value creation further, which allows the former to appropriate some of the value creation by the orchestrator. This results in a somewhat unique configuration when, while the improvement in value creation has to come from the orchestrator, the superior complementor can claim a large portion of it. At the point where orchestrator's total capabilities are just above those of the inferior complementor the superior complementor can claim up to a half of the value created by the orchestrator, which is illustrated in Figure 7 by a discontinuous drop in the orchestrator's marginal returns from $\frac{1}{2}$ to $\frac{1}{4}$.[17]

(Insert Figure 7 about here.)

Anticipating this, the orchestrator starts reducing its effort to avoid overshooting the inferior complementor's capabilities and ending up in the situation where its returns drop. For example, in Figure 5, where the inferior complementor's capabilities are set at $s_{C_L} = 1$, once the orchestrator's *ex ante* capabilities are equal to $\frac{1}{2}$ (point (a)), then it sets the improvement level below the integrated benchmark of $\frac{1}{2}$. As the orchestrator's *ex ante* capabilities increase the equilibrium improvement level is decreased so that its *ex post* capabilities match those of the inferior complementor, lest the orchestrator's returns drop to one fourth instead of one half of the value created (see the downward slope between points (a) and (b) in Figure 5).

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[17] Geometrically, at the point where V_O is just above V_{C_L} the core of the game transforms from a line (when the value is split between the orchestrator and the buyer) to a trapezoid (the value is split three-way). As we noted in Section 4.1, in this case the expected value capture by the complementor will be half of the incremental value created, while the rest will be split equally between the orchestrator and the buyer.

As a result, the overall level of the orchestrator's capabilities, and therefore the total value creation by the ecosystem, plateaus. Figure 6, which maps the total value creation by the integrated actor and by an ecosystem as a function of the orchestrator's *ex ante* capabilities, provides an additional illustration. The flat line between points (a) and (b) in Figure 6 illustrates the plateauing value creation in an ecosystem, and we can see how it creates the highest divergence from the integrated benchmark, where value creation continues to increase.

We dub this situation a "value trap": the orchestrator is behind and constraining the system, yet is not willing to invest more because it wants to keep complementors fully substitutable and its marginal returns high. This results in a lack of innovation for the whole system due to disputes and uncertainty about value capture. For instance, continuing with the example of game consoles, this will correspond to the situation when console producer is reluctant to further improve its motion detection technology – even though console quality is still wanting – because a large share of this improvement will only serve to augment value capture by the producers of higher-quality games.

However, at some point, the orchestrator cannot reduce its improvement effort further as even with the drop in the returns it will still be better off improving value creation. Once we are past the discontinuous drop the orchestrator's marginal returns are increasing in its *ex ante* capabilities thanks to higher value creation (see the upward slope in Figure 7). Thus the orchestrator starts increasing its improvement effort, though it is still below that of the integrated actor because it has to share value with the superior complementor (Figure 5, between points (b) and (c)). Once the orchestrator's *ex post* overall capabilities come close to those of the superior complementor (point (c)), the orchestrator starts scaling down its improvement to match the complementor's level until the latter becomes the weakest link, at which point the orchestrator sets its improvement level to 0 (point (d)).

Note that, consistent with Proposition 3, when the *ex ante* capabilities of the orchestrator and the superior complementor are very similar (around point (c)), the equilibrium improvement level set in an ecosystem by both actors (solid lines) is higher than that by an integrated actor (dashed lines), and leads to a higher total value creation (see Figure 6).

Finally, we look at the situation when complementor is the weakest link:

Proposition 5 *Under the weakest link value creation technology, when the orchestrator and the superior complementor have different* ex ante *capabilities and the superior complementor constrains value creation, the level of improvement is below that of an integrated actor benchmark. The ecosystem penalty is lower when complementors are close substitutes.*

We find a pattern similar to the additive and multiplicative scenarios. As long as the superior complementor is the weakest link and its starting level of capabilities is sufficiently below that of the orchestrator, it will set its equilibrium effort below that of the integrated benchmark, and the best alignment occurs when the two complementors are close substitutes. The intuition is the same as in the additive case: when we start from the situation where complementors are very similar, the superior complementor gains a lot by improving its advantage as it allows it to transform the situation from that of nearly perfect substitutes (close to 0 value capture) to that of imperfect substitutes (positive value capture). When we start from the situation where the superior complementor is way ahead of the inferior complementor, any improvement will have to be shared with the orchestrator who is unique.

Figure 8 shows the complementor's equilibrium effort (black lines) as a function of its advantage over the inferior complementor; to provide the full picture the grey lines show the equilibrium effort in the orchestrator's component. The downward slope of the complementor's effort (between points $r_H = 0$ and (a) in Figure 8 reflects the diminishing returns that the complementor faces.[18] Once the superior complementor's level starts getting close to that of the orchestrator we see the orchestrator starting to make a matching improvement, while the complementor decreases its effort (Figure 8, between points (a) and (b)). Finally, when the complementor's level is high enough so that it no longer constrains the total value creation, it sets its improvement to zero, whereas now the orchestrator is the weakest link. Note that when the orchestrator's and the superior complementor's

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[18] An astute reader may note that while the marginal returns of the superior complementor are expected to be close to that of an integrated actor when $r_H = 0$ it is still below that of an integrated actor in Figure 8. This happens because at equilibrium the effort depends on the starting levels of all players. For instance, higher *ex ante* level of the orchestrator will result in closer alignment at $r_H = 0$ and worse alignment as r_H increases. At extreme values of s_O we will have the complementor's effort going from $\frac{1}{2}$ to $\frac{1}{3}$.

starting capabilities are close (around point (a)), the equilibrium effort in an ecosystem will be above that by the integrated actor, consistent with Proposition 3.

(Insert Figure 8 about here.)

To summarize, when the total value creation in an ecosystem is constrained by its least performing part we observe a complex pattern of incentive alignment and misalignment. On the one hand, when the ecosystem participants have a similar starting level of capabilities, having an ecosystem will lead to a higher value creation than if the ecosystem parts have been integrated, which is in line with the benefits of modular architecture (Baldwin, 2020; Baldwin and Clark, 2000). We also find that when the orchestrator is far behind both complementors, the improvement level will be similar to that of an integrated actor since both complementors will have zero added value allowing the orchestrator to capture most of value. On the other hand, the weakest link scenario features the worst incentive misalignment when the orchestrator starts reducing its effort to continue being behind both complementors because otherwise it will have to give up a large share of the value created to the superior complementor. As a result, the total value creation by the ecosystem stagnates.

These results illustrate, once again, the importance of the underlying complementarities among ecosystem participants for understanding investment incentive alignment. For instance, in the additive value creation scenario, the best alignment is achieved when the orchestrator is strong *ex ante*, whereas under the weakest link scenario it happens when the orchestrator is the weakest actor. Furthermore, our analysis shows that when an ecosystem exhibits a weakest link of complementarities it may sometimes get locked in a situation of a lack of innovation for the whole system due to disputes and uncertainty about value capture (“value trap”), which might be detrimental to the survival of the ecosystem as a whole.

5 DISCUSSION AND CONCLUSION

In this paper, we explore the economic fundamentals of the incentive misalignment in an ecosystem by using a formal model to examine firms’ improvement in value-creating capabilities and how they are shaped by the type of value creation technology and competition over value capture. We find that in most cases there is an ecosystem penalty in terms of the overall value creation that is driven by within-ecosystem competition over value capture. While we acknowledge that there are good reasons why ecosystem parts may not be integrated in the first place (e.g., differences in capabilities, diseconomies of scale and scope, etc.), our analysis shows nevertheless that incentives are often misaligned due to rivalry over value capture. We further show that the existence and the degree of such misalignment is shaped by the type of underlying complementarities (i.e., the value creation technology) and by the *ex ante* quality of ecosystem participants' value creation capabilities, allowing us to identify conditions for the best and the worst incentive alignment in an ecosystem. Table 1 in the Introduction summarizes these results. Our findings offer several contributions to the literature on ecosystems and complements.

Contributions to theory First, our analysis uncovers fundamental economic forces underpinning ecosystem alignment, which is considered crucial to unlock value creation (Adner, 2012, 2017; Baldwin, 2020; Hannah and Eisenhardt, 2018; Ozcan and Hannah, 2020). Extant literature conceives of incentives misalignment as a result of behavioral factors (Adner 2012; Adner and Feiler 2019), disputes over leadership (Adner 2022), moral hazard (Baldwin, 2020) and proposes ecosystem governance tools, such as norms, coordination, social capital (Kretschmer et al., 2022) as solutions. Our analysis suggests that incentive misalignment in ecosystems is "a feature, not a bug" as it is driven by competition over value capture. Understanding the economic fundamentals of incentive (mis)alignment is crucial as it allows to establish a baseline against which to measure the degree of misalignment. This, in turn, helps us to understand how other factors, behavioral and institutional, may contribute to this misalignment. Furthermore, it helps us understand when mitigating this misalignment, for instance, through the tools discussed in ecosystem governance literature (norms, coordination, social capital, etc.), is most urgent.

Second, our findings suggest that, counterintuitively, tighter complementarities – which are often synonymous with the definition of ecosystems (Baldwin, 2018; Jacobides et al., 2018) – may, in fact, entail high misalignment. In the scenario with strong synergies we found that the stronger ecosystem participants are, the larger is the deviation of the value creation improvement from the first best, driven by the increasing amount of positive externalities that have to be split among ecosystem participants. In the other scenario featuring tight complementarities – the weakest link – we found that total value creation may stagnate because the orchestrator wants to maintain its value capture. These findings highlight the dark side of the very nature of the ecosystem, and call for caution when considering the ecosystem's generative abilities, as ignoring competition over value capture in ecosystems may lead to severely overestimating firms' incentives to invest in value creation.

Third, to our knowledge, this paper is the first to unpack how different types of such non-generic complementarities affect value capture of ecosystem participants, and therefore their incentives to improve the ecosystem's value creation. Our analysis shows that ignoring the type of value creation technology may lead to erroneous estimates not only of firm's incentives, but also of the dynamic of these incentives. For instance, in an ecosystem featuring weak synergies the best alignment is achieved when the orchestrator is strong, while in a weakest link scenario a perfect alignment is achieved with a weak orchestrator. This calls for caution when generalizing context-specific empirical results.

Finally, our analysis provides a nuanced view on the incentives to invest into the resolution of ecosystem bottlenecks (Ethiraj, 2007; Hannah and Eisenhardt, 2018; Kapoor, 2018). Our findings suggest that sometimes, the actor who is best poised to resolve a bottleneck may still be poorly incentivized as demonstrated by the "value trap" in the weakest link value creation scenario. It also suggests that being in a position of competitive scarcity or having bargaining power (Jacobides and Tae, 2015; John and Ross, 2022) does not always guarantee high returns on the investment in value creation: in the aforementioned scenario the "value trap" happens not because complementors are squeezed by the monopolistic orchestrator, but because the underlying complementarity between components forces the orchestrator to share with a superior complementor.

Methodological contributions. In this paper we provide a parsimonious and workable formal model that can be enriched to tackle new issues. The formalism of the value-based framework (Brandenburger and Stuart, 2007; Cappelli and Chatain, 2023; Gans and Ryall, 2017; MacDonald and Ryall, 2004; Ross, 2018) allows us to rigorously map value creation by all ecosystem participants into their individual value capture, and to trace how the nature of interdependencies between ecosystem components affects both. The model can be easily adapted for further research questions pertaining to value creation and value capture in ecosystems. For instance, it could be used to explore other configurations of an ecosystem in terms of competition or value creation technology, such as competition between ecosystems, multi-homing, etc.

Relatedly, our paper makes two further methodological contributions to the study of ecosystems. First, our analysis puts the *marginal* returns to value creation front and center. These marginal returns are driving investment incentives and *ipso facto* the trajectory of value creation in the ecosystem. Yet studies of ecosystems are rarely distinguishing total returns from marginal returns when theorizing about value creation. Second, our analysis sets out a clear analytical benchmark to assess the performance of ecosystems and make statements about what ecosystems are comparatively good or bad at. Such benchmark is often lacking in discussions of the benefits and limitations of ecosystems. By contrast, our model allows for transparent comparisons and clearly defined causal mechanisms.

Managerial implications Our analyses suggest that managers need to consider competition over value capture – and, in particular, competitive asymmetry between the component of their firm and complementary components – to understand whether producers of complements will invest in improving the quality of their products. For instance, a firm in an orchestrator position may find it advantageous to pick a value creation technology that promotes higher level of competition, or seek to diminish the differentiation among complementors to induce investment by the latter.

Our results also show that understanding the type of complementarities underlying value creation in an ecosystem is paramount to be able to correctly estimate other actors' incentives to improve overall ecosystem value creation. Firms in ecosystems with stronger synergies between components, or constrained type of complementarities, might need to mitigate potential lack of investment by complementors, for instance by subsidizing complementors, entering complementary component (Ethiraj, 2007; Gawer and Henderson, 2007), or adopting backward compatibility (Kretschmer and

Claussen, 2016).

Moreover, the underlying value creation, and thus the alignment issues, can very well change over time in the same ecosystem. For instance, the current trend of streaming for video games is arguably transforming the technology from "weakest link" to "additive" as the tight combination of components on console is made irrelevant if the game is run on a server. Conversely, the whole point of adding novel hardware features on a cell phone is to create new applications that require these hardware features, but they are often weakest-link types of value creation technologies. In the same vein, consider the PC industry. It exhibited in its early years weakest-link type of complementarities between its components, for instance, microprocessors constraining the productivity of the OS, or OS not allowing the microprocessors to perform to its full abilities (Ethiraj, 2007). Recently, some actors have made the relationship more similar to the multiplicative case where improvements in one component (e.g., OS) amplify the improvements in the other (e.g., ARM chips). Our model suggests that when technologies of value creation transition from one type to another, managers may need to reassess their assumptions about incentive alignment in their ecosystem.

Testable implications Finally, the insights from our model offer a number of empirically testable implications for the dynamic of ecosystem value creation and firms' investment. Given the type of value creation, we can relate how investments in value creation and total value creation vary as a function of the relative levels of capabilities of the ecosystem participants. For instance, in contexts featuring *additive* value creation by components (e.g., streaming video games) we should be able to observe an increase (decrease) in complementors' investment as the complemetors' capabilities become more (or less) close, as well as the overall increase in the ecosystem value creation. Conversely, we should observe that larger initial orchestrator capabilities relate to larger orchestrator investment. In contexts exhibiting *weakest-link* type of technology (e.g., wearable technology) we should observe a drop in the orchestrator's investment and in the total value creation as the orchestrator's capabilities improve and get close to those of a worse complementor.

Limitations and future research We acknowledge several limitations of our model. First, we assume that there is no competing ecosystem, or that there is a sufficiently high horizontal differentiation that allows us to consider a single ecosystem in isolation. This allows us to focus on within-ecosystem competition to elucidate specifically the mechanisms of the value creation technology and competitive asymmetry. Future research could explore more complicated setups with competing orchestrators. Second, for purposes of analytical clarity, we assume away any cost or benefit of integration when constructing the integrated benchmark. This allows us to explore within-ecosystem alignment, while remaining cautious as to claiming superiority of any governance mode. Future research could examine the full spectrum of the ecosystem – hierarchy tradeoffs by incorporating the cost of integration and the potential benefits of ecosystem in terms of innovation (Baldwin, 2020). However, as long as mechanisms leading to integration costs or benefit are unrelated to rivalry in value capture between ecosystem members our analyses will stand. Future work could also further develop the current model to fully endogenize investment and technology choice to understand when the orchestrator is incentivized to increase or dampen the competition among complementors.

In conclusion, we develop a formal model of an ecosystem that examines firms' investment to improve value creation taking into account competition over value capture and the type of complementarities between ecosystem components. Our model provides an analytically consistent account of how competition to capture value can distort firms' incentives to invest. It offers novel insights on value creation in an ecosystem by suggesting the mechanisms underpinning incentive alignment that result in a high variance in firms' investment. We hope that this research will pave the way for further analyses of the mechanisms underpinning value creation and value capture in ecosystems and the implications for firms' strategies.

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FIGURES

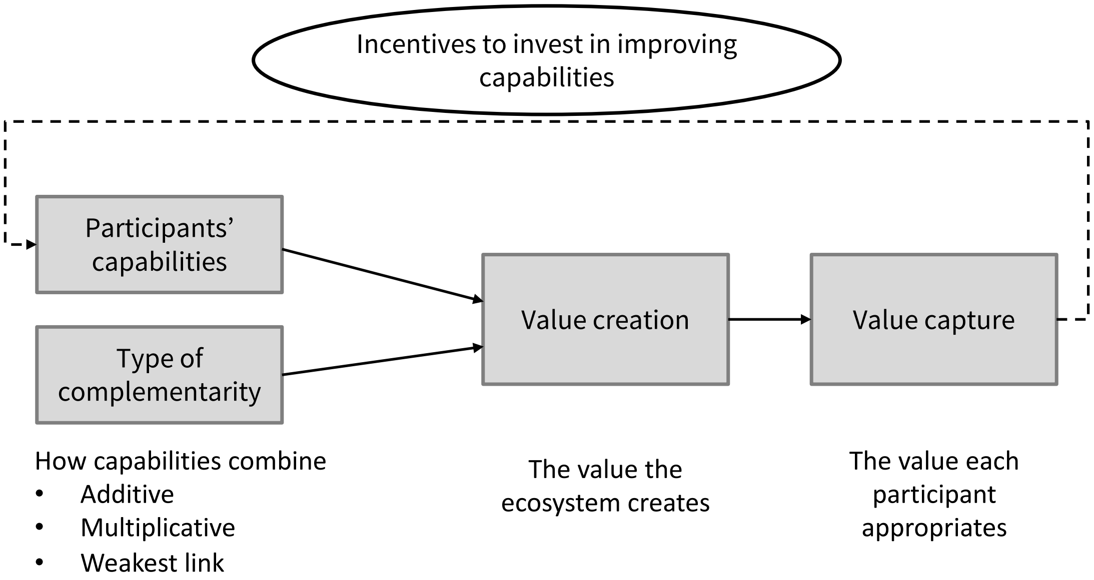
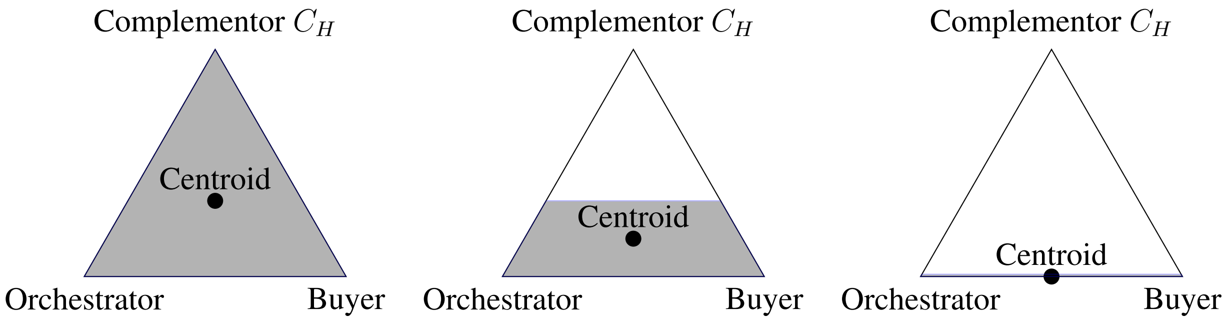


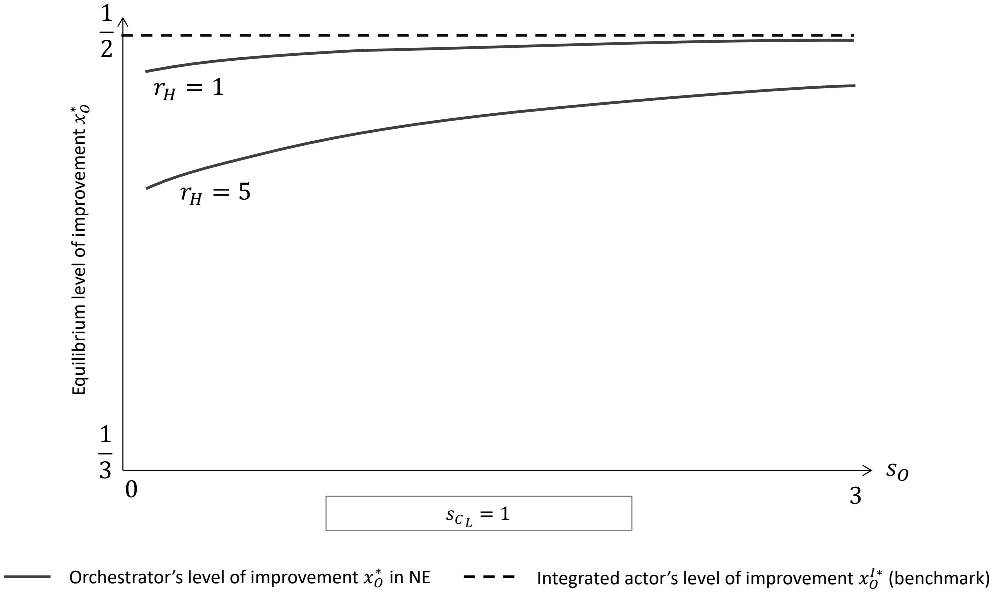
Figure 1: Conceptual model setup



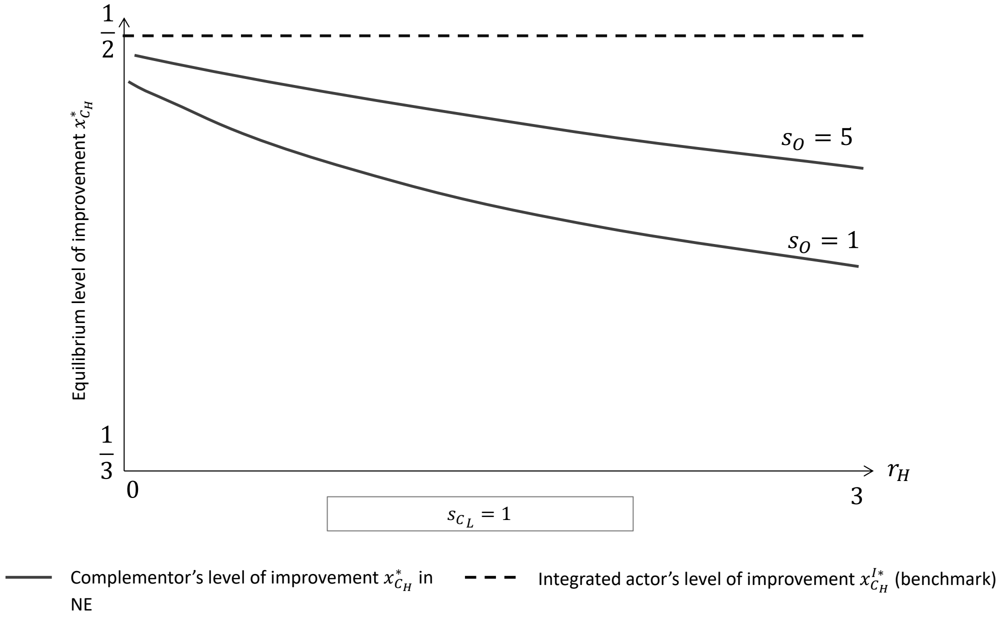
(a) No substitution (b) Partial substitution (c) Full substitution

Figure 2: Core (shaded area), and location of its centroid (black dot), represented in the simplex for different levels of substitution of Complementor C_H. Each point in the simplex represents an allocation of value to the Orchestrator, the Buyer, and complementor C_H that sums to the total value of the game. Inferior complementor C_L receives no value.

Figure 3: Additive value creation: equilibrium improvement efforts as a function of *ex ante* capabilities s_O and r_H

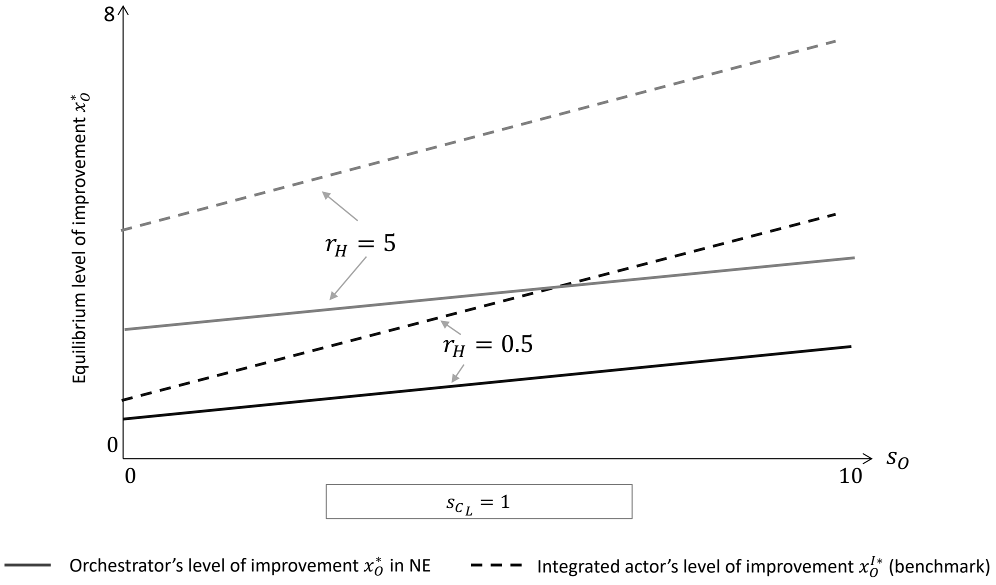


(a) Orchestrator's equilibrium effort x_O

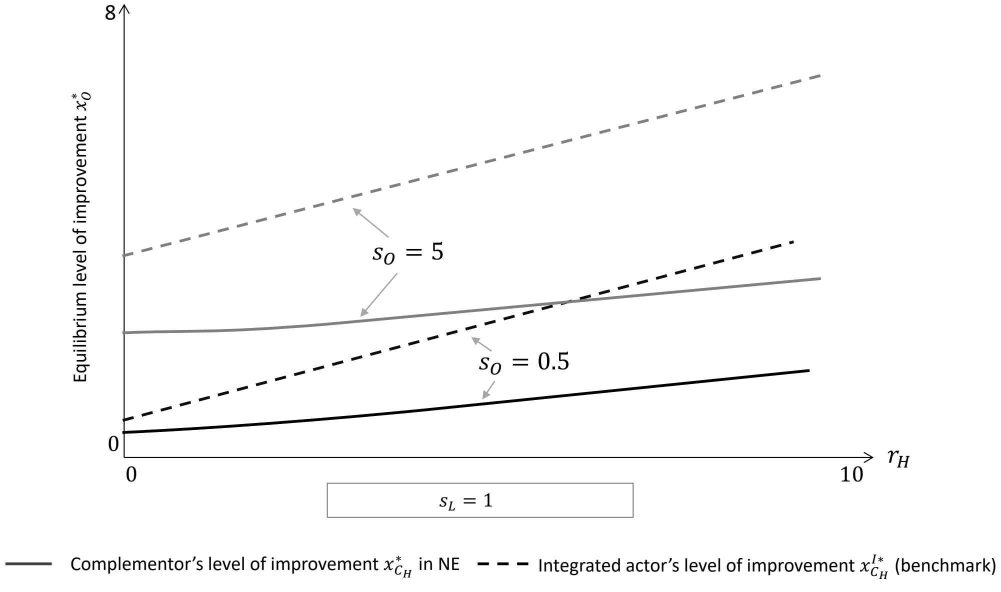


(b) Complementor's equilibrium effort x_{C_H}

Figure 4: Multiplicative value creation: equilibrium improvement efforts as a function of *ex ante* capabilities s_O and r_H



(a) Orchestrator's equilibrium effort x_O



(b) Complementor's equilibrium effort x_{C_H}

Figure 5: Weakest link value creation: equilibrium improvement efforts as a function of s_O

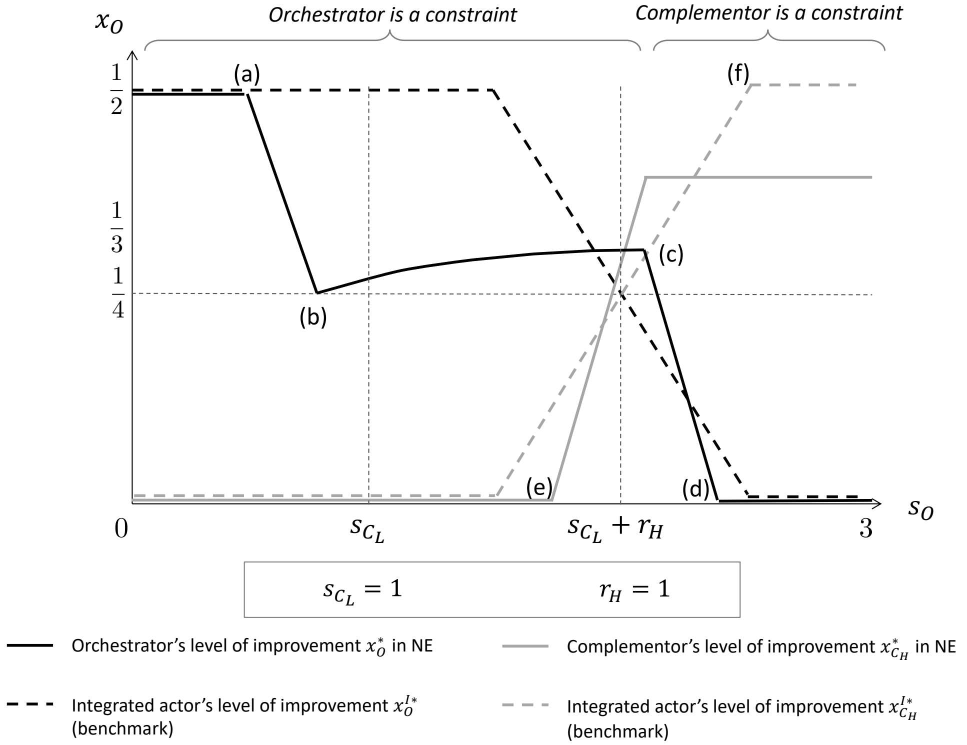


Figure 6: Weakest link value creation: total value creation $v(N)$ as a function of orchestrator's s_O

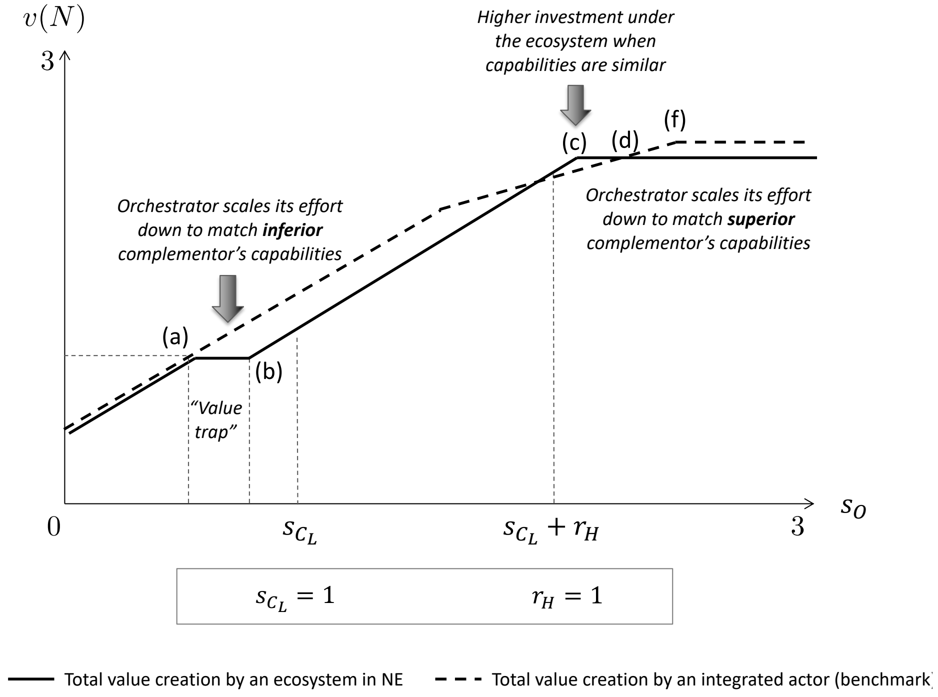


Figure 7: Weakest link value creation: marginal returns to x_O holding $x_O = 0$ and $x_{C_H} = 0$

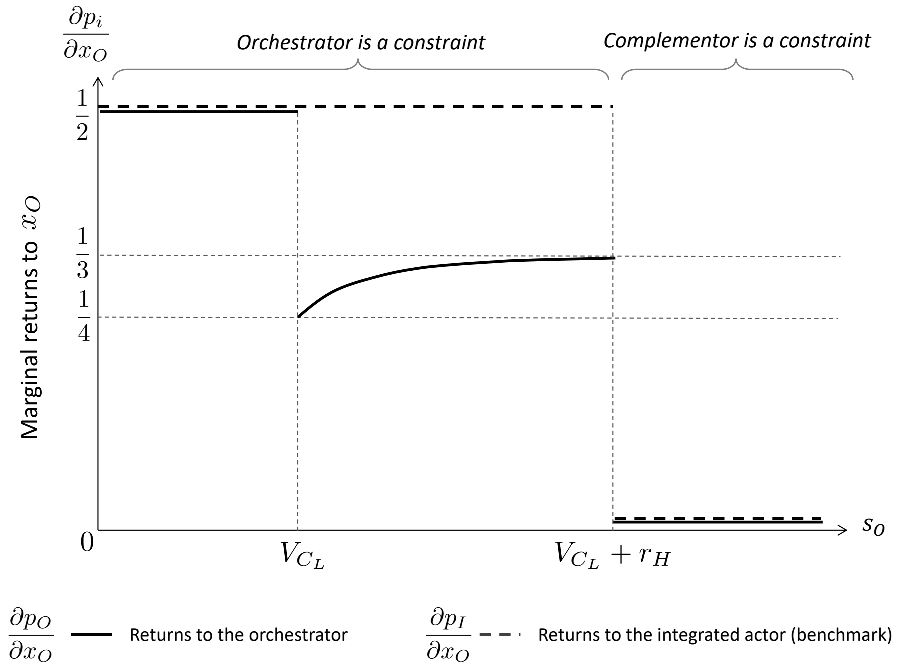
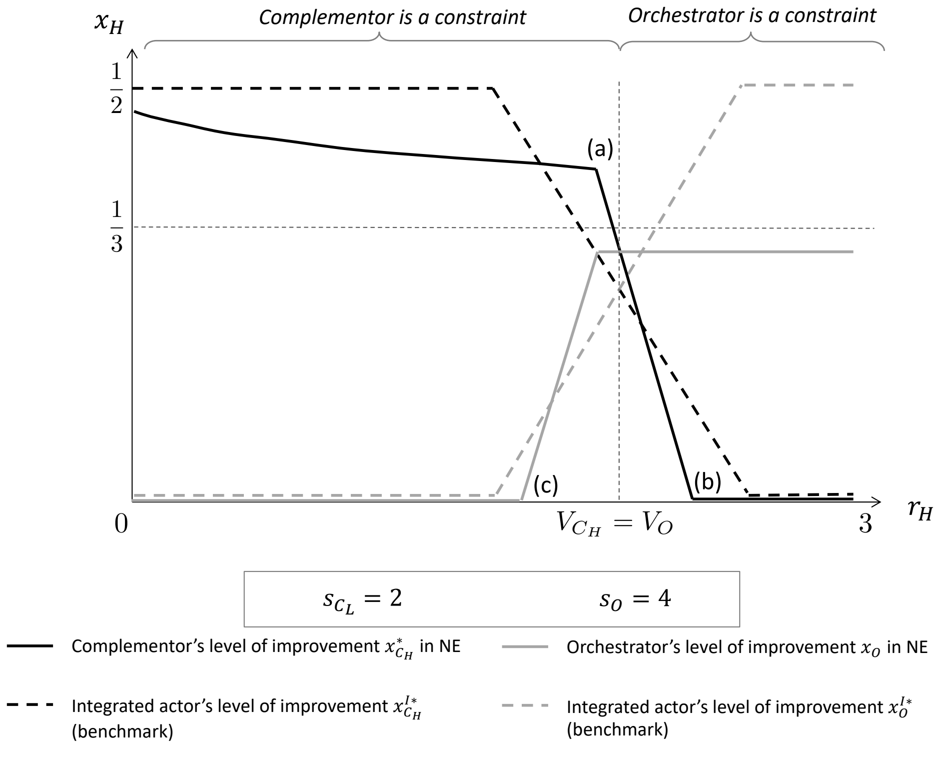


Figure 8: Weakest link value creation: equilibrium improvement efforts as a function of complementor's r_H



APPENDIX A EXPECTED VALUE CAPTURE CALCULATION

We can characterize the core based on its extreme points. Specifically, let $(\pi_O, \pi_B, \pi_{C_L}, \pi_{C_H})$ be an allocation of value. The extreme points of the core, the underlying interpretation and the coordinates are given in Table 2.

Coordinates in the core (i.e., players' value captured)	π_O	π_B	π_{C_L}	π_{C_H}
O and C_H capture all ecosystem value, C_H captures its maximum possible value	$v(O, C_L, B)$	0	0	$v(N) - v(O, C_L, B)$
B and C_H capture all ecosystem value, C_H captures its maximum possible value	0	$v(O, C_L, B)$	0	$v(N) - v(O, C_L, B)$
B captures full ecosystem value	0	$v(N)$	0	0
O captures full ecosystem value	$v(N)$	0	0	0

Table 2: Coordinates of the extreme points of the core in terms of value capture (π_i)

Since C_L never captures any positive value, and the sum of the other value captures is $v(N)$ we can represent the core in the 3-dimension simplex. The simplex in Figure 9 shows all the ways in which value can be split between the three players O, B, and C_H, holding the sum of their value capture constant and equal to the total value of the game ($v(N)$). A point in the simplex represents a way to split the full value of the game among the three players (coordinates thus sum to $v(N)$). The closer a point is to a summit of the triangle, the more value is allocated to the player whose summit it is. For instance, the summit labelled "Orchestrator" gives the coordinate $v(N)$ to the orchestrator, and 0 to the other players. The point of the core closest to "Complementor C_H" summit, on the line between the orchestrator and complementor C_H corresponds to $v(O, C_L, B)$ for the orchestrator, $v(N) - v(O, C_L, B)$ for complementor C_H and 0 for the buyer. In this simplex, the core has the shape of a trapezoid whose extreme points represent situations where one of the players is getting the maximum permitted under the core.

To compute the value capture of each actor we draw on Cappelli and Chatain's (2023) extension of Brandenburger and Stuart's (2007) celebrated biform framework (referred to below as BS07). To motivate the use of this extension, rather than that of the original framework, we now show why relying exclusively on BS07 to calculate a point estimate of players' value capture has substantial drawbacks in situations when more than two players are necessary for value capture, such as in business ecosystems. We then show how Cappelli and Chatain's (2023) generalization offers a solution to these issues.

In BS07's original framework, each player calculates its expected value capture as a linear combination of the lower and upper bound of the allocation in the core, using a parameter (the confidence index α_i) to weight the respective importance of each bound. Using that framework in our model, the buyer would expect to capture $\alpha_B \times 0 + \alpha_B \times v(N) = \alpha_B v(N)$. This formulation does not account for the totality of the constraints that define the core, even though they may matter to how much a player can capture. For instance, in our game, relying on BS07 makes the expected value capture of the buyer and of the orchestrator invariant (respectively equal to $\alpha_B v(N)$ and $\alpha_O v(N)$) to

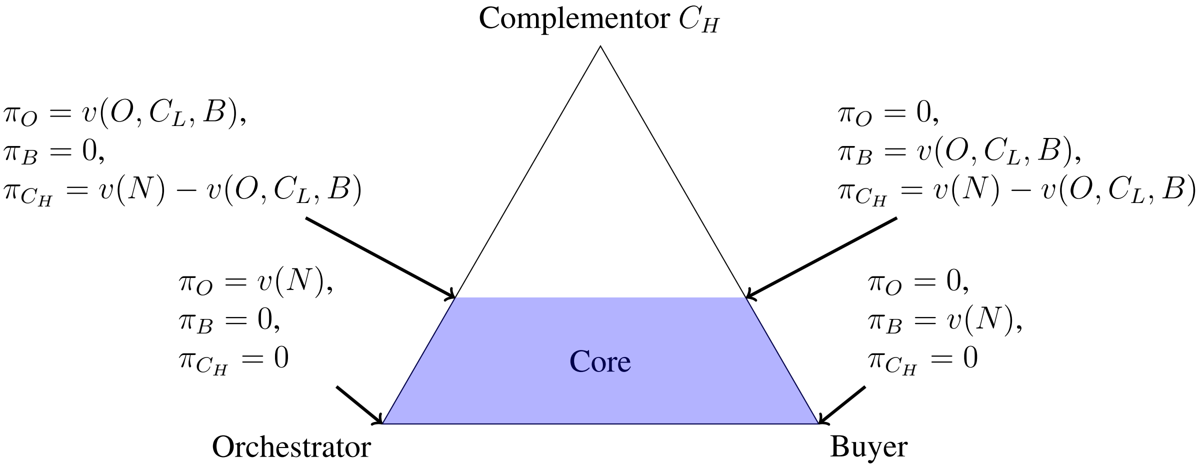


Figure 9: The core and its extreme points represented in the simplex

the degree of substitution between the two complementors even though this is material to how much they can collectively capture.

To see why this matters, consider the case where complementor C_L is so weak that it does not help create value (i.e., $v(O, C_L, B) = 0$). In that situation, the core is the full triangle in Figure 2, and the value $v(N)$ will be split three-ways between the buyer, the orchestrator, and complementor C_H. Now, consider a change in the basic parameters whereby complementor C_L becomes gradually as good as complementor C_H. This is illustrated in panels 2b and 2c. Their competing with each other means that the value is gradually pushed to the buyer and the orchestrator. The core is now reduced to the base of the triangle in panel 2c of Figure 2.

Clearly, the orchestrator and the buyer are better off collectively in 2c than in 2a. In the latter case, C_H cannot capture any value, and consequently O and B must collectively capture more than in the other cases. However, in BS07's formalism, the orchestrator and the buyer would be considering the three situations as strictly equivalent because they would expect to capture the same amount of value, respectively $\alpha_O v(N)$ and $\alpha_B v(N)$, since the lower bound and the upper bound of the core are exactly the same for them (respectively, 0, and $v(N)$), and BS07 only consider these two parameters.

The key difference between 2a and 2c is that the shape of the core has changed from a triangle to a line. This geometric interpretation is directly translating a simple intuition about ecosystem strategy: when members of a component are less differentiated, the force of competition makes them unable to capture value versus the other components, which results in more value available to the other components. It stands to reason that players in the other components must be, *ceteris paribus*, better off in 2c than in 2a, yet this is not accounted for in BS07.

To capture this intuition, and retain the benefits of the value-based framework, we rely on Cappelli and Chatain's (2023) generalization of BS07. In that generalized framework, each actor computes an expected value capture from the core under the assumption that a point in the core is randomly picked under a uniform distribution. This way, all constraints defining the core are accounted for. This information is then used to assess the actor's value capture prospects, in addition to the values of the upper and lower bounds of the actor's value capture interval. When positive weight is given to the expected value capture, the shape of the core matters. In this paper, we focus on the expected value capture under the uniform distribution of the possible payoffs in the core, and leave aside the behavioral aspects further explored in Cappelli and Chatain (2023).

Equating the expected value capture of each player to the average location of a point in the core has many attractive properties for modeling ecosystems. First, we obtain mutually consistent expectations of value capture regardless of the number and types of players without having to resort to *ad hoc* assumptions on confidence indices. This is advantageous in ecosystems as many players have a claim on the quasi-rent they create. Second, it enables capturing subtle shifts in the geometry of the core that may be consequential to how value will be distributed.

We prefer in this paper this method to alternatives such as the Shapley value, because the latter would allocate strictly positive value to actors who have zero added value, making them willing to invest in capabilities while competition would prevent them from capturing anything. For instance, the Shapley value would allocate strictly positive amount of value to the weaker complementor, even though other actors would be better off working without it and not letting it capture anything.[19],

The following lemma gives the closed form of the location of the centroid of a core of shape similar to what we study in this paper. The coordinates of the centroid give the expected value capture of each player under a uniform distribution of allocations in the core.

Lemma 6 *Consider a core allocation* $(\pi_O, \pi_B, \pi_{C_L}, \pi_{C_H})$*, with extreme points* $(a, 0, 0, b{-}a)$*,* $(0, a, 0, b{-}a)$*,* $(0, b, 0, 0)$*, and* $(b, 0, 0, 0)$*, with* $b \geq a > 0$*. The centroid of this allocation is given in barycentric coordinates by:*

$$\left(\frac{a^2+ab+b^2}{3(a+b)}, \frac{a^2+ab+b^2}{3(a+b)}, 0, \frac{(b-a)(2a+b)}{3(a+b)}\right).$$

Moreover, the expected value captured by each player under a uniform probability distribution of core allocation is equal to its respective centroid coordinate.

Proof of Lemma 6.

We have four players: orchestrator (O), buyer (B), superior complementor (C_H), and inferior complementor (C_L). The characteristic function is given by:

S	$v(S)$
$\{O, B, C_L, C_H\}$	b
$\{O, B, C_L\}$	a
$\{O, B, C_H\}$	b

All other coalitions produce zero. The constraints from the core are, assuming $b \geq a > 0$:

$$\begin{aligned} \pi_O + \pi_B + \pi_{C_L} + \pi_{C_H} &= b, \\ 0 \leq \pi_O &\leq b, \\ 0 \leq \pi_B &\leq b, \\ \pi_{C_L} &= 0, \\ 0 \leq \pi_{C_H} &\leq b - a. \end{aligned}$$

From the core, we determine the extreme points of the convex set defined by the core:

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[19] The Shapley value would provide the following value ϕ_i to the players: $\phi_O = \phi_B = \frac{1}{3}v(N) + \frac{1}{12}v(O, C_L, B)$, $\phi_{C_L} = \frac{1}{12}v(O, C_L, B)$, $\phi_{C_H} = \frac{1}{3}v(N) - \frac{1}{4}v(O, C_L, B)$.

Extreme point	π_O	π_B	π_{C_L}	π_{C_H}
A	a	0	0	$b-a$
B	0	a	0	$b-a$
C	0	b	0	0
D	b	0	0	0

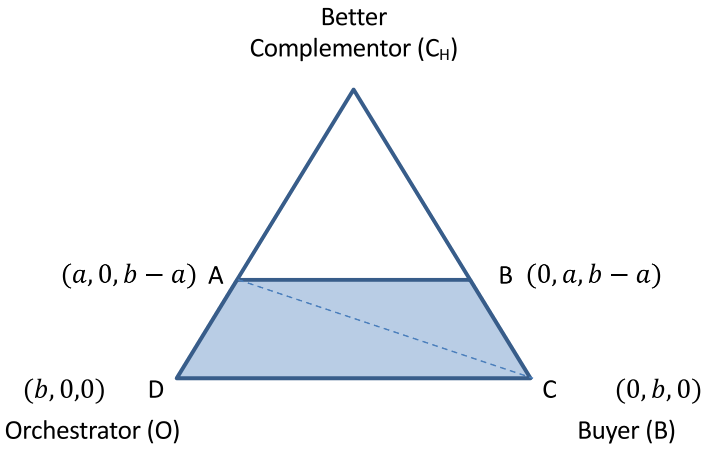


Figure 10: Splitting the core in triangles to calculate centroid coordinates

Because C_L appropriates 0 in the following we keep the analysis on the plane and only consider the simplex consisting of the value appropriated by O, B, and C_H.

To find the centroid of core, we split the trapezoid $ABCD$ into two triangles ADC, and CBA (Figure 10). We are going to use the property that the centroid of a triangle in barycentric coordinates is found by averaging the coordinates of the summits. The coordinates of the centroid of the trapezoid are then given by the average of the coordinates of the centroids of the triangles, weighted by the areas of the triangles. More generally, note that the core is always a convex set and that in higher dimensional spaces, any convex set can be split into a set of tetrahedrons with known centroids and volumes, which guarantees that such centroid coordinate calculation can always be done.

The centroid of ADC is directly given by the average of the coordinates of the summits:

$$\left(\frac{a+b}{3}, \frac{b}{3}, \frac{b-a}{3}\right).$$

For a triangle with barycentric coordinates $P_i(x_i, y_i, z_i)$, $i = 1, 2, 3$, the signed area $[P_1, P_2, P_3]$, as a fraction of the area of the simplex, is given by:

$$[P_1P_2P_3] = \begin{vmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_1 & z_3 \end{vmatrix}.$$

The points have to be listed counterclockwise for the area to be positive.

The signed area of ADC, as a fraction of the area of the simplex, is thus:

$$[ADC] = \begin{vmatrix} a & 0 & b-a \\ b & 0 & 0 \\ 0 & b & 0 \end{vmatrix} = b^3 - ab^2$$

The centroid of CBA is:

$$\left(\frac{a}{3}, \frac{b+a}{3}, \frac{2(b-a)}{3}\right).$$

The signed area of CBA, as a fraction of the area of the simplex, is:

$$[CBA] = \begin{vmatrix} 0 & b & 0 \\ 0 & a & b-a \\ a & 0 & b-a \end{vmatrix} = ab^2 - a^2b$$

The centroid of trapezoid $ADCB$ is given by:

$$\begin{aligned} &\frac{[ADC]}{[ADC]+[CBA]}\left(\frac{a+b}{3}, \frac{b}{3}, \frac{b-a}{3}\right) + \frac{[CBA]}{[ADC]+[CBA]}\left(\frac{a}{3}, \frac{b+a}{3}, \frac{2(b-a)}{3}\right) \\ &= \frac{b}{b+a}\left(\frac{a+b}{3}, \frac{b}{3}, \frac{b-a}{3}\right) + \frac{a}{b+a}\left(\frac{a}{3}, \frac{b+a}{3}, \frac{2(b-a)}{3}\right) \\ &= \left(\frac{a^2+ab+b^2}{3(a+b)}, \frac{a^2+ab+b^2}{3(a+b)}, \frac{(b-a)(2a+b)}{3(a+b)}\right) \end{aligned}$$

Since the inferior complementor C_L captures zero, the expected value capture in the core $(\pi_O, \pi_B, \pi_{C_L}, \pi_{C_H})$ is given by

$$\left(\frac{a^2+ab+b^2}{3(a+b)}, \frac{a^2+ab+b^2}{3(a+b)}, 0, \frac{(b-a)(2a+b)}{3(a+b)}\right).$$

■

APPENDIX B PROOFS

Before showing proofs for each value creation scenario we start with a more detailed explanation about the development game. Importantly, we establish that in a pure strategy Nash equilibrium (NE) at most only one complementor develops.

Competitive investment game in the ecosystem

The investment game is a biform game, with a non-cooperative investment stage followed by a coalitional value capture stage. There are three active players in the non-cooperative investment game, the Orchestrator (O), the complementor that starts at a lower level (C_L), and the complementor that starts at a higher level (C_H). The starting capabilities of each players contributing to the value creation of the ecosystem are respectively: $s_O \geq 0$, $s_{C_L} \geq 0$, and $s_{C_H} \geq 0$. Without loss of generality, we assume $s_{C_L} \leq s_{C_H}$, and define $r_H = s_{C_H} - s_{C_L} \geq 0$.

The strategic variables in the game are the amount of capability development that each player chooses to add to its starting capabilities. Denote these as $x_O \geq 0$, $x_{C_L} \geq 0$, and $x_{C_H} \geq 0$. Player's $i \in \{O, C_L, C_H\}$ resulting capability V_i after development is:

$$V_i = s_i + x_i.$$

As we are exclusively interested in the causal mechanisms stemming from differences in returns to value capture in the negotiation stage, we assume identical development costs functions $c(x_i) = \frac{1}{2}(x_i)^2$ for all players.

Revenues for player i are determined in the coalitional stage and are given by the function $p_i(s_O, s_{C_L}, r_H, x_i, x_{-i})$ where x_{-i} denotes the strategies of the other two players. This function varies depending on the value creation technology considered. However, an important fact is that a complementor whose capability is less or equal to that of the other complementor receives zero revenue as it is unable to capture value in the coalitional game. That is, with $j \in \{C_L, C_H\}$:

$$p_j(s_O, s_{C_L}, r_H, x_j, x_{-j}, x_O) = 0$$

if $s_j + x_j \leq s_{-j} + x_{-j}$.

Given the structure of the game, players in i pick their x_i to maximize their profits:

$$\pi_i(x_i) = p_i(s_O, s_{C_L}, r_H, x_i, x_{-i}) - c(x_i).$$

We focus on pure strategy Nash equilibria of the simultaneous development game.

Lemma 7 *In the simultaneous development game, in a pure strategy Nash-equilibrium, at most one complementor develops. I.e., if* $x_j > 0$ *then* $x_{-j} = 0$, $j \in \{C_H, C_L\}$.

Proof. Suppose not, i.e., $x_{C_H} > 0$ and $x_{C_L} > 0$. Then one of the two complementors (say j) earns no revenue and yet spends $c(x_j) > 0$. This complementor could immediately improve its profits by setting $x_j = 0$, contradicting the assumption of Nash equilibrium. ■

Competitive investment game in the integrated actor benchmark

Our benchmark to evaluate the impact of the ecosystem mode on returns to value creation is the development decision of an integrated actor I. The integrated actor simply splits in two the total value created with the buyer in the coalitional stage of the game, and decides on the investment levels for each component of the ecosystem. Let $V_I(s_O, s_{C_L}, s_{C_H}, x_O, x_{C_L}, x_{C_H})$ the value created by the integrated actor given $x_i \geq 0$, the investment in improving the capability of player i. Then the integrated actor maximizes:

$$\frac{1}{2}V_I(s_O, s_{C_L}, s_{C_H}, x_O, x_{C_L}, x_{C_H}) - c(x_O) - c(x_{C_L}) - c(x_{C_H}).$$

Evidently, given costs functions are identical and convex for both complementors, it is never optimal to invest in developing the capabilities of the complementor C_L since only the capabilities of the best of the two complementors matter and that complementor C_H has a head start in development. Thus the problem of the integrated benchmark reduces to finding the optimal combination of x_O and x_{C_H} for the integrated benchmark while always setting $x_{C_L} = 0$.

Comparison between the two

We will compare the equilibrium where C_H develops in the ecosystem NE to the optimal development in a restricted game including C_H and O but in which C_L has no action available and makes no development. To any NE in this restricted game with only two active players in which C_H develops corresponds a NE in the full game with 3 players in which C_L's strategy is not to develop given the strategies of the other players, since it cannot be that both C_H and C_L develop at the time. We make an assumption that if C_L chooses to develop, then C_H can always match its development, and given that $s_{C_H} = r_H + s_{C_L} > s_{C_L}$, C_L will have zero added value in the coalitional game, and thus zero value capture, which means that the optimal strategy for C_L is not to develop at all.

We will now show proofs for each value creation scenario.

Proof of Proposition 1.

Under the additive value creation scenario we have the following characteristic function:

S	$v(S)$	$v(S)$, detailed
$\{O, B, C_L, C_H\}$	$V_O + V_{C_L} + r_H$	$s_O + x_O + s_{C_L} + r_H + x_{C_H}$
$\{O, B, C_L\}$	$V_O + V_{C_L}$	$s_O + x_O + s_{C_L}$
$\{O, B, C_H\}$	$V_O + V_{C_L} + r_H$	$s_O + x_O + s_{C_L} + r_H + x_{C_H}$
Any other subset of N	0	0

Table 3: Characteristic function under additive value creation technology

Given the characteristic function under additive value creation in Table 3 and the allocation of value from Lemma 6 (where b is substituted for $v\{O, B, C_L, C_H\}$ and a is substituted for $v\{O, B, C_L\}$) we have the following value capture:

$$\begin{aligned}
p_O &= \frac{(r_H + x_{C_H} + 2s_{C_L} + 2s_O + 2x_O)^2 - (r_H + x_{C_H} + s_{C_L} + s_O + x_O)(s_{C_L} + s_O + x_O)}{3(r_H + x_{C_H} + 2s_{C_L} + 2s_O + 2x_O)}, \\
p_B &= \frac{(r_H + x_{C_H} + 2s_{C_L} + 2s_O + 2x_O)^2 - (r_H + x_{C_H} + s_{C_L} + s_O + x_O)(s_{C_L} + s_O + x_O)}{3(r_H + x_{C_H} + 2s_{C_L} + 2s_O + 2x_O)}, \\
p_{C_H} &= \frac{(r_H + x_{C_H})(r_H + x_{C_H} + 3s_{C_L} + 3s_O + 3x_O)}{3(r_H + x_{C_H} + 2s_{C_L} + 2s_O + 2x_O)}, \\
p_{C_L} &= 0.
\end{aligned}$$

Existence of the ecosystem penalty

Consider the optimization problem of the integrated actor. Its maximization problem for value capture is

$$\max_{x_O, x_{C_H}} \pi_I = \frac{1}{2}((s_O + x_O) + (s_{C_L} + r_H + x_{C_H})) - c_O(x_O) - c_H(x_{C_H})$$

Since there is no interaction between x_O and x_{C_H} in the revenue and the cost function, this is equivalent to solving two independent maximization problems:

$$\max_{x_O}\left[\frac{1}{2}x_O - c_O(x_O)\right],$$
$$\max_{x_{C_H}}\left[\frac{1}{2}x_{C_H} - c_H(x_{C_H})\right].$$

Compare this to the maximization problem of the orchestrator in an ecosystem:

$$\max_{x_O}\left[\pi_O(x_O, s_O, s_{C_L}, r_H, x_{C_H}) - c_O(x_O)\right]$$

Since we assume the same cost in an ecosystem and for the integrated actor, we only need to show that $\frac{\partial p_O(x_O,s_O,s_{C_L},r_H,x_{C_H})}{\partial x_O} < \frac{\partial p_I}{\partial x_O} = \frac{1}{2}$ to prove that the orchestrator's improvement level in Nash Equilibrium (NE) x_O will always be strictly less that the improvement level by the integrated actor. A similar reasoning applies to the improvement level by complementor. Formal calculations:

$$\frac{1}{2} - \frac{\partial p_O(x_O, s_O, s_{C_L}, r_H, x_{C_H})}{\partial x_O} = \frac{(r_H + x_{C_H})^2}{6(r_H + x_{C_H} + 2s_{C_L} + 2s_O + 2x_O)^2} > 0,$$
$$\frac{1}{2} - \frac{\partial p_{C_H}(x_O, s_O, s_{C_L}, r_H, x_{C_H})}{\partial x_{C_H}} = \frac{(r_H + x_{C_H})(r_H + x_{C_H} + 4s_{C_L} + 4s_O + 4x_O}{6(r_H + x_{C_H} + 2s_{C_L} + 2s_O + 2x_O)^2} > 0.$$

We conclude that the returns to improvement along a variable (x_O or x_{C_H}) for the integrated actor are always strictly superior to those in the ecosystem, for *any value of the other variable*, i.e., regardless of the improvement effort by the other player. This implies that in the development game in an ecosystem the improvement levels can never reach those of the integrated actor.

Degree of the ecosystem penalty

Because the integrated actor's equilibrium effort is fixed $\frac{1}{2}$ we only need to show how the equilibrium efforts of the orchestrator and complementor change in an ecosystem with s_O and r_H. First, we look at cross-derivatives in x_i and s_O, and x_i and r_H. Note that the full profit function π_i includes a cost function $c_i(x_i) = \frac{x_i^2}{2}$, whose cross-derivative in x_i, s_O, and x_i, r_H will be zero, which is why we do not include it in the following:

$$\frac{\partial p_O^2}{\partial x_O \partial s_O} = \frac{2(r_H + x_{C_H})^2}{3(r_H + x_{C_H} + 2s_{C_L} + 2s_O + 2x_O)^3} > 0,$$
$$\frac{\partial p_{C_H}^2}{\partial x_{C_H} \partial s_O} = \frac{4(r_H + x_{C_H})(s_{C_L} + s_O + x_O)}{3(r_H + x_{C_H} + 2s_{C_L} + 2s_O + 2x_O)^3} > 0,$$
$$\frac{\partial p_O^2}{\partial x_O \partial r_H} = -\frac{2(r_H + x_{C_H})(s_{C_L} + s_O + x_O)}{3(r_H + x_{C_H} + 2s_{C_L} + 2s_O + 2x_O)^3} < 0,$$
$$\frac{\partial p_{C_H}^2}{\partial x_{C_H} \partial r_H} = -\frac{4(s_{C_L} + s_O + x_O)^2}{3(r_H + x_{C_H} + 2s_{C_L} + 2s_O + 2x_O)^3} < 0.$$

We see that s_O and r_H have co-directed effects on x_O and x_{C_H}: both efforts increase in s_O and decrease in r_H. We calculate cross-derivatives in x_O and x_{C_H} to see if the latter are strategic complements or substitutes. Similarly to the above, we do not include the cost function $c_i(x_i) = \frac{x_i^2}{2}$ because its cross-derivative in x_O, x_{C_H} will be zero:

$$\frac{\partial p_O^2}{\partial x_O \partial x_{C_H}} = -\frac{2(r_H + x_{C_H})(s_{C_L} + s_O + x_O)}{3(r_H + x_{C_H} + 2s_{C_L} + 2s_O + 2x_O)^3} < 0,$$
$$\frac{\partial p_{C_H}^2}{\partial x_O \partial x_{C_H}} = \frac{4(r_H + x_{C_H})(s_{C_L} + s_O + x_O)}{3(r_H + x_{C_H} + 2s_{C_L} + 2s_O + 2x_O)^3} > 0.$$

For the orchestrator, x_O and x_{C_H} are strategic substitutes, while for the complementor they are strategic complements. Because s_O and r_H have co-directed effects on x_O and x_{C_H}, and for the complementor, x_O and x_{C_H} are complements, this is enough to conclude that x_{C_H} increases in s_O and decreases in r_H, thus for the complementor the misalignment decreases in s_O and increases in r_H.

For the orchestrator, x_O and x_{C_H} are substitutes, which means that s_O has two countervailing effects on x_O: direct effect where s_O increases x_O, and indirect effect where s_O increases x_{C_H}, which, in turn, decreases x_O. Similarly, r_H has a direct negative effect on x_O and indirect positive effect through x_{C_H}. To understand which effect prevails we need to calculate the orchestrator's effort in NE, i.e. we need to find x_O^* such that $\max_{x_O} \pi_O(s_O, x_O, s_{C_L}, r_H, x_{C_H}^*)$, where $x_{C_H}^*$ is the equilibrium effort by the complementor. Because formulas for π_O and π_{C_H} are very complicated (for instance, $x_{C_H}^*$ is a root of a cubic equation, which we then have to plug into an already complicated formula for π_O) we cannot find a closed-form solution. Instead, we solve it numerically. We need to find $\{x_O^*, x_{C_H}^*\}$ that are the solution to the following system of equations:

$$\begin{cases} x_O = \arg\max_{x_O} \left[p_O(x_O, s_O, s_{C_L}, r_H, x_{C_H}) - \frac{1}{2}x_O^2 \right], \\ x_{C_H} = \arg\max_{x_{C_H}} \left[p_{C_H}(x_O, s_O, s_{C_L}, r_H, x_{C_H}) - \frac{1}{2}x_{C_H}^2 \right], \\ x_O \geq, x_{C_H} \geq 0. \end{cases} \tag{8}$$

We use the *Mathematica* software to do this and generate tables of equilibrium values $\{x_O^*, x_{C_H}^*\}$ for given levels of s_O, r_H and s_{C_L}. Figure 11 shows the results for $s_O \in (0, 3)$, $s_{C_L} = 1$, and different levels of $r_H \in (0, 8)$. It shows that for the orchestrator the direct effects of s_O and r_H prevail: x_O^* increases with s_O and decreases with r_H, i.e. the misalignment decreases in s_O and increases in r_H. In the main body of the paper, Figure 3a shows equilibrium x_O^* for $s_O \in (0, 3)$ and at $s_{C_L} = 1$, $r_H = 1$, and $r_H = 5$, and Figure 3b shows equilibrium $x_{C_H}^*$ for $r_H \in (0, 3)$ and at $s_{C_L} = 1$, $s_O = 1$, and $s_O = 5$.

■

Proof of Proposition 2.

Under the multiplicative scenario value creation we have the following characteristic function.

Given the characteristic function in Table 4 and the allocation of value from Lemma 6 (where b is substituted for $v\{O, B, C_L, C_H\}$ and a is substituted for $v\{O, B, C_L\}$) we have the following

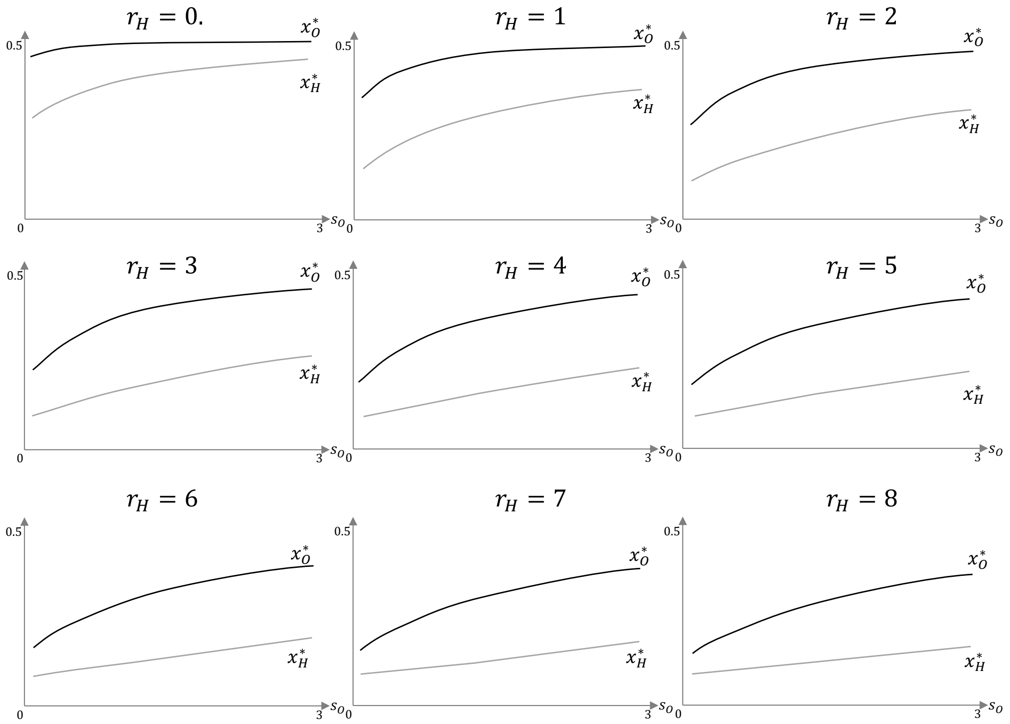


Figure 11: Additive value creation: numerical solutions for equilibrium x_O and x_{C_H} in an ecosystem, at $s_{C_L} = 1$

S	$v(S)$	$v(S)$, detailed
$\{O, B, C_L, C_H\}$	$V_O(V_{C_L} + r_H)$	$(s_O + x_O)(s_{C_L} + r_H + x_{C_H})$
$\{O, B, C_L\}$	$V_O * V_{C_L}$	$(s_O + x_O)s_{C_L}$
$\{O, B, C_H\}$	$V_O(V_{C_L} + r_H)$	$(s_O + x_O)(s_{C_L} + r_H + x_{C_H})$
Any other subset of N	0	0

Table 4: Characteristic function under multiplicative value creation technology

expected value capture allocation:

$$\begin{aligned}
p_O &= \frac{(s_O + x_O)((r_H + x_{C_H})^2 + 3s_{C_L}(s_{C_L} + r_H + x_{C_H}))}{3(r_H + 2s_{C_L} + x_{C_H})}, \\
p_B &= \frac{(s_O + x_O)((r_H + x_{C_H})^2 + 3s_{C_L}(s_{C_L} + r_H + x_{C_H}))}{3(r_H + 2s_{C_L} + x_{C_H})}, \\
p_{C_H} &= \frac{(s_O + x_O)(r_H + x_{C_H})(r_H + 3s_{C_L} + x_{C_H})}{3(r_H + 2s_{C_L} + x_{C_H})}, \\
p_{C_L} &= 0.
\end{aligned}$$

Existence of the penalty

We calculate cross-partial derivatives of p_O and p_{C_H} in x_O and x_{C_H} to see if the latter are strategic complements or substitutes. Note that the full profit function π_i includes a cost function $c_O(x_O) = \frac{x_O^2}{2}$ and $c_H(x_{C_H}) = \frac{x_{C_H}^2}{2}$, whose cross-derivative in x_O, x_{C_H} will be zero, which is why we do not include it in the following.

$$\frac{\partial p_O^2}{\partial x_O \partial x_{C_H}} = \frac{r_H^2 + 3s_{C_L}^2 + 4s_{C_L}x_{C_H} + x_{C_H}^2 + 2r_H(2s_{C_L} + x_{C_H})}{3(r_H + 2s_{C_L} + x_{C_H})^2} > 0,$$
$$\frac{\partial p_{C_H}^2}{\partial x_O \partial x_{C_H}} = \frac{r_H^2 + 6s_{C_L}^2 + 4s_{C_L}x_{C_H} + x_{C_H}^2 + 2r_H(2s_{C_L} + x_{C_H})}{3(r_H + 2s_{C_L} + x_{C_H})^2} > 0.$$

We conclude that the cross derivatives in value capture are positive for both players, and the game is a game of strategic complements, allowing us to rely on monotone comparative statics methods (Topkis, 1998).

In the following, we use an extra parameter ($\Omega \in \{0, 1\}$) to create a game whose NE is the integrated actor optimization when $\Omega = 1$ and that is the restricted development game if $\Omega = 0$. We will show for increasing differences in Ω and respectively x_O and x_{C_H} to prove that the equilibrium of the game with $\Omega = 1$ is larger in both x_O and x_{C_H}. This is equivalent to saying that the values of x_O and x_{C_H} chosen by an integrated benchmark are never less than that obtained in the non-cooperative development game.

The economic intuition is simply that the marginal returns to development for the Orchestrator and Complementor C_H are always less than that of the integrated benchmark and that strategic interactions between the two players are only compounding the tendency to invest less, as less investment by one player entails even less investment by the other.

Recasting the integrated benchmark optimization problem into a non-cooperative game Value capture in the integrated benchmark is (again setting $x_{C_L} = 0$):

$$\pi_I = \frac{1}{2}(s_O + x_O)(s_{C_L} + r_H + x_{C_H}) - c(x_O) - c(x_{C_H}).$$

Define the payoff functions of an alternative game (denoted "RC" for "recast") comprising players O and C_H as:

$$\pi_O^{RC} = \Omega\frac{1}{2}(s_O + x_O)(s_{C_L} + r_H + x_{C_H}) + (1 - \Omega)p_O(x_O, x_{C_H}) - c(x_O),$$
$$\pi_{C_H}^{RC} = \Omega\frac{1}{2}(s_O + x_O)(s_{C_L} + r_H + x_{C_H}) + (1 - \Omega)p_{C_H}(x_O, x_{C_H}) - c(x_{C_H}).$$

When $\Omega = 1$, this defines a game whose NE corresponds to the values picked by the integrated benchmark when it maximizes profitability. This can be seen from the definition of a Nash equilibrium. When $\Omega = 0$, we have the non-cooperative development game restricted to O and H.

We already know that when $\Omega = 0$ the game is one of strategic complements. It is also obviously the case when $\Omega = 1$. We now only need to show increasing differences in Ω with respect to both x_O and x_{C_H} in order to use Topkis's theorem on the comparative statics of supermodular games (e.g., Topkis, 1998, theorem 4.2.2, p.183) to show that in the NE of the recast game both strategic variables are non-decreasing in Ω. We find this is the case as:

$$\begin{aligned}\frac{\partial^2 \pi_O^{RC}}{\partial x_O \partial \Omega} &= \frac{(r_H + x_{C_H})(r_H + 3s_{C_L} + x_{C_H})}{6(r_H + 2s_{C_L} + x_{C_H})} \geq 0,\\ \frac{\partial^2 \pi_{C_H}^{RC}}{\partial x_{C_H} \partial \Omega} &= \frac{(r_H + x_{C_H})(r_H + 4s_{C_L} + x_{C_H})(s_O + x_O)}{6(r_H + 2s_{C_L} + x_{C_H})^2} \geq 0.\end{aligned}$$

In other words, the non-cooperative development games yields equilibrium values that cannot be larger than that in the integrated benchmark optimization.

Degree of the penalty

Unlike the additive scenario, here the equilibrium effort in component i in both the integrated benchmark and the ecosystem depends on the equilibrium effort in the component $-i$. We thus look at cross derivatives of value capture p_i for both integrated benchmark and decentralized ecosystem, and compare. First, we look at the cross derivatives of value capture p_i in x_O and s_O, and in x_O and r_H in the integrated benchmark and in the ecosystem:

$$\begin{aligned}&\frac{\partial p_I^2}{\partial x_O \partial r_H} = \frac{1}{2},\\ &\frac{\partial p_O^2}{\partial x_O \partial r_H} = \frac{(r_H + 2s_{C_L} + x_{C_H})^2 - s_{C_L}^2}{3(r_H + 2s_{C_L} + x_{C_H})^2} < \frac{1}{3},\\ &\frac{\partial p_I^2}{\partial x_O \partial s_O} = 0,\\ &\frac{\partial p_O^2}{\partial x_O \partial s_O} = 0.\end{aligned}$$

We repeat this for x_{C_H} and s_O, and in x_{C_H} and r_H:

$$\begin{aligned}&\frac{\partial p_I^2}{\partial x_{C_H} \partial s_O} = \frac{1}{2},\\ &\frac{\partial p_{C_H}^2}{\partial x_{C_H} \partial s_O} = \frac{1}{3} + \frac{2s_{C_L}^2}{3(r_H + 2s_{C_L} + x_{C_H})^2} < \frac{1}{2},\\ &\frac{\partial p_I^2}{\partial x_{C_H} \partial r_H} = 0,\\ &\frac{\partial p_{C_H}^2}{\partial x_{C_H} \partial r_H} = -\frac{4s_{C_L}^2(s_O + x_O)}{3(r_H + 2s_{C_L} + x_{C_H})^3} < 0.\end{aligned}$$

Orchestrator's x_O increases with *ex ante* superior complementor's advantage r_H in both integrated benchmark and ecosystem, but at a lower rate in an ecosystem. It does not depend directly on s_O, however, there is an indirect positive effect as s_O increases x_{C_H}, which is a strategic complement to x_O, in both benchmark and ecosystem, but at a lower rate in an ecosystem.

Complementor's x_{C_H} increases with *ex ante* orchestrator's capabilities s_O in both integrated benchmark and ecosystem, but at a lower rate in an ecosystem. In the integrated benchmark, x_{C_H}

does not directly depend on r_H, but there is an indirect positive effect (since it increases x_O, which is a strategic complement to x_{C_H}). In an ecosystem, r_H has a direct negative effect on x_{C_H}, which then countervails the indirect positive effect through x_O, which is a strategic complement to x_{C_H}.

Taken together, in an ecosystem, both x_O and x_{C_H} increase with the orchestrator's s_O, but because this happens at a lower rate than in the integrated benchmark, the result is that the ecosystem penalty for both orchestrator and complementor becomes higher with higher s_O. In the integrated benchmark, both x_O and x_{C_H} increase with the complementor's advantage r_H. In the ecosystem, orchestrator's x_O increases, but at a lower rate than in the integrated benchmark, which results in a higher penalty when r_H is higher. Complementor's x_{C_H} exhibits negative direct effect and positive indirect effect, which is lower than that in the integrated benchmark. As a result, for complementor the penalty also increases with higher r_H.

Figures 4a and 4b visualize equilibrium efforts and show how the gap between the integrated benchmark and decentralized ecosystem grows as the players' *ex ante* capabilities grow. Below are the equilibrium efforts for the integrated actor:

$$x_O^{I*} = \frac{1}{3}(s_O + 2r_H + 2s_{C_L}),$$
$$x_{C_H}^{I*} = \frac{1}{3}(2s_O + r_H + s_{C_L}).$$

For the formulas for equilibrium efforts in the ecosystem, we first find x_O such that $\frac{\partial \pi_O(s_O, x_O, x_{C_H}, r_H, s_{C_L})}{\partial x_O} = 0$. This yields $x_O = \frac{1}{3}(r_H + s_{C_L} + x_{C_H} + \frac{s_{C_L}^2}{r_H + 2s_{C_L} + x_{C_H}})$, which we then use to substitute for x_O in $\frac{\partial \pi_{C_H}(s_O, x_O, x_{C_H}, r_H, s_{C_L})}{\partial x_{C_H}} = 0$ to find the complementor's equilibrium effort. Complementor's equilibrium effort $x_{C_H}^*$ is the non-negative root of the equation $\frac{1}{9}(r_H + s_{C_L} + 3s_O - 8x_{C_H} + \frac{s_{C_L}(2s_{C_L}^3 - 2s_{C_L}(s_{C_L} - 3s_O)(r_H + 2s_{C_L} + x_{C_H}) + 3s_{C_L}(r_H + 2s_{C_L} + x_{C_H})^2}{(r_H + 2s_{C_L} + x_{C_H})^3}) = 0$ for the range of parameters $s_O \geq 0$, $r_H \geq 0$, $s_{C_L} \geq 0$. We then use this $x_{C_H}^*$ to substitute for x_{C_H} in the previous formula for $x_O = \frac{1}{3}(r_H + s_{C_L} + x_{C_H} + \frac{s_{C_L}^2}{r_H + 2s_{C_L} + x_{C_H}})$ to find the equilibrium effort of the orchestrator x_O^*. For both equilibrium efforts, $x_{C_H}^*$ and x_O^*, the ensuing formulas are unwieldy. We use *Mathematica* to generate numerical solutions for given levels of s_O, r_H and s_{C_L}, similarly to the additive value creation scenario. We find $\{x_O^*, x_{C_H}^*\}$ that are the solution to the following system of equations:

$$\begin{cases} x_O = \arg\max\limits_{x_O} \left[p_O(x_O, s_O, s_{C_L}, r_H, x_{C_H}) - \frac{1}{2}x_O^2 \right], \\ x_{C_H} = \arg\max\limits_{x_{C_H}} \left[p_{C_H}(x_O, s_O, s_{C_L}, r_H, x_{C_H}) - \frac{1}{2}x_{C_H}^2 \right], \\ x_O \geq, x_{C_H} \geq 0. \end{cases} \tag{9}$$

Figure 12a shows the equilibrium effort in the orchestrator's component by the integrated benchmark (dashed line) and in the ecosystem (solid line) for $s_O \in (0, 3)$, $s_{C_L} = 1$, and different levels of $r_H \in (0, 8)$. It illustrates how the gap between the integrated benchmark and the ecosystem effort grows as the players' *ex ante* capabilities grow (the gap is larger at higher levels of s_O and r_H). Figure 12b provides the illustration for the complementor's component for $r_H \in (0, 3)$, $s_{C_L} = 1$, and different levels of $s_O \in (0, 8)$ and shows that the gap between the integrated benchmark and the ecosystem effort is larger at higher levels of s_O and r_H. ■

Proof of Proposition 3. Under the weakest link value creation technology we have the following characteristic function:

S	$v(S)$
$\{O, B, C_L, C_H\}$	$\min(V_O, V_{C_H})$
$\{O, B, C_L\}$	$\min(V_O, V_{C_L})$
$\{O, B, C_H\}$	$\min(V_O, V_{C_H})$
Any other subset of N	0

Table 5: Characteristic function under weakest link value creation technology

Assuming that complementor C_L does not develop in the equilibrium, we have $v(S) = \min(s_O + x_O, s_{C_L} + r_H + x_{C_H})$. The integrated actor has to solve the following maximization problem:

$$\max_{x_O, x_{C_H}} \pi_I = \frac{1}{2}\min(s_O + x_O, s_{C_L} + r_H + x_{C_H}) - \frac{1}{2}x_O^2 - \frac{1}{2}x_{C_H}^2.$$

Assume that the orchestrator and the complementor C_H have the same starting level of capabilities $s_O = s_{C_H} = s$. Then the integrated actor needs to improve *both* components by w, resulting in payoff $\pi_I(w) = \frac{1}{2}(s + w) - w^2$, and $\frac{\partial \pi_I(w)}{\partial w} = 2(\frac{1}{4} - w)$. The integrated actor will only get $\frac{1}{4}$ return to its investment w.

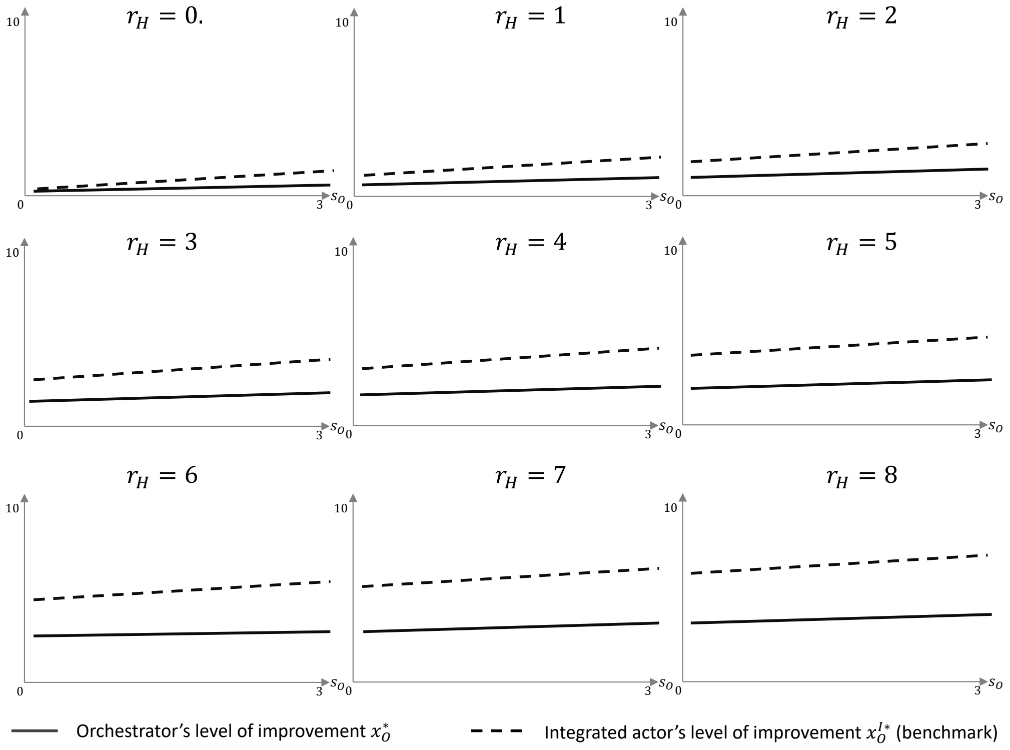
Compare this to the optimization problems of the orchestrator and the complementor in an ecosystem, respectively:

$$\max_{x_O} \left[p_O - \frac{1}{2}x_O^2 \right],$$

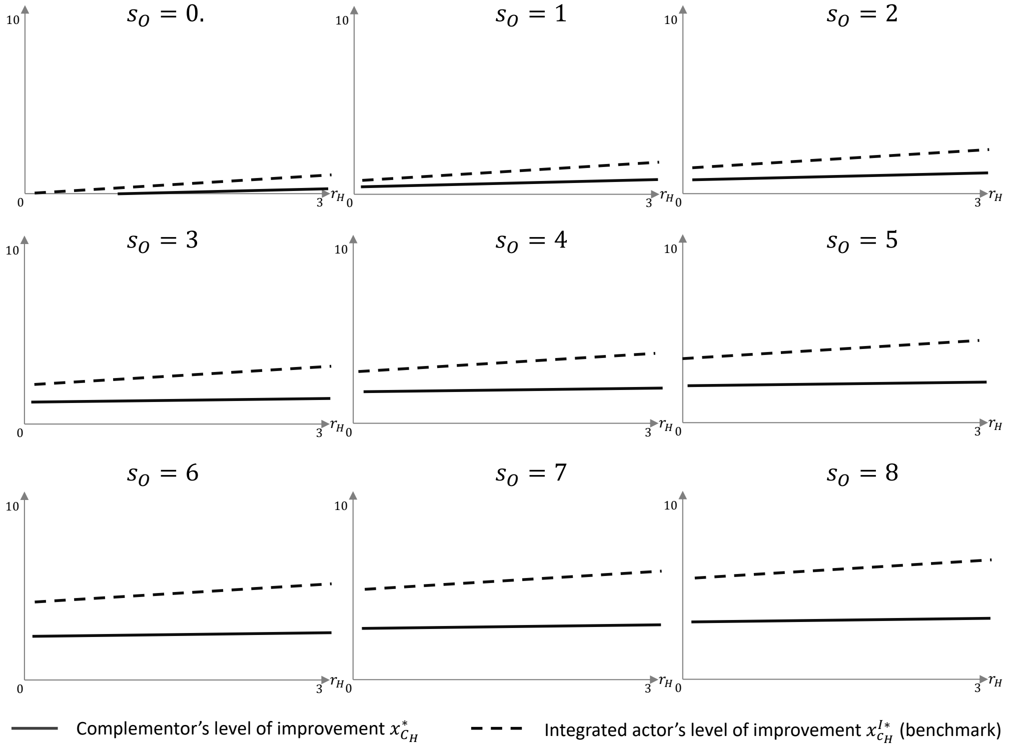
$$\max_{x_{C_H}} \left[p_{C_H} - \frac{1}{2}x_{C_H}^2 \right],$$

Because we are looking at the case when $s_O = s_{C_H} = s$ then by definition $s > s_{C_L}$. We thus have the following value creation: $v\{O, B, C_L, C_H\} = s + w$ and $v\{O, B, C_L\} = s_{C_L}$. Using the allocation of value from Lemma 6 (where b is substituted for $v\{O, B, C_L, C_H\}$ and a is substituted for $v\{O, B, C_L\}$) we have the following expected allocation of value:

$$\begin{aligned} p_O &= \frac{1}{3}(s + w + \frac{s_{C_L}^2}{s + s_{C_L} + w}), \\ p_B &= \frac{1}{3}(s + w + \frac{s_{C_L}^2}{s + s_{C_L} + w}), \\ p_{C_H} &= \frac{1}{3}(s + w - \frac{2s_{C_L}^2}{s + s_{C_L} + w}), \\ p_{C_L} &= 0. \end{aligned}$$



(a) Orchestrator's equilibrium effort x_O



(b) Complementor's equilibrium effort x_{C_H}

Figure 12: Multiplicative value creation: numerical solutions for equilibrium x_O and x_{C_H}, at $s_{C_L} = 1$.

We get the following marginal returns:

$$\frac{\partial p_O}{\partial w} = \frac{1}{3}(1 - \frac{s_{C_L}^2}{(s + s_{C_L} + w)^2}),$$
$$\frac{\partial p_{C_H}}{\partial w} = \frac{1}{3}(1 + \frac{2s_{C_L}^2}{(s + s_{C_L} + w)^2}).$$

If is obvious that for the complementor $\frac{\partial p_{C_H}}{\partial w} > \frac{1}{3}$. Because in this case $s_{C_L} < s$ we can see that for the orchestrator $\frac{s_{C_L}^2}{(s+s_{C_L}+w)^2} < \frac{1}{4}$, meaning that $\frac{\partial p_O}{\partial w} > \frac{1}{4}$. Marginal returns for both the orchestrator and the complementor are higher than $\frac{1}{4}$ meaning that in the equilibrium the orchestrator and the complementor will set a higher development level than the integrated actor, whose return is $\frac{1}{4}$. ■

Proof of Propositions 4 and 5.

If the starting levels of capabilities of the orchestrator's and the complementor's component are different, we have three different scenarios of value creation and expected value capture depending on the relative positioning of V_O with respect to V_{C_L} and $V_{C_H} + r$. Table 6 specifies the characteristic function under each of those scenarios:

	Scenario 1	Scenario 2	Scenario 3
S	$V_O < V_{C_L}$	$V_{C_L} < V_O < V_{C_H}$	$V_{C_H} < V_O$
$\{O, B, C_L, C_H\}$	$V_O = s_O + x_O$	$V_O = s_O + x_O$	$V_{C_H} = s_{C_L} + r_H + x_{C_H}$
$\{O, B, C_L\}$	$V_O = s_O + x_O$	$V_{C_L} = s_{C_L}$	$V_{C_L} = s_{C_L}$
$\{O, B, C_H\}$	$V_O = s_O + x_O$	$V_O = s_O + x_O$	$V_{C_H} = s_{C_L} + r_H + x_{C_H}$
Any other subset of N	0	0	0

Table 6: Three scenarios of value creation under the weakest link value creation technology

Given the characteristic function in Table 6 and the allocation of value from Lemma 6 (where b is substituted for $v\{O, B, C_L, C_H\}$ and a is substituted for $v\{O, B, C_L\}$) we have following value capture in each scenario provided in Table 7.

Since this is a complex scenario with transitions across three cases of value creation and capture, and, on top of that, the orchestrator and the complementor need to match the overall level of capabilities, it is not possible to find a closed-form solution for the equilibrium effort in either ecosystem or integrated benchmark. We thus use numeric solutions to map the equilibrium efforts in the orchestrator's and complementor's components. For the ecosystem, we use p_i from Table 7 to plug into the payoff function of the orchestrator and complementor and solve for the following system of equations:

$$\begin{cases} x_O = \arg\max_{x_O} \left[p_O(x_O, s_O, s_{C_L}, r_H, x_{C_H}) - \frac{1}{2}x_O^2 \right], \\ x_{C_H} = \arg\max_{x_{C_H}} \left[p_{C_H}(x_O, s_O, s_{C_L}, r_H, x_{C_H}) - \frac{1}{2}x_{C_H}^2 \right], \\ x_O \geq 0, x_{C_H} \geq 0, \end{cases} \tag{10}$$

	Scenario 1	Scenario 2	Scenario 3
p_i	$V_O < V_{C_L}$	$V_{C_L} < V_O < V_{C_H}$	$V_{C_H} < V_O$
p_O	$\frac{1}{2}(s_O + x_O)$	$\frac{s_{C_L}^2 + s_{C_L}(s_O + x_O) + (s_O + x_O)^2}{3(s_{C_L} + s_O + x_O)}$	$\frac{s_{C_L}^2 + s_{C_L}(r_H + s_{C_L} + x_{C_H}) + (r_H + s_{C_L} + x_{C_H})^2}{3(r_H + 2s_{C_L} + x_{C_H})}$
p_B	$\frac{1}{2}(s_O + x_O)$	$\frac{s_{C_L}^2 + s_{C_L}(s_O + x_O) + (s_O + x_O)^2}{3(s_{C_L} + s_O + x_O)}$	$\frac{s_{C_L}^2 + s_{C_L}(r_H + s_{C_L} + x_{C_H}) + (r_H + s_{C_L} + x_{C_H})^2}{3(r_H + 2s_{C_L} + x_{C_H})}$
p_{C_H}	0	$\frac{(s_O + x_O - s_{C_L})(2s_{C_L} + s_O + x_O)}{3(s_{C_L} + s_O + x_O)}$	$\frac{(r_H + x_{C_H})(r_H + 3s_{C_L} + x_{C_H})}{3(r_H + 2s_{C_L} + x_{C_H})}$
p_{C_L}	0	0	0

Table 7: Three scenarios of value allocation under the weakest link value creation technology

picking the largest x_O, x_{C_H} that satisfy the equations.

For the integrated benchmark we solve:

$$\max_{x_O, x_{C_H}} \left[\frac{1}{2} \min(s_O + x_O, s_{C_L} + r_H + x_{C_H}) - \frac{1}{2} x_O^2 - \frac{1}{2} x_{C_H}^2 \right], x_O \geq 0, x_{C_H} \geq 0$$

Figures 5 and 8 show the results. While we cannot provide a closed-from solution we can still use mathematical calculations to explain the intuition behind the numerical results, through marginal returns in each scenario in Table 7.

Marginal returns:

Scenario 1, $V_O < s_{C_L}$: It is straightforward from Table 7 that in this case each complementor has zero added value and thus captures zero. Value is split between the orchestrator and the buyer. Marginal returns for the orchestrator are $\frac{\partial p_O}{\partial x_O} = \frac{1}{2}$.

Scenario 2, $V_{C_L} < V_O < V_{C_L} + r_H$: Using value capture by the orchestrator p_O from Table 7, the marginal returns to the orchestrator's investment in an ecosystem are $\frac{\partial p_O}{\partial x_O} = \frac{1}{3} - \frac{s_{C_L}^2}{3(s_{C_L} + s_O + x_O)^2}$, and cross derivative in x_O and s_O is $\frac{\partial p_O^2}{\partial x_O \partial s_O} = \frac{2s_{C_L}^2}{3(s_{C_L} + s_O + x_O)^3} > 0$. Thus, x_O and s_O are complements. When $s_O + x_O \to +\infty$ we have $\frac{\partial p_O}{\partial x_O} \to \frac{1}{3}$. When $s_O + x_O \to s_{C_L}$ (lower bound since in this scenario $V_{C_L} < V_O < V_{C_H}$) we have $\frac{\partial p_O}{\partial x_O} \to \frac{1}{4}$. Therefore, in the scenario where the overall orchestrator's capabilities $s_O + x_O$ are sitting between the total capabilities of the complementors, the lowest marginal return to the orchestrator's improvement will be $\frac{1}{4}$, and the highest marginal return will be $\frac{1}{3}$, and increasing in s_O.

Scenario 3, $V_{C_H} < V_O$: Using value capture by the complementor p_{C_H} from Table 7, the marginal returns to the complementor's investment in an ecosystem are $\frac{\partial p_{C_H}}{\partial x_{C_H}} = \frac{1}{3} + \frac{2s_{C_L}^2}{3(r_H + 2s_{C_L} + x_{C_H})^2}$, and cross derivative in x_{C_H} and r_H is $\frac{\partial p_{C_H}^2}{\partial x_{C_H} \partial r_H} = -\frac{4s_{C_L}^2}{3(r_H + 2s_{C_L} + x_{C_H})^3} < 0$. Thus, x_{C_H} and r_H are substitutes. When $r_H + x_{C_H} \to +\infty$ we have $\frac{\partial p_{C_H}}{\partial x_{C_H}} \to \frac{1}{3}$. When $r_H + x_{C_H} \to 0$ we have $\frac{\partial p_{C_H}}{\partial x_{C_H}} \to \frac{1}{2}$. Therefore, in the scenario where the complementor's total capabilities are below those or the orchestrator, the highest marginal return to the complementor's improvement will be $\frac{1}{2}$, and the lowest marginal return will be $\frac{1}{3}$, and decreasing in r_H.

Linking marginal returns to numerical solutions in Figure 5

We explain the mathematical intuition behind Figure 5 using marginal returns calculated above. The explanation is from left to right.

1. **From** $s_O = 0$ **to** (a): Development level by the orchestrator is a straight line defined by $c'(x_O) = \frac{1}{2}$, and $x_O = x_O^A$ (where A stands for "Aligned") as long as $s_O + x_O < s_{C_L}$ (scenario 1 from the above).

2. **Breaking point** (a)**, and from** (a) **to** (b): Breaking point (a) happens when $s_O + x_O^A = s_{C_L}$. This is where the orchestrator transitions from the state with marginal return of $\frac{1}{2}$ to just matching the level of the inferior complementor s_{C_L} (because $x_{C_L} = 0$ by assumption). The orchestrator reduces its development to match the inferior complementor's level because if it goes further then the marginal return jumps down to $\frac{1}{4}$ (see scenario 2 from the above, where $s_O + x_O \to s_{C_L}$). We have the orchestrator setting its development level such that $s_O + x_O = s_{C_L}$ which defines $x_O^{MI} = s_{C_L} - s_O$ (where MI stands for "Matching Inferior complementor"). This means that x_O decreases in s_O in that segment, in a 45 degree line, until the next breaking point at which $s_{C_L} - s_O = x_O^{FD}$ (see below)

3. **Breaking point** (b)**, and from** (b) **to** (c): The second breaking point happens when the orchestrator finds it profitable to resume the development, without just matching s_{C_L} by stopping development at the level x_O^{MI}. This happens when its x_O^{FD} (where FD stands for "Full Development") given the level of its marginal returns when $s_O + x_O = s_{C_L}$ becomes as high as its x_O^{MI} from matching the inferior complementor.

   On the right side of the breaking point (b) the orchestrator is developing for the marginal return of $\frac{1}{4}$ (from scenario 2 from the above when $s_O + x_O \to s_{C_L}$). Here the equation $c'(x_O) = \frac{1}{4}$ defines the level of development $x_O^{FD^{(b)}}$ such that $x_O^{FD^{(b)}} = c'^{-1}(\frac{1}{4})$ (c'^{-1} being the inverse function of c'), or $x_O^{FD^{(b)}} = \arg\max_{x_O} p_O - c(x_O)$ when $s_O + x_O = s_{C_L}$.

   At the breaking point we have development just to match $x_O^{MI} = s_{C_L} - s_O$, and then $x_O^{FD^{(b)}} = s_{C_L} - s_O$. This means that the breaking point happens at $s_O(b) = s_{C_L} - x_O^{FD^{(b)}} = s_{C_L} - c'^{-1}(\frac{1}{4})$, and the development level is $x_O^{FD^{(b)}}$.

   From (b) to (c): the orchestrator develops at $x_O^{FD} = \arg\max_{x_O} p_O(s_O) - c(x_O)$.

4. **Breaking point** (e): Until point (e) the superior complementor C_H does not develop because the orchestrator is far below, and $s_O + x_O < s_{C_L} + r_H$. At point (e) we have $s_O + x_O = s_{C_L} + r_H$ and in that situation the superior complementor starts developing, to match the level of the total capability of the orchestrator. This happens because the marginal return to development for that complementor is always strictly higher than that of the orchestrator. Thus, with the same cost function, the complementor is simply catching up and stopping when it reaches the orchestrator's level. See scenario 3 from the above (because after point (e), when the orchestrator develops, while *ex ante* orchestrators capability s_O is less that that of the complementor, the total *ex post* capabilities of the orchestrator $s_O + x_O$ are above): complementors returns are between $\frac{1}{3}$ and $\frac{1}{2}$, while when the orchestrator develops it's scenario 2, and the orchestrator's returns are between $\frac{1}{4}$ and $\frac{1}{3}$.

5. **From point** (e) **to point** (c): Orchestrator still develops at $x_O^{FD} = \arg\max_{x_O} p_O(s_O) - c(x_O)$. Complementor develops at $x_{C_H} = s_O - s_{C_L} - r_H + x_O^{FD}(s_O)$ so that it matches the *ex post* total level of orchestrator's capabilities.

6. **Breaking point** (c): At point (c), s_O is so high that the superior complementor develops at a constant level because it is reaching its own maximum, which implies that the orchestrator now is just matching that level as the complementor is now the weakest link. Maximum rational development by the complementor is defined as $x_{C_H}^{FD}$ (where FD stands for "Full Development") given s_O, which is the solution to $\partial_{x_{C_H}} p_{C_H}(x_{C_H}, s_O) = c'_H(x_{C_H})$. Complementor stops developing when $x_{C_H}^{FD}(s_O)$ reaches the level of development of the $s_{C_L} + r_H + x_{C_H}^{FD}(s_O) = s_O + x_O^{FD}(s_O)$, which is the case at $s_O^{(c)}$, i.e., $s_O^{(c)}$ is defined by the above equation.

7. **From point** (c) **to** (d) **and on**: Now that the complementor is reaching a plateau and is the weakest link, the orchestrator is just matching the level of the development of the complementor. Given that the complementor develops at fixed level $x_{C_H}^{FD}(s_O^{(c)})$, the orchestrator develops at level x_O such that $s_O + x_O = s_{C_L} + r_H + x_{C_H}^{FD}(s_O^{(c)})$. Thus, for $s_O \geq s_O^{(c)}$ we have $x_O = s_{C_L} + r_H + x_{C_H}^{FD}(s_O^{(c)}) - s_O$ until $x_O = 0$ at $s_O = s_{C_L} + r_H + x_{C_H}^{FD}(s_O^{(c)})$, which defines breaking point (d) in the figure. Then $x_O = 0$ for any value of s_O.

Linking marginal returns to numerical solutions in Figure 8

1. **From** $r_H = 0$ **to** (c): this is a counterpart to point 7 from the previous, beyond point (d) in Figure 5, showing x_{C_H} at fixed s_O as a function of r_H. Here the complementor is behind the orchestrator, and $s_{C_L} + r_H + x_{C_H} < s_O$. Complementor sets its development level $x_{C_H}^{FD} = \arg\max_{x_{C_H}} p_{C_H}(r_H) - c(x_{C_H})$.

2. **Breaking point** (c) **and from** (c) **to** (a): Until point (c) orchestrator doesn't develop because the complementor is far below, so $s_{C_L} + r_H + x_{C_H} < s_O$. At point (c) we have $s_{C_L} + r_H + x_{C_H} = s_O$, so the orchestrator starts developing to match the complementor. For the orchestrator, this is a mirror image of the area between points (d) and (c) in Figure 5. Complementor continues to make effort $x_{C_H}^{FD} = \arg\max_{x_{C_H}} p_{C_H}(r_H) - c(x_{C_H})$.

3. **Breaking point** (a) **and from** (a) **to** (b): At the breaking point (a) r_H is so high that the orchestrator develops at a constant level (in r_H) because it is reaching its maximum and is now becoming the weakest link. This corresponds to the area to the left of point (c) in Figure 5. Complementor is simply matching the level of the orchestrator. This is the reverse of the dynamic described in point 6 in the previous discussion. At point (b) we have $s_{C_L} + r_H = s_O + x_O(r_H^{(b)})$, i.e. the *ex ante* capabilities of the complementor are equal to the *ex post* total level of the orchestrator's capabilities given the orchestrator's equilibrium development effort. At this point and afterwards $x_{C_H} = 0$.

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