VALUE CREATION AND CAPTURE IN A WORLD OF BOTTLENECKS

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Firms in ecosystems depend on one another to provide the components that together comprise valuable costumer solutions. As a result, the performance of individual firms may be limited by bottlenecks, which are components of the ecosystem that constrain overall performance due to their scarcity or insufficient quality. Bottlenecks are critical to the functioning of ecosystems. But despite their importance, gaps remain with respect to how firms can address bottlenecks that lie outside their boundaries. We address this gap through a formal mathematical model. Specifically, we examine two strategies with which firms can work with partners to resolve bottlenecks: improving partner capabilities, and collaboratively introducing systemic innovations. We find that the viability of each depends on the interaction between firm capabilities, the level of technological uncertainty, and the contracting environment. Through this analysis, we contribute to the growing body of research on ecosystems.

Key words: *ecosystems, bottlenecks, biform game*

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Many industries consist of networks of interdependent firms, called *ecosystems*, wherein the products that consumers value are composed of multiple, distinct components (Adner, 2012; Ozcan and Santos, 2014). Examples of such industries include personal computers (hardware and software), mobile phones (handsets, network, operating systems, content), and electric vehicles (cars, batteries, and charging infrastructure). In ecosystems, firms depend on one another to create value, which occurs when firms are able to collectively produce all of the components that comprise the final product (Adner and Kapoor, 2010; Brusoni and Prencipe, 2013). But their ability to do so is not always assured. As Adner (2006: 3) describes in his seminal article:

> *"Along with new opportunities, innovation ecosystems also present a new set of risks – new dependencies that can brutally derail a firm's best efforts. Even if a firm develops its own innovation brilliantly, meets and exceeds its customers' needs, and successfully excludes its rivals, a market may not emerge. Whether – and when – it emerges is determined as much by the firm's partners as by its own performance."*

In this paper, we develop a formal model that describes how and when firms are able to work with partners to address *technical bottlenecks*, which are the components of the ecosystem that inhibit its overall performance due to either scarcity or insufficient quality (Baldwin, 2015; Jacobides et al, 2006). Bottlenecks are critical to the functioning of ecosystems because they limit firms' ability to jointly create value (Ethiraj, 2007; Adner and Feiler, 2015; Hughes, 1983). At the same time, bottlenecks also affect how value is distributed across ecosystem participants, by shaping power dynamics, dictating firm profitability, and determining the contribution of each participant to the overall ecosystem (Jacobides and Tae, 2015). Bottlenecks, and the ways in which firms attempt to address them, are thus a critical determinant of firm performance.

The literature abounds with examples of bottlenecks. For example, Hughes (1983) documents how a bottleneck in transmission infrastructure (a component of the electric utility ecosystem) delayed the implementation of new technologies in the generation component: by limiting the ability of utilities to deliver electricity to their customers, the transmission bottleneck rendered any improvements in generation immaterial. Similarly, Adner (2012) discusses how the lack of cost effective battery technology represents a "weak link" that has hindered the development of the broader electric vehicle (EV) ecosystem. Hannah and Eisenhardt (2015) document how the lack of affordable consumer financing initially constrained the growth of the US residential solar industry. A key insight is that bottlenecks are driven by the performance, quality, or availability of one component falling behind that of its complements (Jacobides et al, 2006). They are thus likely to emerge when the rate of innovation in one component lags behind the innovation in others (Ethiraj, 2007; Christensen, Verlinden, and Westerman, 2002).

Recent research has identified several strategic responses to the emergence of bottlenecks in an ecosystem. For example, scholars have noted that firms may enter bottleneck components that constrain their ability to create value in their own components (Gawer and Henderson, 2007; Uzunca, Sharapov, and Tee, 2015). Entering bottlenecks allows firms to resolve bottlenecks directly, and to do so without relying on partners (Zhu and Liu, 2015). For example, Tesla began producing batteries in order to address that bottleneck in the EV ecosystem.

In this analysis, we focus on an alternate strategy, which is to work with partners to resolve bottlenecks. For example, research has found that firms may develop and distribute knowledge of components outside their own in order to improve the ability of their partners to innovate (Patel and Pavitt, 1997; Gawer and Henderson, 2007; Dyer and Hatch, 2006). Alternately, firms may collaborate with partners to resolve bottlenecks by introducing novel systemic innovations that span previous component boundaries (Kapoor, 2013b; Sanchez and Mahoney, 1996). But while research has hinted at what form these strategies may take, we know less about the conditions under which they are effective, or what firms are likely to implement them.

We address this gap through a formal model. In particular, we draw on work in cooperative game theory and the value based approach (Brandenburger and Stuart, 1996; MacDonald and Ryall, 2004) to model the creation and allocation of value across an ecosystem. We develop a *biform game*; a two-stage model that represents both the competitive moves (e.g., partnerships and investments) that firms make in order to position themselves favorably in the ecosystem as well as their subsequent negotiation over the distribution of value (Brandenburger and Stuart, 2007; Chatain and Zemsky, 2007; 2011). Unlike the non-cooperative game theory methods used in older formal models of ecosystem strategy (e.g., Farrell et al, 1998), biform games require few assumptions regarding how firms interact, and are thus well-suited modeling the "free-form" negotiations that characterize interactions between ecosystem participants (Adner, 2012).

We contribute to research on strategy in ecosystems. Our main contribution is to examine two strategies by which firms can work with partners to resolve bottlenecks, and to identify the firm and industry characteristics under which each is viable. We first examine the *improving strategy*, in which firms devote resources to improving the capabilities of firms in the bottleneck component. This strategy is attractive to firms with relatively strong capabilities (i.e., the leaders in each component), as these firms are unable to realize the full value of their capabilities when constrained by deficient partners. In contrast, weaker firms benefit more from improving their own capabilities. We also examine the *co-innovating strategy*, in which firms work with partners to introduce novel systemic innovations. This strategy allows firms to create additional value by closely coordinating with one another, but also constrains firms' ability to capture value by requiring them to co-specialize. It is most attractive to firms with weaker capabilities, who are likely to capture little value otherwise. In contrast, firms with stronger capabilities generally have more to lose from co-specialization (and thus co-innovation), and are thus likely to co-innovate only when they can pre-specify the allocation of value across partners through contracts. A related contribution is to examine the impact of technological uncertainty on firm performance and willingness to co-innovate or improve partners. We find that uncertainty attenuates competition by increasing the risk that stronger firms fail. As a result, weaker firms actually benefit from greater levels of uncertainty, and are more willing to co-innovate or improve partners.

BACKGROUND

Ecosystems occupy a growing role in the business and academic literature (Adner, 2006; Kapoor and Lee, 2013). A central question in this research is how interdependence affects firms' ability to create and capture value, and how firms navigate the interdependencies that define ecosystem participation (Kapoor and Lee, 2013; Hannah, Bremner, and Eisenhardt, 2015). A key insight is that the value of any one component is contingent on the availability and access to the other components that comprise the final product. In settings where firms cannot produce all of the required components internally, firms thus rely on one another to *jointly* create value.

One implication of this interdependence is that bottlenecks in one part of an ecosystem can constrain the performance of firms across the ecosystem (Ethiraj, 2007; Baldwin, 2015). For example, Adner and Kapoor (2010) show that in the semiconductor lithography industry, technological setbacks in complementary components (masks and resists) limited the first mover advantages that accrued to lithography tool manufacturers. Similarly, executives at Intel realized that the performance of their microprocessor business was constrained by the bottlenecks that existed in the peripherals component that supplied data to the microprocessors (Gawer and Henderson, 2007). As one manager stated, *"the real way you make money is by selling faster processors. And you can't sell faster processors if you don't have data to operate on"* (2007: 12). In other words, bottlenecks such as these limit the ability of firms to create value (Ethiraj, 2007).

One way in which firms can address bottlenecks is to enter the bottleneck components and resolve them internally (Hannah and Eisenhardt, 2015; Gawer and Henderson, 2007). However, in many cases this may not be possible. For example, firms may lack the capabilities or resources to effectively address the bottleneck. In their case study of Intel, for example, Gawer and Henderson (2007) find that Intel entered bottlenecks only when it already had the required technological capabilities. Similarly, firms may lack the financial resources to enter the bottleneck, as Hannah and Eisenhardt (2015) observe in the residential solar industry. In other cases, firms may be prohibited from entering the bottleneck due to intellectual property or other legal barriers. For example, regulations prevent many electric utilities from owning transmission or generation infrastructure, thus preventing them from directly addressing bottlenecks that arise in those components. Finally, it may be that executives may choose not to enter bottlenecks in order to maintain organizational focus (Hannah et al, 2015). But whatever the reason, firms that do not enter bottlenecks will still be constrained, and thus need another strategy to address them.

Collaborating with complementors

Another way firms can address bottlenecks is by collaborating with the firms already in the bottleneck components. Prior research on modular systems and transaction cost economics offers insight into how they may do so (Teece, 1986; Langlois and Robertson, 1996; Jacobides et al, 2015a; Hoetker, 2006; Kapoor, 2013b). A key consideration is the *modularity* of the ecosystem, which describes the degree to which the components interact through standardized interfaces, rules, and specifications (Baldwin and Clark, 2000). Within modular ecosystems, changes in one component do not require extensive changes or coordination across components (Simon, 1962; Baldwin and Clark, 2000; Garud, Kumaraswamy, and Langlois, 2003). As a result, firms may be able to address the bottleneck without affecting their interactions with their complementors (i.e., the firms producing complementary components). In contrast, in less modular settings, changes made in one component must also be coordinated with complementors.

But modularity is both a technological feature and a strategic outcome (Prencipe, 1997;

Kapoor, 2013b; Fixson and Park, 2008; Schilling, 2000). That is, firms can choose to work with partners to resolve bottlenecks by innovating *within* a single component or by innovating *across* multiple components. Each strategy brings its own distinct advantages and disadvantages.

One strategy is to work with partners to improve the performance of the bottleneck component without changing its relationship or interface with the remaining components. In other words, to innovate *within* the bottleneck. For example, Hannah and Eisenhardt (2015) show that in the nascent residential solar industry, firms in the sales component were constrained by the inferior capabilities of the firms in the installation component. The sales firms addressed this bottleneck by providing their installation partners with training and logistics support in order to improve the quality of their output, and thus the performance of the overall ecosystem. Similarly, Intel addressed the lagging capabilities of its complementors in the semiconductor ecosystem by providing them with IP and technical support (Gawer and Henderson, 2007). We term this strategy – investing in improving the capabilities of the firms in the bottleneck component – an *improving strategy*. The advantage of an improving strategy is that it addresses the bottleneck while preserving the modularity of the ecosystem. In other words, changes in the bottleneck component do not require changes in other components. As a result, components can be readily mixed and matched (Farrell et al, 1998), and firms do not necessarily depend on specific partners to provide complementary components. The primary disadvantage of the improving strategy is that it may not allow firms to realize *greater* gains that might be achieved by changing the interfaces or arrangements of components (Baldwin and Clark, 2000; Ethiraj and Levinthal, 2004).

A second strategy is to work with partners to innovate *across* component boundaries. We term this strategy a *co-innovation strategy*. Co-innovation involves firms working together to introduce systemic or architectural innovations, which are those that require extensive changes in the coordination and interface between components (Brusoni and Prencipe, 2006; Kapoor, 2013).

For example, Garmin (a fitness hardware company) and Strava (an online fitness network) have co-specialized their products in order to realize innovative features through the close integration of Garmin's precise GPS data with Strava's online community. Similarly, Adner (2012) explores Amazon's entry into the electronic book ecosystem. In addition to developing its own hardware component (the Kindle e-reader), Amazon worked with publishers to develop novel e-book pricing and distribution methods for the remaining component (e-books). The advantage of the co-innovation strategy is that it can allow firms to create additional value by relaxing the constraints imposed by standard interfaces, and by allowing firms to obviate bottleneck components by introducing new and better ways of meeting consumer demand for the final product (Kapoor, 2013b; Fixson and Park, 2008; Ulrich, 1995). The disadvantage of the co-innovation strategy is that firms' ability to create value depends on the collaboration and performance of their specific co-innovation partners (Casadesus-Masanell and Yoffie, 2007; Adner and Feiler, 2015).

Both the *improving strategy* and the *co-innovation strategy* may allow firms to address bottlenecks and thus to create value. But while this is understood in general, unresolved issues remain. First, the choice of strategies by which firms resolve bottlenecks is likely to have a profound impact on their subsequent ability to capture value. For example, firms that co-innovate to introduce systemic innovations are subsequently more likely to be dependent on one another to create value (Teece, 1986; Qian et al, 2012). In other words, they will have *co-specialized* (Santoro and McGill, 2005; Mowery, Oxley, and Silverman, 2001). Co-innovating firms may thus be more likely to be able to create value (Kapoor, 2013a; Baldwin and Clark, 2000), but are simultaneously subject to greater expropriation concerns (Williamson, 1985; Dyer and Singh, 1998). At the same time, the improving strategy may limit firms' ability to capture value as well, by increasing partners' relative bargaining power (Katila, Rosenberger, and Eisenhardt, 2008; Lavie, 2007; Adegbesan and Higgins, 2010). For example, Hannah and Eisenhardt (2015) observe that as a result of improving their partners' capabilities, solar companies found it more difficult to maintain bargaining power to these firms. However, prior work has yet to examine the tradeoff between value capture and value creation in the collaborative resolution of bottlenecks. Thus, a gap remains with respect to how doing so will impact firm and ecosystem performance.

Second, even if a particular strategy is attractive to a focal firm, it is not clear when *partners* will be willing to collaborate in its implementation. Both improving and co-innovating require "buy-in" from multiple firms: firms cannot force their partners to collaborate. But because firms in ecosystem simultaneously collaborate to create value and compete to capture it, their incentives regarding potential changes may be misaligned (Adner, Chen, and Zhu, 2015; Casadesus-Masanell and Yoffie, 2007). For example, cinemas initially resisted the switch from 35mm film to digital projection technology, which alleviated a bottleneck in projector quality (benefiting consumers and movie studies) but did not improve the performance of the cinemas themselves (Adner, 2012). Similarly, Ozcan and Santos (2014) document the reticence of firms in the nascent mobile payments ecosystem to collaborate on the development of new technologies that they perceived as benefiting their partners more than themselves. But despite the rich examples of firms working (and sometimes failing) to address bottlenecks (e.g., Adner, 2012), gaps remain with respect to how the resolution of bottlenecks affects firms across the ecosystem, as well as the conditions under which firms will be able to collaboratively resolve them.

Finally, although the literature identifies several variables that affect the performance of each strategy, the relationship between these variables is not clear. In particular, the distribution of capabilities (Ethiraj, 2007; Lavie, 2007), the degree of modularity and the value created by systemic innovations (Baldwin and Clark, 2000), the appropriability regime and the availability of effective contracts (Teece, 1986; Jacobides et al, 2006), and the level of technological uncertainty (Afuah, 2000; Brusoni and Prencipe, 2013) may all affect the viability of each strategy. It is not clear, however, how the variables interact, whether they compound or counteract one another, and how they affect firms' ability create and capture value. This limits the prescriptive value of existing findings to real-world situations, which vary across multiple dimensions.

We address these gaps with a formal game theoretic model. The paper is structured as follows. We first develop a benchmark model that depicts a set of interdependent firms jointly creating value and then competing over its allocation. We demonstrate that its basic predictions are consistent with the received wisdom on ecosystems. We then examine the conditions under which each of the two strategies, *improving* and *co-innovation*, is viable. We first examine the role played by the distribution of capabilities, the contracting environment, value of systemic innovations. We then extend the model by introducing and examining uncertainty.

The value-based approach

We adopt the value-based approach originally developed by Brandenburger and Stuart (1996) and since employed in a growing line of research (e.g., Chatain and Zemsky, 2007; 2011; Jia, 2013; Obloj and Zemsky, 2014). The value-based approach draws on cooperative game theory to model how value is created and allocated among interdependent players.

The use of concepts from cooperative game theory is appropriate for modeling value creation and capture within ecosystems because it is consistent with the idea that players can bargain extensively with one another (Stuart, 2002; Lippman and Rumelt, 2003; MacDonald and Ryall, 2004). In other words, exchange is not anonymous. In contrast, classic models such as Bertrand and Cournot assume existence of price mechanism that allows for anonymous exchange within a well-defined market. Cooperative game theory requires fewer assumptions regarding how players interact, and is thus appropriate for modeling the "free-form" negotiations that characterize interactions between the members of an ecosystem (Adner; 2012; Kapoor, 2013a).

Specifically, we set up a biform game (Brandenburger and Stuart, 2007). Biform games consist of a first stage in which agents take actions, such as forming partnerships or investing in partners, in order to influence the competitive landscape. In a second stage, agents compete over the allocation of value in a landscape shaped by their first-stage actions. This second stage is solved using cooperative game theory methods, which allows a rich depiction of the interactions between agents – in this case, between the firms within an ecosystem.

A BENCHMARK ECOSYSTEM MODEL

We start with a general cooperative game, which consists of a set of N-1 firms and a characteristic function v. We assume that firms have heterogeneous capabilities, and that these capabilities manifest in differences in the quality of the components they produce.[1] Formally, denote K components, each containing N_k firms, and let K_i denote a firm in component k. Further, let k_i be the capability of firm K_i, and rank order the firms such that $k_i > k_{i-1}$ $\forall$ k, i. Thus, K_1 has the strongest capabilities firm in component k, K_2 the second strongest, etc.

We start with a single consumer, denoted C. As is standard in value-based analysis, we assume that value is created by a set of players only if it contains the consumer and at least one firm in each component. Formally, the set of players can be split into K+1 nonempty, disjoint sets $\{N_A, N_B, \ldots, N_K, C\}$ such that $v(G)=0$ if $G \cap N_j = \emptyset$ for any $j \in \{A, \ldots, K+1\}$. The characteristic function v maps any group of players $S \subseteq N$ to the value that they create, so that v(N) gives the total value created by the full set of players. We also assume that $v(\emptyset)=0$ and that v is superadditive so that adding a firm to a set does not decrease the value created: $v(S \backslash j) \leq v(S)$ $\forall$ $j \in N$.

The consumer has a unit demand for the final product, which consists of one of each component. We assume that these components are complements. With firm capabilities (k_i) de-

[1] Prior work has described ecosystem components in terms of both quality (e.g., Ethiraj, 2007; Hannah and Eisenhardt, 2015) and cost (e.g., Farrell et al, 1998; Arora and Bokhari, 2007). We adopt the former, which is used more commonly in the literature on complex product systems (e.g., Baldwin, 2015; Ethiraj and Levinthal, 2004).

noting component quality, this implies that the value created by a set of firms is constrained by component with the lowest maximum capability. Value is created when the lowest maximum capability is greater than the minimum quality threshold demanded by the consumer (which we normalize to 0). Formally, let the characteristic function $v(G) = \min(k_1)$ for $\forall k \in K$, which corresponds to the idea that a group of firms is constrained by the "weakest link" among them.[2]

$$v(G) = \min(k_1) \text{ for } \forall k \in K \quad (1)$$

The intuition of the model is as follows: there is a consumer that demands a single unit of the *ecosystem good* (e.g., a smartphone), which consists of one unit each of the K components (e.g., handset, OS, carrier). Each firm produces a particular type of component, and value is created when the firms come together to provide all of the components that comprise the ecosystem. If a given group of firms does not contain any one type of firm, or the consumer, no value is created (e.g., a handset with no network, or a fully operable phone with no buyer).

To illustrate, assume there is an ecosystem comprised of two components $K=\{A,B\}$, each of which contains two firms $N=\{A_1,A_2,B_1,B_2\}$. Further, let the capability of each firm (and the quality of the components they produce) be as follows:

$a_1=10$ $\quad$ $b_1=8$

$a_2=5$ $\quad$ $b_2=2$

Possible value creation scenarios thus include:

$v(A_1,B_1,C)=8$ $\quad$ $v(A_2,B_1,C)=5$ $\quad$ $v(\ )=0$ otherwise

$v(A_1,B_2,C)=2$ $\quad$ $v(A_2,B_2,C)=2$

We assume that the value created by a set of firms will be equal to the maximum value created by any subset (Stuart, 2002). Thus, in the above, A_1 and B_1 will each produce one com-

[2] More generally, we can denote $v = \gamma(\min(k_1))$, where γ is a monotonic increasing function. The case we analyze in the benchmark model where $\gamma = 1$ thus corresponds to the value created being a linear function of the weakest firm.

ponent, consumer C will consume those components, and value v(N)=8 will be created.

How is this value, once created, allocated across firms? The standard approach in cooperative game theory is to solve for the *core*, which is the set of allocations such that no subset of players can capture more value by breaking away and transacting on their own (Chatain and Zemsky, 2011). Formally, denote x_i the value captured by player i, and define the core so that:

$$\Sigma_{(i \in N)} x_i = v(N) \qquad (2)$$

$$\Sigma_{(i \in G)} x_i \geq v(G) \text{ for all } G \subset N \qquad (3)$$

The first condition ensures efficiency, such that all value is created and divided among the players. The second condition ensures stability, in that no subgroup of players can benefit from breaking away and transacting on its own. The core is an attractive solution concept because it reflects relative power and bargaining among various groups of firms. Moreover, in this game it can be shown that for any firm, an allocation x_{ki} is in the core only if $x_{ki} \in [0, AV(K_i)]$, where $AV(K_i)$ is the firm's *added value*.[3] Added value is the decrease in value creation that would occur if a firm were to be removed from the game. A firm's added value represents the upper bound on its payoff (Brandenburger and Stuart, 1996; 2007). Formally,

$$AV(K_i)(G) \equiv v(G) - v(G \backslash K_i). \qquad (4)$$

Two key limitations of the core as a solution concept are that it can be empty (i.e., no feasible, stable distribution exists) or indeterminate (i.e., it contains a range of possible payoffs). In our model, it is straightforward to show that a stable core exists.[4] In order to address the indeterminacy, we follow Brandenburger and Stuart (2007) and map the core onto *expected value capture* by introducing a confidence index $\alpha_{Ki} \in [0,1]$, which represents firms' subjective expecta-

[3] Formally, our model satisfies Assumptions 1 and 2 in Chatain and Zemsky (2007): the set of players N can be split into k nonempty, disjoint sets $\{N_A, N_B, \ldots, N_{K+1}\}$ such that v(G)=0 if $G \cap N_j = \emptyset$ for any $j \in \{A, \ldots, k\}$, and the ability of sets of firms to create value is independent, such that $v(N) = \Sigma(i \in N) v(\{i\} \cup S)$. See Appendix.

[4] Existence of the core is again ensured due to Assumptions 1 and 2 in Chatain and Zemsky (2007).

tions regarding their ability to capture value through bargaining. Confident firms ($\alpha_{Ki} \rightarrow 1$) expect to capture most or all of their core allocation, while less confident firms ($\alpha_{Ki} \rightarrow 0$) expect to capture only the minimum core allocation. This allows expected value capture to be calculated in the following way: solve for the full set of core allocations, and then assume that firms expect to achieve a convex combination of their minimum and maximum allocations. That is, firm K_i's expected value capture is $\alpha_{Ki}x(K_i)^{max} + (1 - \alpha_{Ki})\, x(K_i)^{min}$, where $x(K_i)^{min}$ and $x(K_i)^{max}$ represent the firm's minimum and maximum core allocations, respectively.[5] Formally,

$$\pi(K_i) \equiv \alpha_{Ki}\, x(K_i)^{max} + (1 - \alpha_{Ki})\, x(K_i)^{min} \tag{5}$$

Together, equations (1) – (5) offer a general framework with which to explore value creation and capture within an ecosystem of interdependent firms.

-- Insert Table 1 and Figure 1 About Here --

As in all research, we make several assumptions in order to clarify and bound the analysis. For example, we model a setting in which there is only one consumer. This is equivalent to modeling a population of homogenous consumers and firms with unconstrained production capacity. It is a reasonable assumption for examining settings in which consumers have largely similar preferences, such as in high-end cars (e.g., high power) or residential solar (e.g., low cost). Similarly, we assume that firm capabilities are common information. This is appropriate for settings in which relative capabilities are largely known (e.g., Apple in consumer hardware). Relaxing this assumption would introduce additional uncertainty in terms of the distribution of capabilities in the ecosystem, and is an excellent avenue for further research. Finally, we normal-

[5] An important implication of using confidence indices to calculate expected value capture is that firms may hold mutually inconsistent expectations regarding their subjective bargaining ability (e.g., two parties may both expect to capture all or nearly all of the value created). Although Chatain and Zemsky (2007) identify a class of games for which consistency is guaranteed, they apply a "no complementarity" assumption inconsistent with our desire to explore the impact of complementarity. We adopt the view of Brandenburger and Stuart (2007), who stress that inconsistent expectations are perfectly natural given the subjectivity of players' views.

ize the value of firms' alternative applications of their capabilities to zero. In other words, there is no opportunity cost associated with participating in the ecosystem. We relax this assumption in additional analysis, and find it not to have a substantive impact on the model results.

Value creation and capture in ecosystems

With these assumptions in place, we can explore the interaction between a group of firms competing and collaborating in an ecosystem setting. Moreover, we have a ready definition for the bottleneck component. With the quality of each component defined by the capabilities of the firms within it, the bottleneck is the component whose strongest firm has the weakest capabilities: $j \in K$ such that $j_1 < k_1 \ \forall \ j,k \in K$. For example, in the early personal computer ecosystem, the capabilities of the best chipset manufacturers lagged behind those of the firms in the microprocessor component, thus making chipsets the bottleneck (Gawer and Henderson, 2007).

Equation (1) gives the value created by the firms participating in the industry: $v(N) = \min(k_1) \ \forall \ k$. By construction, value creation is strictly increasing in the capability of the strongest firm in the bottleneck component, and weakly increasing in the capabilities of all firms in the industry.[6] Once created, how is this value allocated across firms and the consumer? The added value of any firm K_i, which gives its maximum possible value capture, is as follows:

$$AV_{Ki} = \max(0, v(N) - k_{i+1}) \tag{6}$$

The interpretation is straightforward. A firm K_i's added value is driven by the amount of value that would be lost if it were removed from the industry. This is equal to the value it can create, which is a function of the quality of the bottleneck component, as above, less the quality of its closest competitor (or zero, if $k_{i+1} > v(N)$). Added value is weakly increasing in a firm's own capabilities, strictly increasing in the capability of the bottleneck firm, and decreasing in the

[6] Although not central to this analysis, we note that this model can be readily extended to explore the impact of a variety of variables. For example, if capabilities are drawn from a uniform distribution over $[\theta^{min}, \theta^{max}]$, value creation increases in N and decreases in K (for a fixed number of components K and firms N, respectively).

capability of the firm's closest competitor. Returning to our preceding example:

a_1=10, b_1=8 $AV(A_1) = \min(a_1,b_1) - a_2 = 3$ $AV(B_1) = \min(a_1,b_1) - b_2 = 6$

a_2=5, b_2=2 $AV(A_2) = AV(B_2) = 0$ $AV(C) = \min(a_1,b_1) - \min(a_2,b_2) = 6$

Calculating the core and expected allocations is then straightforward. The minimum core allocation for any firm is zero and the maximum is its added value. Similarly, the minimum core allocation for the consumer is the amount of value it can capture by relying on the next best firms in each component, and its maximum is its added value:

$x(K_1) \in [0, \min(k_1) - k_2]$ $\pi(K_1) = \alpha_{ki}(\min(k_1) - k_2)$

$x(C) \in [\min(k_2), \min(k_1)]$ $\pi(C) = \alpha_C(\min(k_1)) + (1- \alpha_C)(\min(k_2))$

$x(K_i) = \pi(K_i) = 0 \;\forall\; i \in N_K > 1$

Returning to the previous example, $x(A_1) \in [0,3]$, $x(B_1) \in [0,6]$, $x(C) \in [2,8]$, and $x(A_2) = x(B_2) = 0$. For the firm with the strongest capabilities in each component, expected value capture increases in its added value (and is thus weakly increasing in the firm's own capabilities, strictly increasing in the capability of the bottleneck firm, and decreasing in the capability of the firm's closest competitor). Expected value capture also increases, intuitively, in the firm's confidence in its own negotiating ability relative to its partners, α_{Ki}.

We summarize these findings in the following proposition:

Proposition 1: Value creation and capture

(i) The total value created v(N) weakly increases in the capabilities of all firms, and strictly increases in the capability of the strongest firm in the bottleneck component.

(ii) A firm's expected value capture $\pi(K_i)$ increases in its own capabilities, increases in its partners' capabilities, increases in its bargaining ability α_{Ki}, and decreases in the capabilities of its direct competitors.

(iii) The consumer's expected value capture increases in the capabilities of all firms.

Overall, this model provides a precise specification of value creation and value capture in an ecosystem setting. It also reproduces key empirical findings described in the previous literature, particularly with respect to the role of bottlenecks. A key insight is that bottlenecks – which in this model are the components containing the firms with the relatively weakest capabilities - constrain the ability of firms *throughout* the ecosystem to create value (Ethiraj, 2007; Jacobides et al, 2006). Moreover, although firms with superior capabilities outperform those with weaker capabilities (Ozcan and Eisenhardt, 2009), *partner* capabilities are also critical to creating and capturing value (Adner, 2012; Hannah and Eisenhardt, 2015). The model also confirms that the ability to capture value is a function of how 'irreplaceable' a firm is in the ecosystem (Jacobides et al, 2015b). Thus, value capture decreases in the strength of the firm's direct competitors (Adegbesan and Higgins, 2010; Ferraro and Gurses, 2009; Lavie, 2007).

The model also extends existing literature by adding additional insight into the dynamics of value creation and capture. One key finding is the importance of the *distribution* of capabilities in the ecosystem. Prior research suggests that a disproportionate share of value tends to accrue to bottlenecks (Jacobides et al, 2006; Jacobides et al, 2015c). Our model suggests that while this may be true, it is in fact the distance between the capabilities of a firm and those of its competitors that dictates how much value is captured (e.g., Jacobides and Tae, 2015).

For example, consider four firms with capabilities as follows: $a_1 > a_2 > b_1 > b_2$. Here, $v(N) = b_1$ and neither A_1 nor A_2 will capture any value (in fact, all value in the core allocation will be distributed between B_1 and the consumer). The underlying logic is that because the capabilities of firm A1 *and its competitor* so far outstrip those of the firms in the bottleneck component, both are fully replaceable and have no ability to capture value. In contrast, consider four firms with capabilities $a_1 > b_1 \approx b_2 > a_2$. Here, B_1 and B_2 reside in the bottleneck component, but are less likely to capture value because in this scenario they are relatively interchangeable. In contrast, A_1 is relatively irreplaceable: removing A_1 from the game would decrease the maximum value created from $v(N) = b_1$ to $v(a_2, b_1, b_2) = a_2$. Thus, residing in the bottleneck is less important for value capture than having relatively weak competitors.

Improving strategy: innovating within components

In order to understand how and when firms are able to work with partners to resolve bottlenecks, we first examine the *improving strategy*, wherein firms invest in improving the capabilities of the firms in the bottleneck components in order to improve the innovative ability of those firms. To do so, we extend our cooperative model into a two stage biform game:

- **Stage 1:** A focal firm can invest in improving its own capabilities and/or those of any other firms in the ecosystem. Improving capabilities incurs a nonzero cost λ, where λ increases in the size of the improvement.
- **Stage 2:** All firms and the consumer negotiate over the allocation of any jointly created value, as in the benchmark model, to yield a set of core and expected allocations.

In order to avoid a multiplicity of equilibria, we consider the problem as it faces each firm independently. For the remainder of the analysis, we consider the case where K=2, corresponding to two firm components and one consumer. While we allow an arbitrary number of firms in each of the components A and B, it is sufficient to consider two in each.

Define k_j^0 as the initial capabilities of firm j in component k and k_j as the same firm's final (post investment) capability. Firms can improve the capabilities of any firm to level k_j, given the initial capability k_j^0 of that firm, according to the cost function $\lambda(k_j, k_j^0)$. The total cost incurred by a firm investing in one or more partners is thus $\Sigma\lambda(k_j,k_j^0)$. Further, assume that costs are increasing in the scale of the improvement: $d\lambda/d(\Delta k_j) > 0$ and $d^2\lambda/d(\Delta k_j)^2 > 0$.

Assume that $a_1^0 > b_1^0$, so that component B is the bottleneck and $v(N)=b_1^0$ prior to any investment (no assumptions are required on a_2 or b_2). What should each firm do?

Firm A_1 (the firm with the strongest capabilities in the non-bottleneck component) will select an investment in order to maximize its expected value capture (analogously, its added value), less the cost of investment, according to the following equation:

$$\pi(A_1) = \begin{cases} \alpha_{A1}\,(b_1 - a_2) - \Sigma\lambda(k_j,k_j^0) & \text{if } a_1 > b_1 > a_2 \\ \alpha_{A1}\,(a_1 - a_2) - \Sigma\lambda(k_j,k_j^0) & \text{if } b_1 > a_1 > a_2 \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

With B_1 limiting joint value creation, A_1 will not realize a benefit by improving a_1 unless b_1 is brought up at least to the level of a_1^0 – and only then if $b_1 > a_2^0$. If there is an interior solution for b_1, then it satisfies the first order condition:

$$\alpha_{A1} - d\backslash d(b_1)\,\lambda(b_1,b_1^0) = 0 \quad (8)$$

There are three possibilities. If $d\backslash d(b_1)\,\lambda(b_1,b_1^0) > \alpha_{A1}$, then it does not pay for A_1 to try to improve B_1's capabilities, so no investment occurs. In other words, although improving B_1 would increase A_1's value capture, it is not economical to do so. If $d\backslash d(b_1)\,\lambda(b_1,b_1^0) < \alpha_{A1}$ but $d\backslash d(a_1)\,\lambda(a_1,a_1^0) > \alpha_{A1}$, then the firm invests *only* in improving B_1's capabilities. In this case, A_1 improves its value capture by improving its ability to jointly create value with B_1. Finally, if $d\backslash d(b_1)\,\lambda(b_1,b_1^0) < \alpha_{A1}$, then it pays to exceed a_1^0 in attained b_1. This makes a_1 the bottleneck, so as long as $d\backslash d(a_1)\,\lambda(a_1,a_1^0) < \alpha_{A1}$, A_1 benefits from investing in a_1 as well, with $a_1 = b_1$ at the optimum. Finally, because $\pi(A_1)$ is decreasing in a_2, A_1 will never invest in A_2.

To summarize, it is never optimal for the strongest firm in a component to invest only in its own capabilities as long as its ability to create value is constrained by a bottleneck elsewhere in the ecosystem. Instead, such firms are best served by mitigating that constraint on value creation, and in doing so increasing the value available to be captured. One critical observation is that no contractual obligation is required to achieve this collaboration: instead, A_1's position as the dominant firm in its own component ensures a return on its investment in bottleneck firm B_1.

When (if ever) will A_1 invest in other firms? Unless A_1 can improve B_2 to the point where $b_2 > b_1$, investing in firms other than B_1 cannot impact the core allocation, which depends only on the strength of A_1's competition (A_2), the capabilities of the strongest firm in the bottleneck component (B_1), and its confidence index (α_{A1}): $\pi(A_1) = \alpha_{A1}[\min(a_1,b_1) - a_2]$.

This is a surprising finding, as prior empirical work suggests firms can improve their value capture by simultaneously improving the capabilities of multiple partners (e.g., Jacobides et al, 2015b; Gawer and Henderson, 2007). Specifically, prior work suggests that doing so makes potential partners more replaceable, thus lowering their relative bargaining power and their ability to capture value. In fact, our model is consistent with this finding: improving B_2 *does* lower B_1's expected value capture. The key insight is that B_1's loss does not lead directly to A_1's gain. Although less value accrues to B_1, it is the consumer C that benefits. Nor is this simply an artifact of how the core is calculated: in additional analysis we achieve the same result using a different measure of bargaining power (the *marginal residual*, per MacDonald and Ryall, 2004).

The other firms in the ecosystem face a different set of incentives. For example, the firm in the bottleneck, B_1, might be able to benefit from improving its own capabilities, but will not benefit from improving other firms. Similarly, the added value of the weaker firms in each component (A_i, B_j, for $i,j \geq 2$) is zero, and thus they cannot benefit from improving other firms until their own capabilities exceed those of their direct competitors.[7]

Overall, this analysis suggests a number of insights regarding how firms may work with partners to resolve bottlenecks. Firms that have stronger capabilities than their competitors are likely to benefit from improving the capabilities of their partners, in order to address the bottlenecks that limit value creation. In contrast, weaker firms play a different game: they cannot bene-

[7] Implicit in this analysis is the assumption that the costs of investment depend only on the initial and final capability levels of an individual firm, rather than the identity of the investor or the presence of concurrent investments. In reality, firms may share knowledge or technology more broadly in order to improve the capabilities of multiple firms. In our model, this type of spillover between investments would allow firms to simultaneously invest in all of the firms in complementary component, possibly increasing value creation v(N) or expected value capture $\pi(A_1)$.

fit from improving value creation, since they are unable to *capture* the value that is already created. As a result, they benefit only from improving their own capabilities. Unexpectedly, we find that improving multiple partners – a common strategy in the empirical literature (Gawer and Henderson, 2007; Hannah and Eisenhardt, 2015) improves neither value creation nor value capture for a focal firm. We summarize these findings in the following proposition:

Proposition 2: Improving partner capabilities

- *(i)* *It is optimal for the strongest firm in the non-bottleneck component (A_1) to improve the strongest firm in the bottleneck component (B_1) iff the cost is sufficiently low: $d\backslash d(b_1)\ \lambda(b_1,b_1^0) < \alpha_{A1}$ such that $b_1 > a_2^0$. Incentive to invest is decreasing in cost $\lambda(k_i,k_i^0)$ and the capabilities of the focal firm's competitor (A_2).*
- *(ii)* *Improving the capabilities of weaker firms in the bottleneck component does not increase value creation $v(N)$ or expected value capture $\pi(A_1)$ of firm A_1.*
- *(iii)* *Weaker firms in either component have no incentive to invest in partner capabilities as long as their own capabilities are below that of their direct competitors.*

Co-innovation strategy: innovating across components

A second strategy to resolve bottlenecks is the *co-innovating strategy*, in which firms collaborate with specific partners to introduce a systemic innovation. For example, firms might jointly develop a new technology (e.g., Garmin and Strava with their data-rich fitness tracking). This strategy potentially allows firms to create additional value by freeing them from the constraints of pre-existing component interfaces. Consider the following biform game:

- **Stage 1:** Any pair of firms (A_i and B_j) can choose to co-innovate by forming a coalition to mutually produce the two components that comprise the final product, and in doing so create $r(A_i,B_j)$ additional value,[8] so that $v(A_i,B_j)=\min(a_i,b_j)+r(A_i,B_j)$.
- **Stage 2:** All firms and the consumer negotiate over the allocation of any jointly created value, as in the benchmark model, to yield core and expected allocations.

[8] This formulation readily admits a variety of costs associated with coalition formation, which may be reflected by considering r to be the *net* value created after these costs. Thus, $r(A_i,B_j)$ can take any negative or positive value.

We first assume that firms are not able to specify the allocation of value prior to the stage two negotiations (in other words, effective contracts are not available). The added value of any coalition (i.e., pair of co-innovating firms) is then as follows:

$$AV(A_i,B_j) = \begin{cases} v(A_i,B_j) - \max v(A_x,B_y),\ x \neq i,\ y \neq j & \text{if } v(A_i,B_j) \geq \max v(A_x,B_y) \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

The added value of a given coalition is increasing in its members' capabilities (a_i,b_j), increasing in the additional value they can create by partnering $r(A_i,B_j)$, and decreasing in the value created by competing coalitions. For example, the Garmin-Strava coalition is valuable due to its members' relatively strong capabilities and the additional value created through their close coordination, but is rendered less valuable by competing coalitions (e.g., Fitbit-RunKeeper).

In order to determine which coalitions (can) actually form, we assume that any coalition can form as long as it is incentive compatible for both participants – that is, that both firms benefit from participating. This yields a pair of incentive compatibility conditions, IC-A_i and IC-B_j respectively, which must be met in order for a given coalition A_i-B_j to form:

$$\alpha_{Ai}[v(A_i,B_j) - \max_{x\neq i,\, y\neq j} v(A_x,B_y)] \geq \alpha_{Ai}[\max_{z\neq j} v(A_i,B_z) - \max_{x\neq i,\, t\neq z} v(A_x, B_t)] \quad \text{(IC-}A_i\text{)}$$

$$\alpha_{Bj}[v(A_i,B_j) - \max_{x\neq i,\, y\neq j} v(A_x,B_y)] \geq \alpha_{Bj}[\max_{z\neq i} v(A_z,B_j) - \max_{y\neq j,\, t\neq z} v(A_t, B_y)] \quad \text{(IC-}B_j\text{)}$$

Where the left hand side (LHS) of each represents the each firm's expected value capture from participating in the A_i-B_j coalition and the right hand side (RHS) represents the value to be achieved from the "next best" option (either forming a coalition or remaining independent).

Solving IC-A_i and IC-B_j, we can determine the conditions under which a given coalition can exist. Trivially, any coalition can form if the additional value created $r(A_i,B_j)$ is high enough. Otherwise, the viability of a coalition trades against two risks: (1) that the consumer chooses an alternate coalition, and (2) that one of the partners in the coalition prefers to "defect" and partner with a different firm. Consider, for example, a coalition between A_1 and B_1 in an industry composed of four firms: A_1, A_2, B_1, and B_2. IC-A_1 and IC-B_1 can then be rewritten as:

$$r(A_1,B_1) + \min(a_1,b_1) - v(A_2,B_2) \geq v(A_1,B_2) - v(A_2,B_1) \quad (11)$$

$$r(A_1,B_1) + \min(a_1,b_1) - v(A_2,B_2) \geq v(A_2,B_1) - v(A_1,B_2)$$

Here, the stability of the A_1-B_1 coalition is increasing in the amount of value that is created by co-innovation (first term LHS) and in the capabilities of the firms themselves (second term LHS). Stability is decreasing in the amount of value created by the next best coalition (third term LHS), which is the consumer's alternative to the focal coalition. At the same time, the stability of A_1-B_1 is decreasing in the amount of value each firm can create by working with an alternate partner (first term RHS) and increasing in the amount of value the partner can create by doing the same (second term RHS). These latter two terms represent the value that the focal firm (A_1 or B_1) could capture by defecting and working with the current partners' competitors. Note that A_i, B_j, $i,j \geq 2$ capture no value in the benchmark model, so they always prefer to co-innovate.

From IC-A_i and IC-B_j, it is straightforward to calculate $r^*(A_i,B_j)$, which is the threshold additional value that must be created in order for a given coalition to form:

$$r^*(A_i,B_j) \geq v(A_i,B_z)_{z \neq j} - v(A_x,B_t)_{x \neq i,\, t \neq z} + v(A_x,B_y)_{x \neq i, y \neq j} - \min(a_i,b_j) \quad (12)$$

$$r^*(A_i,B_j) \geq v(A_z,B_j)_{z \neq i} - v(A_t,B_y)_{t \neq z,\, y \neq j} + v(A_x,B_y)_{x \neq i, y \neq j} - \min(a_i,b_j)$$

Can coalitions form when no additional value is created ($r^*(A_i,B_j)=0$)? As formulated, the only coalition that can form is the trivial case between the strongest firms in each component – and only then if $a_1 > b_2$ and $b_1 > a_2$. The underlying intuition is that entering into a coalition in stage 1 requires firms to co-specialize, and thus constrains their ability to bargain effectively in stage 2. Entering into a coalition other than A_1-B_1 when $r=0$ must therefore constrain the bargaining power of one firm – which might otherwise have had viable partners outside the coalition –

without offering a compensating increase in the total value being created. For example, a coalition between A_1 and B_2 will be successful as long as $v(A_1,B_2) = b_2 > v(A_2,B_1)$, but the total value created v(N) will decrease ($b_1 \rightarrow b_2$) and $AV(B_2)$ will increase from zero to a positive sum. $\pi(A_i) = \alpha_{A1}AV(A_i)$ must therefore decrease and A_1 will decline to co-innovate with B_2.

This assumes, however, that firms are unable to specify contracts prior to forming coalitions. If we instead assume that the pair of firms is able to enforce an allocation of value prior to forming a coalition, the game reduces to a single stage non-cooperative game. Here, we see that two types of coalitions can form, even when r=0. The first is the trivial coalition between A_1 and B_1. The second depends on the relative strength of A_2 and B_2. If $a_2>b_2$, then a coalition between B_1 and A_2 will generate $v(A_2,B_1)=a_2$. Moreover, because A_2 would capture no value on its own, it will accept a contract from B_1 in which it captures zero, allowing B_1 to negotiate with the consumer for the full a_2. Analogously, when $a_2<b_2$, a coalition between A_1 and B_2 can form, B_2 will capture nothing, and A_1 will bargain with the consumer over the division of $v(A_1,B_2)=b_2$.

For r=0 coalitions to form we require that (1) firms are able to pre-specify the allocation of value between them, and (2) the consumer does not have "too much" bargaining power (i.e., that α_{k1} is sufficiently high). This requirement arises from the fact that less value is created in an A_1-B_2 or B_1-A_2 coalition, so incentive compatibility requires that the strong firm (A_1 or B_1) expects to capture a greater share of this smaller sum. This is intuitively plausible: because one firm in the coalition (A_1 or B_1) is able to enforce the condition that its partner (B_2 or A_2, respectively) captures zero value, it competes only with the consumer to capture value.

The interaction between firm capabilities, the contracting regime, and the confidence indices of the firms can be readily visualized in the following way:

-- Insert Figure 2 About Here --

Overall, this analysis suggests that firms may form coalitions either to increase value creation or to increase their own relative bargaining power. But the two goals may conflict: a strong firm may, for example, form a coalition with a weaker one in order to ensure its bargaining power relative to its partner (and thus its ability to capture value), even though relying on a weaker partner reduces its ability to create value. We summarize these findings as follows:

Proposition 3: Co-innovating with partners

(i) *Without contracts, weak firms (A_i, B_j, $i,j \geq 2$) always prefer to co-innovate. Preference of strong firms (A_1, B_1) to co-innovate with a given partner increases in the capabilities of the partner, decreases in the capabilities of the partners' competitors, and increases in the additional value generated by the coalition $r(A_i,B_j)$.*

(ii) *The amount of additional value $r(A_i,B_j)$ that must be created in order for a coalition to form (r^*) is decreasing in the capabilities of the firms in the coalition, increasing in the capabilities of those not in the coalition, and increasing in the additional value created by any other coalition $r(A_x,B_y)$.*

(iii) *Coalitions other than A_1-B_1 may form when $r(A_i,B_j)=0$ iff firms are able to enforce contracts that pre-specify the allocation of value between them or $a_i > b_j \; \forall \; i,j$.*

Value creation and capture under uncertainty

Thus far, we have developed a model in which firms rely on one another to create value, and compete with one another to capture value. This model links the distribution of capabilities (Jacobides and Tae, 2015; Dedrick et al, 2010; Jacobides, 2005), the contracting environment (Jacobides et al, 2006; Teece, 1986), and firm ecosystem strategy (Ozcan and Eisenhardt, 2009; Adner, 2012; Ethiraj, 2007). But the model thus far is deterministic. In contrast, prior empirical research has identified uncertainty as a central factor in governing firm performance within ecosystems (Adner and Kapoor, 2010; Afuah, 2000) – and particularly early-stage ecosystems (Ozcan and Eisenhardt, 2009; Santos and Eisenhardt, 2009; Ozcan and Santos, 2014).

In this section, we extend the model to include a measure of technological uncertainty: the probability that any given firm will fail in its individual innovation attempt. This probability reflects a range of risks that firms face in trying to bring a product to market. For example, there may be unpredictable outcomes associated with basic research (McGrath and Nerkar, 2004), as well as challenges in scaling and marketing the product (Brusoni et al, 2001). As a result, firms that had once been expected to participate in an industry – and even to be leaders – may instead realize only failure. By incorporating uncertainty, we extend the model to examine the improving and co-innovating strategies in evolving or early-stage ecosystems.

We incorporate uncertainty into the model by assigning each firm a probability f_{Ki}, which denotes the likelihood that it fails in its attempt to develop its individual component (conversely, the firm succeeds in doing so with probability $1 - f_{Ki}$). The resulting biform game is thus:

- **Stage 1:** Firms enter the industry and determine whether or not to improve their partners or to co-innovate, and with which partners.
- **Stage 2:** Firms succeed or fail in their individual innovation attempts with probability f_{Ki}.
- **Stage 3:** All firms and the consumer negotiate over the allocation of any jointly created value, as in the benchmark model.

Let $k_{(i)}$ denote the capabilities of the i^{th} ranked firm in component k following the resolution of uncertainty (i.e., after stage 2). From equation (1), we obtain the expected value creation:

$$E[v(N)] = min(E[a_{(1)}], E[b_{(1)}])$$

Algebraic manipulation then yields (derivation in Appendix):

$$E[v(N)] = \Sigma_{i=1}^{N_A} \Sigma_{j=1}^{N_B} min(a_i, b_j)(1 - f_{A_i})(1 - f_{B_j})\Pi_{x=0}^{i-1}\Pi_{y=0}^{j-1} f_{A_x} f_{B_x}$$

In many cases, failure rates may be similar across firm in a given component, as these firms are likely to face a similar set of technological challenges (Eggers, 2012). Given component-level uncertainty (that is, $f_{Kj} = f_K \ \forall \ j \in k$), E[v(N)] reduces to the more intuitive:

$$E[v(N)] = \Sigma_{i=1}^{N_A} \Sigma_{j=1}^{N_B} min(a_i, b_j)(1 - f_A)(1 - f_B) f_A^{i-1} f_B^{j-1} \quad (13)$$

Expected value creation is weakly increasing in the capabilities of all firms in the industry and weakly decreasing in the likelihood of failure for each firm. Moreover, the impact of uncertainty on value creation depends on the distribution of capabilities: for a given set of firms with capabilities $k_1 \ldots k_i$, the impact of an increase in the level of uncertainty will be lower when $(k_1 - k_i)/k_1$ is greater. In other words, when firms are relatively comparable (both within and between components), the marginal impact on value creation of any one firm failing is lower.

In terms of the distribution of this value across firms, equations (5) and (6) yield:

$$E[AV_{A_i}] = [min(a_i, \Sigma_{x=1}^{N_B} b_x (1 - f_B) f_B^{x-1}) - \Sigma_{y=i+1}^{N_A} a_y (1 - f_A) f_A^{y-1}]^+ (1 - f_A) f_A^{i-1} \quad (14)$$

$$E[\Pi_{A_i}] = \alpha_{A_i} E[AV_{A_i}] \quad (15)$$

Both added value and expected value capture are curvilinear (that is, exhibit an inverted U) in uncertainty. In other words, firm performance peaks at moderate levels of uncertainty. However, the location of the peak depends on the relative strength of the firm. Those with the highest capabilities (i.e., A_1, B_1) see peak performance at low levels of uncertainty. For weaker firms, the peak occurs at higher values (see Figure 3). The intuition is that without uncertainty, only the only the strongest firms in each component (A_1, B_1) capture any value. Uncertainty offers the possibility that these two firms will fail, thus allowing other firms to capture value instead. However, the lower a given firm K_i is ranked (i.e., the weaker its capabilities), the greater the number of firms that would need to fail in order for it to end up on top (e.g., $K_{(1)}$). As a result, the performance of weaker firms peaks at higher levels of uncertainty.

--Insert Figure 3 About Here --

A key insight is that uncertainty upsets the status quo by introducing the chance that the firms that would otherwise dominate the industry instead fail. In other words, it exerts a damping effect on competition by attenuating the relative advantage of stronger firms. As a result, while the performance of stronger firms is always higher than that of weaker firms, the weaker firms actually benefit from greater uncertainty, as it increases their ability to effectively compete.

Proposition 4: Expected value creation and capture under uncertainty

(i) *Expected value creation E[v(N)] is decreasing in uncertainty f_A, f_B.*

(ii) *Expected value capture E[π(K_i)] is decreasing in the uncertainty facing complementors f_L, and is curvilinear in the uncertainty facing a given firm f_K, with performance E[π(K_i)] of weaker firms peaking at higher uncertainty.*

Improving partners under uncertainty

How does uncertainty affect firms' incentives to improve their partners' capabilities? Assume that the capabilities of the firms in component A outweigh those of the firms in component B, so that component B is the bottleneck. From equation (14), A_i will attempt to maximize:

$$E[AV_{A_i}] = \begin{bmatrix} min(a_i, b_1)p(b_1 = b_{(1)}) - E[a_{(2)}] \\ min(a_i, b_2)p(b_2 = b_{(1)}) - E[a_{(2)}] \\ min(a_i, b_3)p(b_3 = b_{(1)}) - E[a_{(2)}] \end{bmatrix} p(a_i = a_{(1)}) - \Sigma_{k \in N} \lambda(k_i, k_{i0})$$

Which reduces to:

$$E[AV_{A_i}] = \Sigma_{x \in N_B} (min(a_i, b_x)p(b_x = b_{(1)})$$

$$-N_B \cdot E[a_{(2)} | a_i = a_{(1)}] - \Sigma_{k_i \in N} \lambda(k_i, k_{i0}) \quad (16)$$

Consider a four firm case (N_A=2, N_B=2). A relatively strong A firm (e.g., A_1) is likely to see its added value and expected value capture constrained by its partner, and thus has an incentive to invest in and improve the capabilities of the capabilities of the B firms. The wrinkle added by uncertainty is that A_1 does not know which firm will succeed. For example, investing in B_1 in order to reduce the bottleneck incurs costs, but will not yield any benefit in the event that B_1 fails (which occurs with probability f_B). This reduces the marginal benefit of investing in any specific partner B_j. So too does the probability that A_1 itself will fail (which occurs with probability f_A).

In contrast, component-specific uncertainty *increases* the expected return of investing in weaker firms (e.g., B_2). In the benchmark model, improving the capabilities of weaker firms has no impact on focal firm added value $AV(A_1)$ or expected value creation $\pi(A_1)$. Under uncertainty, improving the capabilities of weaker firms improves expected value capture: in the event that the strongest firm B_1 fails, A_1 is less likely to be left with a substantially weaker partner. Moreover, the magnitude of this tradeoff increases in the level of uncertainty: as uncertainty climbs ($f_B \to 1$), the benefit of investing in weaker firms for $E[AV(A_1)]$ and $E[\pi(A_1)]$ is greater.

The problem facing a weaker firm in the A component (e.g., A_2) is similar. Without uncertainty, these firms are unable to capture value unless they can improve their own capabilities such that $a_2 > a_1^0$. Until they have done so, they have no incentive to invest in complementors. With uncertainty ($f_A>0$), there exists the possibility that the stronger firms will fail, such that $A_2 = A_{(1)}$. As a result, the benefit from investing in complementors may be positive. In other words, firm uncertainty increases not only the expected performance of the weaker firms, but also their incentive to invest in improving their potential partners.

Conversely, the firms in B are unlikely to benefit from improving firms in the A component, since it is their own capabilities that constrain overall value creation. Investment incentives thus strictly favor the firms in B improving their own capabilities, as occurs in the benchmark model. The key difference is that the strongest firm has a decreased incentive to invest in its own capabilities, as its expected value capture is reduced by a factor of $(1-f_B)$. In contrast, weaker firms have an *increased* incentive to invest in their own capabilities. In the benchmark case, firm B_2 has no incentive to invest in its capabilities unless $b_2 > b_1^0$. Under uncertainty, it benefits from investing in its capabilities as long as $(1-f_B)b_2 > b_1^0 f_B$. In other words, uncertainty prompts weaker firms to invest in their own capabilities by giving them a chance to play.

We summarize these findings in the following proposition:

Proposition 5: Improving partner capabilities under uncertainty

(i) *The incentive of stronger firms (A_1, B_1) to improve their own capabilities is decreasing in own-component and complementor uncertainty.*

(ii) *The incentive of weaker firms (A_2, B_2) to invest in their own and their complementors' capabilities is decreasing in complementor uncertainty (f_B, f_A) and curvilinear in own-component uncertainty (f_A, f_B).*

Co-innovating with partners under uncertainty

How does uncertainty impact the viability of co-innovating with partners? Intuitively, uncertainty makes co-innovation risky because a firm's ability to succeed depends on the ability of its chosen partner to do the same (Adner and Feiler, 2015). Because uncertainty increases the chance that a firm's partner will fail, firms may thus be less likely to co-innovate. But the puzzle is actually more complex: by introducing a chance that the strongest firms (and coalitions) will fail, uncertainty also gives weaker firms (and coalitions) an opportunity to come out on top.

To understand this puzzle, we consider a biform game with the following assumptions. As before, co-innovation allows a pair of firms to produce an additional $r(A_i,B_j)$ in value, where $r(A_i,B_j)$ can take any positive or negative value. We also assume that firms whose partners fail are left stranded and are unable to later pair with unmatched firms. This reflects the idea that by co-innovating, firms make co-specialized investments in particular technologies or components that are then rendered valueless without their partner. The tension facing firms is thus whether to co-innovate with a partner, creating additional value but risking that partner failing, vs. remaining independent. Finally, we examine failure rates at the component level (f_A, f_B), which implies that the probability of firm failure is independent of its or its partners' capabilities.

The expected value created by any co-innovating pair is thus:

$$E[v(Ai, Bj)] = [min(A_i, b_j) + r(Ai, Bj)](1 - f_A)(1 - f_B) \qquad (17)$$

Similarly, the added value (and analogously the core allocation) for a firm in a coalition is a function of the value it is able to create with its partner less the "next best option" in the eyes of the consumer, which may be either another coalition or the output of any independent firms:

$$AV_{A_i,B_j} = max(0, v(A_i, B_j) - max(v(A_x, B_y))_{x \neq i, y \neq j})$$

Where $v(A_x,B_y)$ is the value of the highest value coalition other than A_i-B_j *or* the output of the firms that remain independent in stage 1. Taking the expectation, this gives the expected added value for any A_i-B_j co-innovating pair, where superscript I denotes the independent firms and subscript $_{(1)}$ denotes the strongest firm in each component following stage 2:

$$E[AV_{A_i,B_j}] = v(A_i, B_j)(1 - f_A)(1 - f_B) - \qquad (18)$$

$$max(E[v(A_x, B_y)], E[min(a^I_{(1)}, b^I_{(1)}])$$

As in the benchmark model, coalitions will form if and only if they are incentive compatible for both members. Moreover, because both members must survive in order for the coalition to create value (and either party to capture value), uncertainty affects coalitions more dramatically than it affects independent firms. For example, consider an industry with two A firms and two B firms. The probability that A_i succeeds as a member of a coalition succeeds is $(1-f_A)(1-f_B)$, while the probability that an independent A_i succeeds is $(1-f_A)(1-f_B^2)$. This implies that firms are less likely to form coalitions, relative to remaining independent, when the level of uncertainty is high. At the same time, the additional value created by forming a coalition is idiosyncratic to the pair of firms (and is independent of f_K). Thus, for any given level of additional value $r(A_i,B_j)$, co-innovation is more likely to form when uncertainty is low – and for any given level of uncertainty, some firms may co-innovate and others may not.

Those firms that do not co-innovate remain independent and enter a common "pool" following the resolution of uncertainty. The expected value capture for these firms is a function of their own capabilities, their chance of success, and the identity of the other independent firms:

$$E[AV_{A_i}] = (min(a_i, E[b_j]) - v_{(1)}(A_x, B_y) - E[a_{(2)}|a_i = a_{(1)}])p(a_i = a_{(1)})$$

An important observation is that because each co-innovating pair has committed to work only with one another, these firms are "off limits" to the independent firms, and vice versa. Thus, coalitions and independent firms view one another purely as competitors.[9]

Consider first an industry with only two firms: A_1 and B_1. These firms rely on one another, regardless of whether they co-innovate, because no alternative partners exist. Thus, they will form a coalition as long as $r(A_1,B_1) \geq 0$: doing so adds $r(A_1,B_1)$ and incurs no additional risk.

With three firms (e.g., A_1, A_2, B_1), firms may elect not to co-innovate. Assume $r(A_1,B_1) \geq r(A_2,B_2) \geq 0$. Here, A_1 always prefers to co-innovate because it has no alternative partners, but firm B_1 must balance the additional value created by co-innovation with the benefit of being able to work with A_2 if needed. Thus, when uncertainty in the A component (f_A) is low, firms A_1 and B_1 will co-innovate in order to realize additional value $r(A_1,B_1)$. When uncertainty f_A is high, B_1 will prefer to remain independent. Because A_1 and A_2 both need B_1 to create value, the viability of co-innovation is unaffected by uncertainty in the B component f_B.

With four or more firms, a new dynamic emerges. With sufficiently high $r(A_i,B_j)$, firms will always co-innovate, and the coalition that creates the most value will come out on top and bargain with the consumer over the allocation of this value. When $r(A_i,B_j)$ is lower, co-innovation is less attractive. The strongest firm in each component – and in particular the firm that faces the weakest direct competition – thus generally prefers to remain independent in order

[9] Because multiple coalitions can coexist, the sorting mechanism by which firms meet and select partners becomes salient. In this analysis, we consider a subset of possible coalitions, in which each firm $A_i \in N_A$ has an opportunity to co-innovate with its corresponding partner $B_j \in N_B$, where i=j. Thus, A_1 and B_1 evaluate a possible coalition, A_2 and B_2, and so forth. In general, it is possible to simply denote $x \in min(N_A,N_B)$ as the rank of a given coalition, formed under any arbitrary mechanism, where $v(A_i,B_j)_x > v(A_x,B_y)_{x+1} \ \forall x$.

to (1) maximize its ability to work with either A_2 or B_2, should its first choice partner fail, and (2) avoid constraining its bargaining power by being dependent on a specific partner. This holds across all levels of uncertainty. But unexpectedly, we find that for a low level of uncertainty in one component (e.g., f_A), an increase in the level of uncertainty in the other (e.g., f_B) actually makes all firms in the industry *more* likely to co-innovate. In other words, the impact of uncertainty on the viability of co-innovation is actually curvilinear, rather than decreasing.

This effect is driven by the fact that coalitions are more sensitive to uncertainty. As a result, weaker firms benefit from their stronger competitors co-innovating. Should the firms both succeed, the weaker firms are left no worse off, but should either one fail, the weaker firms may find themselves on top. In contrast, the strong firms (A_1 and B_1) would prefer to remain independent. But by co-innovating together, A_2 and B_2 commit to work with one another (and thus *not* with A_1 or B_1), which then prompts A_1 and B_1 to co-innovate on their own. Although A_2 and B_2 now face a greater risk of joint failure, this risk is outweighed by the benefit of potentially outliving A_1 and B_1. This effect diminishes at higher levels of uncertainty: past a critical threshold, all coalitions become unviable. As a result, uncertainty has a curvilinear impact on the viability of the co-innovation strategy: for a given level of uncertainty in one component, an increase in uncertainty in other makes an industry composed entirely of coalitions more likely. Critically, this configuration reduces the expected value creation E[v(N)] as well as the expected value for A_1, B_1, and the consumer. But it *does* achieve an increase in the expected value capture for weaker firms, who may find themselves able to shape the industry in their favor.

Proposition 6: Co-innovating with partners under uncertainty

(i) *For industries with two firms, firms will always co-innovate when $r(A_i,B_j) \geq 0$. When $N_A>1$ or $N_B>1$, firms co-innovate when additional value $r(A_i,B_j)$ outweighs risk of partner failure, and remain independent otherwise.*

(ii) *When $N_A>1$ <u>and</u> $N_B>1$, a small increase in uncertainty ($f_A = 0 \rightarrow f_A>0$ or $f_B=0 \rightarrow f_B > 0$) increases the likelihood of co-innovation by all firms.*

DISCUSSION

Bottlenecks play a pivotal role in ecosystems. They constrain value creation, shape power dynamics, and determine firm profitability (Moore, 1993; Jacobides et al, 2006; Adner and Kapoor, 2010; Baldwin, 2015). But in terms of strategies to address them, prior work has largely examined how firms can benefit from entering and controlling bottlenecks (Ferraro and Gurses, 2009; Hannah and Eisenhardt, 2015). In this study, we examine how firms can work with partners to address bottlenecks. In doing so, we contribute broadly to research on ecosystems.

Strategies for addressing bottlenecks

Our primary contribution is to examine the strategies by which firms can work with partners to address bottlenecks. Prior empirical research has identified a number of means by which firms may attempt to resolve bottlenecks and improve joint value creation with partners. For example, firms may provide knowledge in order to improve the capabilities of partners, and thus their ability to innovate *within* their component (Dyer and Hatch, 2006; Gawer and Henderson, 2007; Ethiraj, 2007). Alternately, firms may co-innovate *across* components to introduce systemic innovations that offer new and better ways to meet consumer needs (Kapoor, 2013b; Hannah and Eisenhardt, 2015). But while research has identified what form these strategies may take, we know less about what firms are likely to use them, the conditions under which they will do so, and how their use affects firms' subsequent ability to capture value (Bremner et al, 2016).

We distinguish two archetypal strategies, and identify the conditions under which each strategy improves firm performance, as well as the mechanisms by which they do so. We first explore the *improving strategy*, in which firms invest in improving the capabilities of firms in the bottleneck component. We find that the incentive to improve partners is not even across firms. In particular, firms with strong capabilities benefit more from improving their deficient partners in the bottleneck component, since they are unable to realize the full value of their own capabilities as long as they are constrained by the weaker firms in the bottleneck. In contrast, weaker firms have less incentive to improve their partners, and instead benefit more from improving their *own* capabilities in order to compete more effectively in their own component.

A second insight is that while improving the strongest firm in the bottleneck component increases firm performance, improving *multiple* firms in the bottleneck does not. Prior literature suggests that firms are likely to capture more value when they are relatively irreplaceable in the ecosystem – that is, when they have few close substitutes and their partners have many (Jacobides et al, 2006; Lavie, 2007). This suggests that by improving multiple partners (and thus making individual partners more replaceable), firms can increase their own ability to capture value (Jacobides et al, 2015b; Gawer and Henderson, 2007). Consistent with this research, we do find that firms with stronger competitors capture less value. Thus, by improving multiple partners, or by improving a partner's weaker competitor, a focal firm can reduce the ability of its partners to capture value. But in contrast to prior research, we find that doing so may not actually lead the focal firm to capture more value. Instead, it is the consumers who are most likely to benefit, as the increased competition provides them with better alternatives and more bargaining power.

We also examine the *co-innovation strategy*, in which firms collaborate to introduce systemic innovations that meet customer needs in new ways. Prior work suggests that co-innovation allows firms to create value by modifying component boundaries and by relaxing the constraints imposed by existing interfaces (Baldwin and Clark, 2000; Ethiraj and Levinthal, 2004; Kapoor, 2013b). Consistent with prior research, we find the co-innovation strategy to be more attractive in the degree of additional value created by close coordination. That is, when there exist opportunities to create value by modifying component boundaries, firms will be likely to take them. At the same time, we also extend prior research by examining the constraints that co-innovation imposes on firms' value capture. In particular, to the extent that co-innovation incurs co-specialization, co-innovating firms are likely to be subject to ex-post appropriation by their partners. We thus find that the willingness to co-innovate is not even across firms. Firms with strong direct competition (e.g., weaker firms, or firms with close competitors) are likely to find co-innovation attractive, as these firms capture little value otherwise. In fact, co-innovation may even *improve* their ability to capture value, by ensuring that their co-specialized partners depend on them to create value. In contrast, those with little direct competition (e.g., the strongest firms in each component) are already likely to capture value on their own. Thus, they have more to lose from co-innovation, and are instead happy to capture a larger slice of a smaller pie.

A related contribution is to highlight an unexpected benefit of co-innovation. Prior literature highlights the benefit of co-innovation in terms of firms' ability to create value (Baldwin and Clark, 2000). We contribute the insight that co-innovation simultaneously prevents competitors from doing the same. As a result, co-innovation may occur *even when the additional value created by doing so is negative.* Our model allows insight into this counterintuitive result. In particular, we show that while firms compete with rivals in their own component and cooperate with partners in complementary components, they implicitly compete against *potential coalitions* at the ecosystem level as well (i.e., their rivals and their partners' rivals). By "claiming" attractive partners for itself, co-innovation allows a focal firm to deny rivals of potential partners, thus decreasing rivals' ability to compete effectively at the ecosystem level. This result is consistent with those of Santos and Eisenhardt (2009) and Ozcan and Eisenhardt (2009), who observe entrepreneurs in the nascent internet and mobile gaming sectors using preemptive alliances to deprive rivals of partners. We extend these results by identifying the conditions under which this strategy is viable. Specifically, we find that such "value-decreasing" co-innovation is viable only when the strong firms can effectively safeguard their ability to capture value (e.g., through contracts) and when the capabilities of the firms in the industry are highly dispersed, such that depriving rivals of a potential partner leaves them with few available alternatives.

Creating and capturing value in ecosystems

A second area of contribution is to clarify the relationship between the variables that govern firm performance and strategy with respect to bottlenecks. Prior literature identifies several important variables that might affect firms' ability to jointly resolve bottlenecks. The distribution of capabilities in the industry determines the location and magnitude of the bottleneck (Ethiraj, 2007; Gawer and Henderson, 2007; Jacobides et al, 2015c). Technological uncertainty affects the likelihood that firms or their partners will fail (Afuah, 2000; Eggers, 2012). Finally, the degree to which firms can effectively govern their collaborations and the allocation of value with contracts determines their vulnerability to holdup by partners (Teece, 1986; Jacobides et al, 2006; Qian et al, 2012). Yet, the focus on individual variables has left their joint impact unclear.

We find important interactions between these variables. For example, we find that the impact of uncertainty on firm performance and value creation is greater when there is greater variation in the capabilities of the firms in a given component. In other words, if a component contains only a few "leading" firms, the loss of one of these leaders is likely to be greater than the loss of one of several comparable firms. Similarly, we find that uncertainty and capabilities exert a joint impact on firm performance and strategy. For strong firms, uncertainty generally reduces performance, as well as their willingness to improve partners or engage in co-innovation. In contrast, weaker firms tend to benefit from uncertainty: their performance is curvilinear (i.e., an inverted U) in uncertainty, as is their willingness to improve or co-innovate with partners. The underlying intuition is that while uncertainty decreases value creation, it also introduces an element of luck, attenuating competition by giving weak firms a chance to end up on top.

A final contribution is to identify a surprising impact of uncertainty on the viability of the co-innovation strategy. Prior research suggests that technological uncertainty makes it difficult for firms to identify and evaluate partners, and increases the risk that specific partners fail (Hannah and Eisenhardt, 2015; Afuah, 2000; Eggers, 2012). As a result, firms may be less likely to work closely with partners to resolve bottlenecks (Afuah, 2000; Beckman et al, 2004). Consistent with this work, we find that at high levels of uncertainty, the co-innovation strategy is indeed less viable. However, we also find that at lower levels of uncertainty, firms are actually *more* likely to co-innovate than they are without uncertainty. This effect is driven, perversely, by the fact that co-innovation under uncertainty makes firms doubly likely to fail, as firms are dependent on both their own *and* their partners' success (Adner and Feiler, 2015). Because weaker firms cannot capture value unless their stronger competitors fail, they would thus prefer to see their stronger competitors co-innovate, and thus run a greater risk of failing. Moreover, by co-innovating *with one another*, weaker firms can deprive stronger firms of potential partners, thus prompting them to co-innovate among themselves. Although doing so is risky for weaker firms, it forces the stronger firms to be risky as well – thus giving weaker firms a chance to come out ahead.

CONCLUSION

This analysis extends existing theory related to ecosystems to describe the strategies by which firms work collaboratively to address bottlenecks. Existing work has generally focused on *entry* into bottleneck components (Gawer and Henderson, 2007; Langlois and Robertson, 1995), and less is known about how firms resolve bottlenecks that lie outside their boundaries. We contribute to theory and practice by developing a mathematically precise framework for examining the viability of two archetypal strategies for doing so. Our analysis highlights the importance of understanding the role of interdependence in governing firm performance – and the agency of firms in shaping their ability to create and capture value in a world of bottlenecks.

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APPENDIX A: TABLES AND FIGURES

Table 1: Variable and Parameter Definitions

Symbol	Name	Definition and Notes
		Benchmark model
N	Set of all firms	All firms in the model, where N_k is the set of firms in component k.
K_i	An individual firm	Denotes an individual firm in component K.
k_i	Firm capabilities	Denotes capabilities of firm k_i, where $k_i \geq k_{i+1}$.
C	Consumer	Denotes the consumer.
f_K	Uncertainty	f_{Ki} is the probability K_i fails, f_K the same for any firm in component k.
$k_{(i)}$	An individual firm	Denotes the i^{th} ranked firm following the resolution of uncertainty.
		Value creation and capture
$v(N)$	Value creation	Denotes the value created by the full set of firms N. The value created by any subset G is denoted v(G).
$x(K_i)$	Core allocation	Core allocation for firm Ki, generally a range of values.
$AV(K_i)$	Added value	Added value of firm K_i, given by $AV(K_i) = v(G) – v(G/K_i)$.
$\pi(K_i)$	Expected value capture	Expected value capture of firm K_i, $\pi(K_i)= \alpha_{Ki}x(K_i)^{max}+(1 – \alpha_{Ki})x(K_i)^{min}$.
α_{Ki}	Confidence index	Denotes the subjective negotiating ability of firm K_i.
		Improving strategy
K_j^0	Initial capabilities	Pre-improvement capabilities of firm K_j.
K_j	Final capabilities	Post-improvement capabilities of firm K_j.
$\lambda (k_j, k_j^0)$	Improvement cost	Cost of improvement from K_j^0 to K_j.
		Co-innovating strategy
$r(A_i,B_j)$	Additional value	Additional value created by co-innovation.
$v(A_i,B_j)$	Coalition value	Value created when A_i and B_j co-innovate, given by $\min(a_i,b_j)+r(A_i, B_j)$.

Figure 1: Relationship between Model Parameters

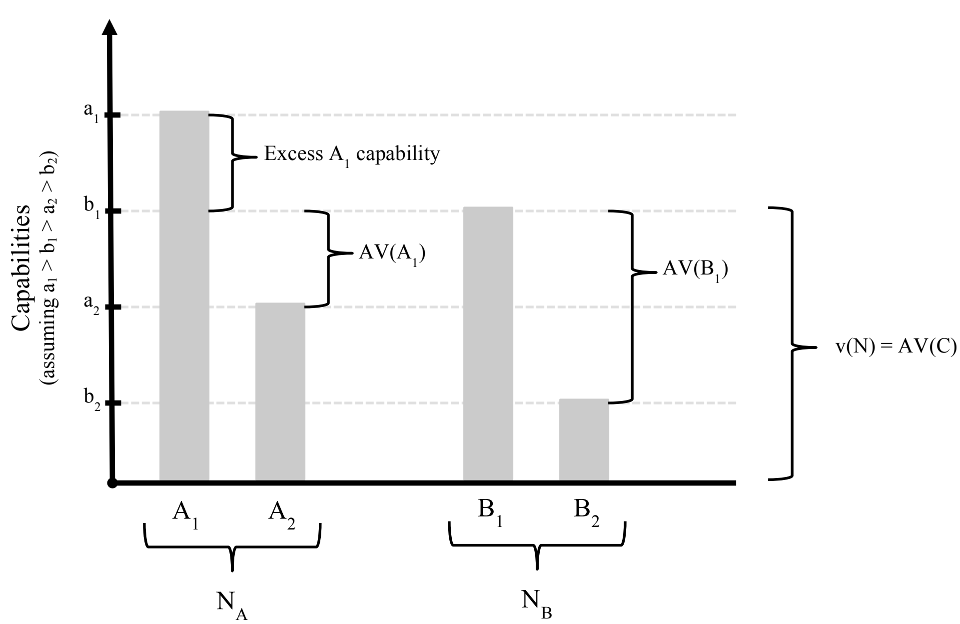
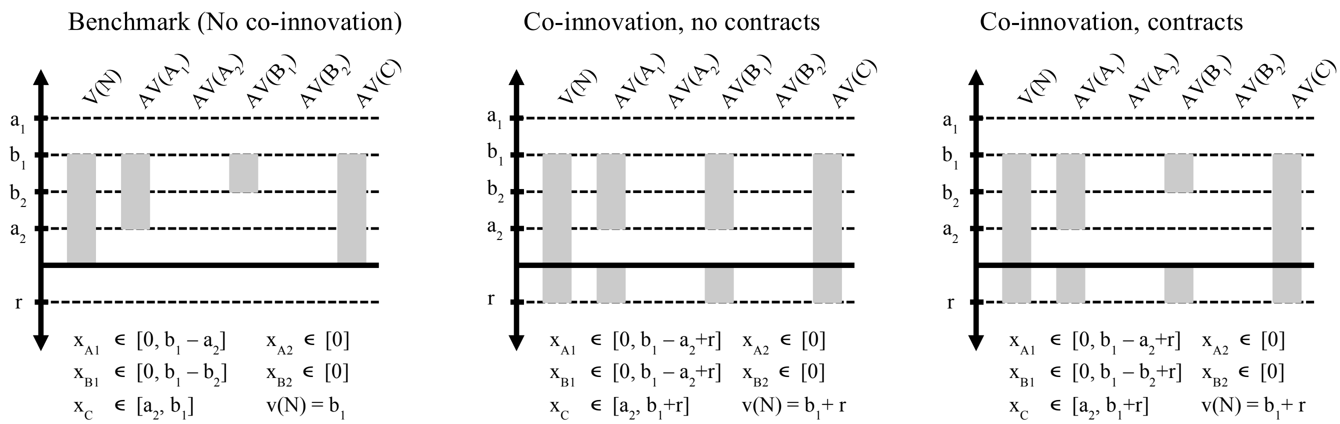


Figure 2: Co-innovation Value Capture

2.1 Co-innovation between A_1 and B_1, when $a_1 > b_1 > b_2 > a_2$.

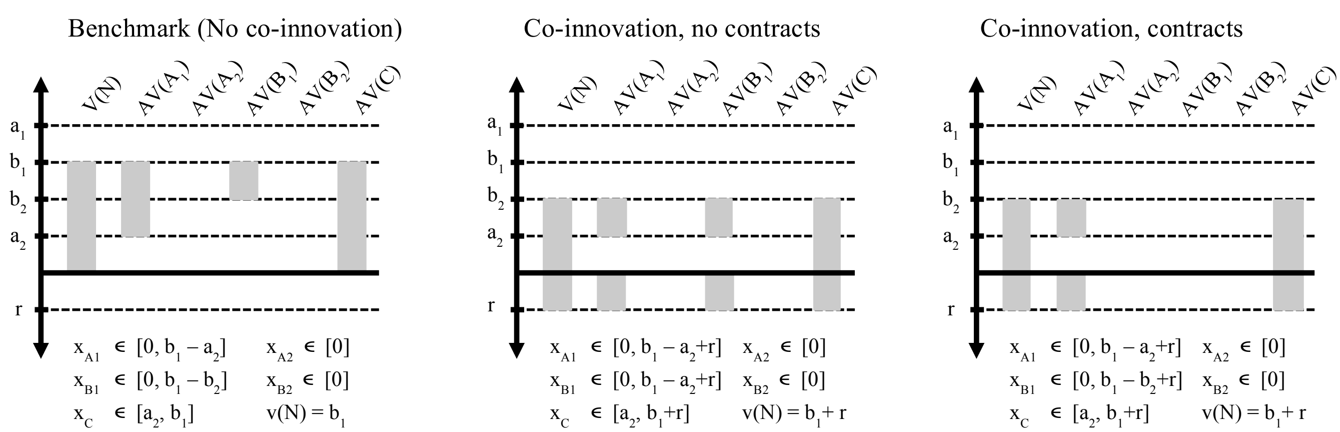


Note: r, a_2, b_2, b_1, and a_1 are all positive measured away from the horizontal axis. Magnitude is thus given by the height of the column.

Without co-innovation, each firm's added value is a function of the total value created, v(N) and the relative strength of its direct competition. When A_1 and B_1 co-innovate without contracts, they generate an additional r value. The consumer is able to capture a_2 by dropping both A_1 and B_1 (to work with A_2 and B_2), and thus captures at least a_2 in the core. A_1 and B_1 then compete with each other and the consumer for the remaining $b_1 - a_2 + r$.

When effective contracts are available, A_1 and B_1 generate b_1+r by co-innovating: $v(N) = b_1+r$. The consumer captures at least a_2, as above. A_1's added value is then the additional value r plus $b_1 - a_2$, which is the value that would be lost if it were to not participate. Similarly, B_1's added value is the additional value r plus $b_1 - b_2$.

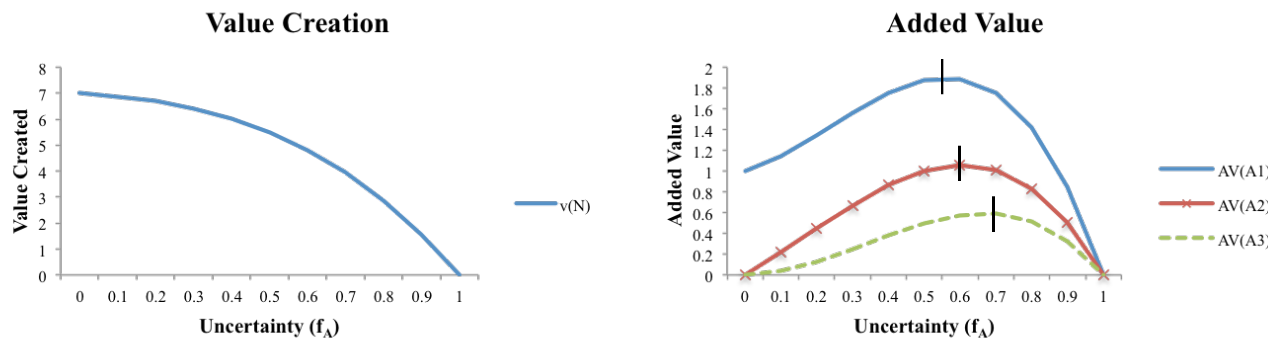
2.2 Co-innovation between A_1 and B_2, when $a_1 > b_1 > b_2 > a_2$.



Note: r, a_2, b_2, b_1, and a_1 are all positive measured away from the horizontal axis. Magnitude is thus given by the height of the column.

When A_1 and B_2 co-innovate, they create b_2+r in value (whether this is more than the value that would be created without co-innovating, b_1, depends on the magnitude of b_1, b_2, and r). The consumer must capture at least a_2 in the core, which is the value it can obtain by dropping A_1 and B_2 in favor of A_2 and B_1. Without contracts, A_1 and B_2 compete with one another and with the consumer for the value that is created. With contracts, A_1 offers B_2 a zero value contract and competes against the consumer alone (B_2 captures zero value without co-innovation).

Figure 3: Performance as a Function of Uncertainty



Value creation is strictly decreasing in uncertainty. Added value (and expected value capture) is curvilinear in uncertainty, and peaks at higher levels for weaker firms (peak AV denoted by the vertical lines).

Illustrated for $a_1 = 8, a_2 = 6, a_3 = 4, b_1 = 7, f_B = 0$.

APPENDIX B: PROOFS

A Note on the Model

The core and added value are widely used solution concepts in value-based analysis and biform games (e.g., Chatain and Zemsky, 2011; Jia, 2013). But despite their value, both are limited. For example, the relationship between added value and firm performance may not be straightforward (MacDonald and Ryall, 2004), and the core may be empty (Stuart, 2002).

In this analysis, we benefit from a class of games identified by Chatain and Zemsky (2007), in which firm payoffs are proportional to their added value and the core is always nonempty (see also Adner and Zemsky, 2006). Here we demonstrate that our model is consistent with their assumptions, such the minimum core allocation is zero and the max is $AV(K_i)$, thus allowing $\pi(K_i) = \alpha_{Ki}AV(K_i)$ to be a valid measure of firm performance.

Following Chatain and Zemsky (2007: 554), we split the set of players into K+1 nonempty, disjoint sets $\{N_A, N_B, \ldots, N_K, C\}$ such that $v(G)=0$ if $G \cap N_j = \emptyset$ for any $j \in \{A, \ldots, K+1\}$. This corresponds to Assumption 1. We also assume the ability of firms to create value with the consumer is independent: $v(N) = \Sigma v(\{K_i\} \cup C)\ \forall\ k_i \in N$. This corresponds to Assumption 2.

Proof of Proposition 1: Value creation and capture

Omitted. The results are easily derived from the value creation and core allocation expressions in the preceding paragraphs (pages 17 and 18).

Proof of Proposition 2: Improving partner capabilities

(i) Firm A_1 maximizes $\pi(A_1) = \alpha_{Ai}(\min(a_1,b_1) - a_2) - \sum\lambda(k_i,k_i^0)$. We assume component B is the bottleneck, such that $a_1 > b_1$. Then, following stage 1, $\pi(A_1)$ then depends on the relative strength of a_1, a_2, and b_1. If $a_1>b_1>a_2$, $\pi(A_1) = \alpha_{A1} (b_1 - a_2) - \Sigma\lambda(k_j,k_j^0)$. If $b_1>a_1>a_2$, $\alpha_{A1} (a_1 - a_2) - \Sigma\lambda(k_j,k_j^0)$. Finally, if $a_1>a_2>b_1$, $\pi(A_1) = 0$.

Note that because $\pi(A_1)$ is decreasing in a_2, A_1 will never improve A_2. Thus, taking the first order conditions of the above with respect to a_1 and b_1, we obtain:

$\alpha_{A1} - d\backslash d(b_1)\ \lambda(b_1,b_1^0) = 0$, if $a_1 > b_1 > a_2$

$\alpha_{A1} - d\backslash d(a_1)\ \lambda(a_1,b_1^0) = 0$, if $b_1 > a_1 > a_2$

Thus, it is optimal to invest in b_1^0 iff $\alpha_{A1} > d\backslash d(b_1)\ \lambda(b_1,b_1^0) = 0$ such that $b_1 > a_2^0$. If $b_1 > a_2^0$ and $\alpha_{A1} > d\backslash d(a_1)\ \lambda(a_1,b_1^0)$, it is optimal to improve a_1^0 as well such that $a_1=b_1$.

Given increasing costs $d/dki\ \lambda(k_i,k_i^0)$, we also have that the incentive to improve A_1 and B_1, $\pi(A_1|a_1,b_1) - \pi(A_1|a_1^0,b_1^0)$, is also decreasing in a_2 and cost $\lambda(k_i,k_i^0)$.

(ii) This result follows directly from equations (1) and (6). $d/d(b_i)\ v(N) = d/d(b_i) \min(k_1) = 0\ \forall\ i \geq 2$. Similarly, $d/d(b_i)\ \pi(A_1) = d/d(b_i)\ \alpha_{A1}AV(A_1) = d/d(b_i)\ v(N) - a_2 = 0\ \forall\ i \geq 2$.

(iii) $\pi(A_i) = \pi(B_i) = \alpha_{Ai}AV(A_i) = \alpha_{Bi}AV(B_i) = 0$ for all $i \geq 2$ by equation (6). Thus, for any positive cost $\lambda(k_i,k_i^0)$, $\pi(A_i) - \lambda(k_i,k_i^0) < 0$ if $a_i < a_1^0$, and analogously for B_i, $b_i < b_1^0$.

Proof of Proposition 3: Co-innovating with partners

(i) Firm A_i prefers to co-innovate with a given partner B_j iff doing so increases $\pi(A_i)$ relative to not co-innovating. Co-innovating with B_j, $\pi(A_i) = \alpha_{Ai}[v(A_i,B_j) - \max v(A_x,B_y)]^+$, $i\neq x$, $j\neq y$, where $[q]^+$ denotes max (0, q). Similarly, not co-innovating with B_j, $\pi(A_i) = \alpha_{Ai}[\max v(A_i,B_z) - \max v(A_x, B_t)]^+$, $z\neq j$, $x\neq i$, $t\neq z$, which describes the value created by Ai co-innovating with any other firm B_z, less the value created by competing coalitions.

For a weak firm (e.g., A_i, $i \geq 2$), $\pi(K_i) = 0$ without co-innovating. Thus, IC-A_i weakly holds and weak firms weakly prefer with any B_j to co-innovate as long as $r(A_i,B_j) \geq 0$.

For a strong firm (e.g., A_1), $\pi(K_i) \geq 0$ in the benchmark model (and is strictly positive when $a_1 > b_1 > a_2$). Thus, IC-A_1 will not hold for all B_j. Substituting $\min(a_i,b_j) + r(A_i, B_j)$ in place of $v(A_i,B_j)$, we see that $\pi(A_i)$ with co-innovation increases in b_j, increases in $r(A_i,B_j)$, and decreases in the strength of the competing coalitions: $\max (\min(a_x,b_y)+r(A_x,B_y))$, $i\neq x$, $j\neq y$. Similarly, the value of not co-innovating with B_j increases in the capability of the firms that remain outside the coalition: b_x, $x\neq j$, or B_j's competitors.

(ii) The amount of additional value $r^*(A_i,B_j)$ that must be created in order for a coalition to form follows directly from IC-A_i and IC-B_j.

(iii) First, we show that coalitions other than A_1-B_1 are not viable without contracts when r=0. We then show that coalitions other than A_1-B_1 are viable with contracts.

The added value of any coalition A_i,B_j is $AV(A_i,B_j) = \min(a_i,b_j) - \min(a_x,b_y)$. For an A_1-B_1 coalition, $AV(A_1,B_1) = \min(a_1,b_1) - \min(a_2,b_2)$. An A_1-B_2 coalition yields $AV(A_1,B_2) = \min(a_1,b_2) - \min (a_2,b_1)$, which is strictly lower than $AV(A_1,B_1)$ a long as $a_1 \geq b_1$. Thus, $\pi(A_1) = \alpha_{A1}AV(A_1,B_1) > \pi(A_1) = \alpha_{A1}AV(A_1,B_2)$, so A_1 will decline to participate in this coalition, and similarly for any coalition with B_j, $j \geq 3$. An A_2-B_1 coalition yields $AV(A_2,B_1) = \min(a_2,b_1) - \min(a_1,b_2)$. This is strictly lower than $AV(A_1,B_1)$ unless $a_1>a_2>b_1$.

We now show a coalitions other than A_1-B_1 is viable if contracts can pre-specify the allocation of value in stage 1. In particular, assume $a_2 > b_2$, so that a coalition between B_1 and A_2 generates $v(A_2,B_1)=a_2$ and the next best coalition produces $v(A_1,B_2)=b_2$. Because $\pi(A_2) = 0$ without co-innovation, it is indifferent to a contract from B_1 in which it captures $\pi(A_2) = 0$. This allows B_1 to bargain with the consumer over $AV(A_2,B_1) = a_2 - b_2$, yielding $\pi(B_1) = \alpha_{B1}(a_2 - b_2)$. In contrast, by remaining independent $\pi(B_1) = \alpha_{B1}(b_1-b_2)$, which is strictly lower. Thus, A_2-B_1 is incentive compatible for both A_2 and B_1.

Derivation of Value Creation and Capture under Uncertainty

Uncertainty is represented by the probability that a given firm fails in stage 2 of the game. The chance of failure (conversely, chance of success) of firm K_i is given by f_{Ki} (conversely, $1-f_{Ki}$). Let $K_{(i)}$ be the firm with the i^{th} strongest capabilities following the resolution of uncertainty, and denote those capabilities $k_{(i)}$. We start by deriving the expected value creation under uncertainty (equation 13) when K=2. $V(N) = \min(a_1,b_1)$, so taking the expectation yields $E[v(N)] = \min(E[a_{(1)}, E[b_{(1)}])$. Each term $E[a_{(1)}]$ and $E[b_{(1)}]$ is given by the product of each firms' capabilities times the probability that it survives and all stronger firms fail (i.e., that $k_i=k_{(1)}$), $k_i(1-f_{Ki})\Pi_{(j<i)}f_{Kj}$, summed across all firms in component K in stage 1. This yields:

$$E[v(N)] = \Sigma_{i=1}^{N_A}\Sigma_{j=1}^{N_B} min(a_i, b_j)(1-f_{A_i})(1-f_{B_j})\Pi_{x=0}^{i-1}\Pi_{y=0}^{j-1} f_{A_x} f_{B_x}$$

Which, given component-specific uncertainty (that is, $f_{Ki} = f_K \ \forall\ k \in K$), reduces to:

$$E[v(N)] = \Sigma_{i=1}^{N_A}\Sigma_{j=1}^{N_B} min(a_i, b_j)(1-f_A)(1-f_B) f_A^{i-1} f_B^{j-1}$$

Added value may be derived in the same way. From equation (6), added value $AV(K_i) = v(N) - k_{i+1}$ for i=1, and 0 otherwise. Taking the expectation, we have $E[AV(K_i)] = E[v(N) - k_{i+1}]$. Without loss of generality, consider a firm A_i. Because $AV(A_i) = 0$ for $i \geq 2$, $E[AV(A_i)] = (\min(a_i, E[b_{(1)}]) - E[a_{(2)}|a_i=a_{(1)})p(a_i=a_{(1)})$. In other words, a firm's E[AV] is the minimum of its own capabilities and the expected value of the strongest surviving complementor, less the capabilities of its strongest competitor, times the probability that it survives and enters stage 3 as the strongest firm in its component. Letting $[q]^+$ denote max(0,q), this yields:

$$E[AV_{A_i}] = [min(a_i, \Sigma_{x=1}^{N_B} b_x(1-f_B) f_B^{x-1}) - \Sigma_{y=i+1}^{N_A} a_y(1-f_A) f_A^{y-1}]^+ (1-f_A) f_A^{i-1}$$

Expected value capture (equation 14) follows suit, with $E[\pi(K_i)] = \alpha K_i\ E[AV(K_i)]$.

Proof of Proposition 4: Expected value creation and capture under uncertainty

(i) Expected value creation $E[v(N) = \min(E[a_{(1)}],E[b_{(1)}])$, or the minimum of the strongest firm in each component after stage 2. Moreover, $k_i > k_{i+1}$ for all i, so $a_{(1)} = \Sigma a_i(1-f_A)f_A^{i-1}$ is decreasing in f_A and $b_{(1)}$ is decreasing in f_B, implying $E[v(N)]$ is decreasing in f_A and f_B.

(ii) To determine the impact of f_A and f_B on expected value capture, we simply take the derivate of $E[\pi(K_i)]$ with respect to each. For the first part, note that f_B affects firms in A only by decreasing expected value creation $E[v(N)]$, and that $d/df_B\ \Sigma_{(x \in NB)} b_x(1-f_B)f_B^{x-1} < 0$. Thus, $E[\pi(A_i)]$ is decreasing in f_B. For the second part, $d/df_A\ E[\pi(A_i)]$ is similarly zero when $f_A=1$, zero for $i \geq 2$ when $f_A=0$, and positive for all i when $f_A \in (0,1)$. In other words, f_A increases the probability that a given firm A_i fails, but at the same time increases the probability that its competitors do as well, so that $E[\pi(A_i)]$ is curvilinear in f_A. Finally, note that the positive interaction between i and f_A on $E[\pi(A_i)]$. Formally, $d^2/df_A di > 0$: thus, the performance maximizing level of uncertainty f_A is increasing in i (i.e., for weaker firms).

Proof of Proposition 5: Improving partner capabilities under uncertainty

(i) We first examine the incentives of a focal firm to invest in its own capabilities given uncertainty in its own component (f_A on A_1). For $f_A = f_B = 0$, $\pi(A_1) = \min(a_1,b_1) - a_2$. For $f_A > 0$, $f_B > 1$, we have $\pi(A_1) = (\min(a_1,b_1) - a_2)(1-f_A)^2(1-f_B)) + \min(a_1,b_1)(1-f_A)f_A(1-f_B) + (\min(a_1,b_2) - a_2)(1-f_A)^2 f_B(1-f_B)) + \min(a_1,b_2)(1-f_A)f_A f_B(1-f_B)$. Taking the derivative with respect to f_A and f_B, we get $d\pi(A_1)/df_A < 1$ and $d\pi(A_1)/df_B < 1$. We have made no assumptions on a_1 and b_1, so this holds for both bottleneck and non-bottleneck components.

(ii) We first examine the impact of own-component uncertainty on a weak firm's improvement incentive (e.g., f_A on A_2). By 2.iii, it is never optimal for a weak firm to improve partner capabilities until its own capabilities exceed its direct competitor: $\pi(A_i) = \pi(B_i) = \alpha_{Ai}AV(A_i) = \alpha_{Bi}AV(B_i) = 0$ for all $i \geq 2$ by equation (6). Thus, for any positive cost $\lambda(k_i,k_i^0)$, $\pi(A_2) - \lambda(k_i,k_i^0) < 0$ if $a_2 < a_1^0$. With $fA > 0$, $\pi(A_2) = \alpha_{A2}\min(a_2^0,b_1^0)(1-f_A)f_A(1-f_B) + \alpha_{A2}\min(a_2^0,b_2^0)(1-f_A)f_A(1-f_B)f_B - \lambda(k_i,k_i^0)$, which is increasing in a_2^0, b_1^0, and b_2^0. Taking the derivative with respect to f_A, we see that $\pi(A_2)$ is increasing for $f_A < ½$. Thus, the incentive to improve $a_2^0 \rightarrow a_2$ and $b_1^0 \rightarrow b_1$ is increasing for all $a_2 \leq b_1$ and for $b_2^0 \rightarrow b_2$ when $a_2 \leq b_2$ when $f_A < ½$, and is decreasing when $f_A > ½$. At $f_A=1$, $\pi(A_2)=0$ and there is no incentive to invest in a_2, b_1, or b_2. Note that we have made no assumptions on a_2 and b_1, so this holds for the weak firms in both bottleneck and non-bottleneck components.

We next examine the impact of complementor uncertainty on a weak firm's improvement incentive (e.g., f_B on A_2). As above, $\pi(A_2) = \min(a_2^0,b_1^0)(1-f_A)f_A(1-f_B) + \min(a_2^0,b_2^0)(1-f_A)f_A(1-f_B)f_B - \lambda(k_i,k_i^0)$. Taking the derivate with respect to f_B, we see that $\pi(A_2)$ is decreasing in f_B. Again, this holds for both bottleneck and non-bottleneck.

Proof of Proposition 6: Co-innovating with partners under uncertainty

(i) With only two firms in the industry, $E[\pi(A_1)] = E[\pi(B_1)] = \alpha_{Ki}(1-f_A)(1-f_B)(\min(a_1,b_1) + r(A_1,B_1))$ if A_1 and B_1 co-innovate. Without co-innovating, $E[\pi(A_1)] = E[\pi(B_1)] = \alpha_{Ki}(1-f_A)(1-f_B)(\min(a_1,b_1))$. Thus, A_1 and B_1 co-innovate when $r(A_1,B_1) \geq 0$. When $N_A > 1$ and $N_B = 1$, B_1 will co-innovate iff $E[\pi(A_i,B_1)] = v(A_i,B_1)(1-f_A)(1-f_B) \geq \min(E[a_i], b_1)(1-f_B)$, which is increasing in $r(A_i,B_1)$ and decreasing in f_A. The $N_A=1$, $N_B>1$ case follows suit.

(ii) Without uncertainty, $\pi(A_i) = \pi(B_j) = 0$ for $i,j \geq 2$. Under uncertainty, $\pi(A_i) > 0$ requires that all firms A_j, $j < k$, fail. Consider a four firm industry, with $N_A = N_B = 2$. The probability that A_1 fails without co-innovation is f_A. If A_1 co-innovates, it fails with probability $(1-(1-f_A)(1-f_B)) > f_A$. Thus, weaker firms strictly prefer to have A_1 and B_1 co-innovate. Let $r(A_i,B_j)$ be sufficiently low, such that $E[AV(A_1)] > E[AV(A_1,B_1)]$ and $E[AV(B_1)] > E[AV(A_1,B_1)]$. In other words, A_1 and B_1 prefer to remain independent. Then, select a level of uncertainty f_A,f_B such that $E[\pi(A_2,B_2) \mid A_1,B_1 \text{ co-innovate}] > E[\pi(A_2,B_2) \mid A_1, B_1 \text{ independent}]$. A_2 and B_2 will thus co-innovate, as will A_1 and B_1 by 6.i