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SUPPLY-SIDE NETWORK EFFECTS AND THE DEVELOPMENT OF INFORMATION TECHNOLOGY STANDARDS

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Appendix A

Summary of Relevant Literature on IS/IT Standards

Study	Context	Main Findings	Impact of Standards	Standard Diffusion	Standard Creation	Network Effects
Axelrod et al. (1995)	A formal model of standard-setting alliance formation, tested in the context of Unix standards coalitions	A firm's utility from joining a standard-setting alliance increases with the size of an alliance and decreases with the presence of close rivals in the alliance. The resulting alliance pattern may be sensitive to small historical events and expectations.			•	
Brynjolfsson and Kemerer (1996)	An empirical analysis of the pricing of microcomputer spreadsheet software between 1987 and 1992	Network externalities (size of the installed base) and adherence to the dominant standard both significantly increase the price of a spreadsheet product.	(•)	(•)		•

Study	Context	Main Findings	Impact of Standards	Standard Diffusion	Standard Creation	Network Effects
Kauffman et al. (2000)	An empirical analysis of network adoption and diffusion in an electronic banking network among 78 Connecticut banks between 1984 and 1987	In line with the network externalities hypothesis, banks in markets that can generate a larger effective network size and a higher level of externalities tend to adopt early, while the size of a bank's own branch network (a proxy for the opportunity cost of adoption) decreases the probability of early adoption.		•		•
West and Dedrick (2000)	A case study of the Japanese PC market in the 1980s and 1990s	A victory in standards competition can provide long-lasting economic advantages. The introduction of a new architectural layer that spans previously incompatible architectures can negate these advantages.	•	•		•
Au and Kauffman (2001)	An economic model of the adoption of electronic bill presentment and payment (EBPP) technology	Network externalities may lead to an early adoption of the existing technology by the billers even though next technology may be superior to the current one. The relative costs and benefits of adoption and upgrading influence billers' decision to wait for a new and better but compatible technology.		•		•
Gallaugher and Wang (2002)	An empirical analysis of network effects and web server pricing between 1995 and 1997	Network effects lead to a positive relationship between market share and pricing. Higher market share in one market leads to a higher market share and price for the complement. Supporting a dominant standard also provides a price benefit.	•	•		•
Garud et al. (2002)	A case study of Sun's sponsorship of its Java technology as a common standard	Common technological standards are a key facet of the institutional environment of network technological fields and have built-in tensions. Establishing a standard involves cooperation between competitors, and sponsors face the challenge of both mobilizing and controlling the coalition around the standard.		•	(•)	
Chellappa and Shivendu (2003)	An analytical model of the effects of multiple incompatible regional DVD standards on piracy and pricing	Maintaining multiple incompatible technology standards may be crucial in order to reduce losses from piracy, especially when consumer preferences and copyright enforcement differ across regions.	•			
Hovav et al. (2004)	A conceptual model of the adoption of Internet standards, illustrated through a case study of the IPv6 standard	The adoption of Internet-based standards depends on the usefulness of the features of the standard and the conduciveness of the environment. There can be partial adoption where both old and new standards coexist for extended periods of time.		•		•
Parker and Van Alstyne (2005)	A formal model of information product design under two-sided network effects	A firm can rationally invest in a product it intends to give away when the increase in profits in a complementary market covers these costs. Either the market of content providers or the market of end consumers can be a candidate for a free good. Product coupling can increase consumer welfare even as it increases firm profits.		•		•

Study	Context	Main Findings	Impact of Standards	Standard Diffusion	Standard Creation	Network Effects
Wigand et al. (2005)	A case study of information systems standards and industry structure in the US home mortgage industry	Whereas costly-to-implement standards such as EDI can lead to industry consolidation, more-accessible (e.g., XML-based) standards can have more complex structural effects, such as disintegration, disintermediation, and the emergence of new entrants. The specific effects depend on the organizations' standards implementation strategies.	•			
Yoo et al. (2005)	A case study of the role of standards in the evolution of mobile infrastructure in South Korea	Successful innovation and diffusion of broadband mobile services are collective achievements that require the mobilization of networks and resources. Standards mediate different interests and motivations among the actors.	•	•	•	
Backhouse et al. (2006)	A qualitative case study of the first standard in information security management (BS 7799, later ISO 17799)	De jure standards are initially generated in a cooperative manner. The institutionalization of the standard development process results from the power interactions among the stakeholders involved. The interests and objectives of the stakeholders are influenced by exogenous contingencies and institutional forces.			•	
Bonaccorsi et al. (2006)	A survey of 146 Italian software firms entering the open source (OS) field	Firms have adapted to an environment dominated by incumbent standards through a hybrid business model that combines the offering of proprietary and OS software under different licensing schemes.	•	•		•
Chen and Forman (2006)	An empirical analysis of vendor choice in the market for routers and switches of over 22,000 establishments between 1996 and 1998	There are significant switching costs despite open standards. Vendors may have influence over switching costs and the speed of new technology adoption.	(•)	•		
Hanseth et al. (2006)	A case study of the standardization process of an electronic patient record (EPR) in a Norwegian hospital	Socio-technical complexity is a major issue in information system standardization. Under certain circumstances, efforts aimed at reducing complexity through standardization may generate the opposite outcome. Traditional standardization approaches cannot address complexity appropriately: they fail to deliver the intended outcome and can even lead to the opposite effects of greater disorder and instability.	•		•	
Lee and Oh (2006)	A case study of China's attempts to set its own WAPI national wireless standard	The Chinese government failed to set WAPI as a national standard largely due to its inability to mobilize other actors, given the closed nature of the standard.		•		
Lin and Kulatilaka (2006)	An analytical model of the impact of network effects on licensing choice	For the firm controlling a standard, a fixed-fee license is optimal under strong network effects. With weaker network effects, the optimal license uses a royalty rate.		•		•
Lyytinen and King (2006)	An introduction to a special issue with a brief review of standard-making literature	IS standardization is becoming an important, legitimate and growing branch of research.			•	

Study	Context	Main Findings	Impact of Standards	Standard Diffusion	Standard Creation	Network Effects
Markus et al. (2006)	A case study of vertical information systems standardization in the U.S. residential mortgage industry	Vertical information systems standardization involves two linked collective action dilemmas – standards development and standards diffusion – with different characteristics, such that a solution to the first may fail to resolve the second.		•	•	
Nickerson and zur Muehlen (2006)	A case study of the history of Web services choreography standards	The ecological approach applies well to Internet standards. Changes to institutional Internet governance, especially to the bylaws of standards bodies, can have significant effects on standard-making ecology.			•	
Weitzel et al. (2006)	A formal analysis of communication standard diffusion using equilibrium analysis and simulation modeling	Network topology and density have a strong effect on standard diffusion, and the emergence of a single standard may be less common than prior research often suggests. Centralized coordination (e.g., through consortia) may ensure convergence on a single standard when optimal.		•		•
Zhu et al. (2006)	A survey of open-standard interorganizational system (IOS) adoption by 1,394 firms from multiple countries and industries	Network effects and expected benefits are significant drivers of the adoption of a new standard. Experience with older standards may create switching costs and inhibit the shift to potentially better standards. The managerial complexity of migrating to the new standard is a key determinant of adoption costs.		•		•
Bala and Venkatesh (2007)	A multiple case study of the assimilation of inter-organizational business process standards in 11 firms in the high-tech industry	The drivers of assimilation vary by firm type (non-dominant versus dominant) and assimilation stage. Dominant firms tend to be driven by normative pressures and collaboration gains (e.g., cost savings), whereas non-dominant firms are driven by the desire to maintain relationships with dominant partners and to comply with institutional pressures. Overcoming inertia is important for both types of firms to reach general deployment.		•		
Lee and Mendelson (2007)	An analytical model of adoption dynamics in a multi-segment market characterized by network effects	Technology benefits to users depend on vendor strategies, which are driven by the existence of standards. Total social welfare is maximized by up-front de jure standards, but how these benefits are divided between users and vendors depends on market structure.		•		•
Malhotra et al. (2007)	A survey of 41 supply chain partnerships in the IT industry	Standard electronic business interfaces between supply chain partners facilitate collaborative information exchange and, through that, both mutual adaptation and adaptive knowledge creation.	•			
Zhao et al. (2007)	A formal model of consortium-based e-business standardization	The development and adoption of standards are interlinked, and developers should also take into account the network effects provided by firms outside the consortium. There are different equilibria regarding the developer network, both with and without passive adopters.		•	•	•

Study	Context	Main Findings	Impact of Standards	Standard Diffusion	Standard Creation	Network Effects
Leiponen (2008)	A panel data analysis of cooperative standard-setting in the context of the 3GPP standards-development organization	Participation in external industry consortia increases firms' contributions to the development of new technical specifications in formal standard-setting committees.			•	
Rysman and Simcoe (2008)	An empirical analysis of patent citations in the context of standard-setting organizations (SSOs)	Patents disclosed to SSOs are cited more frequently and at later ages. SSOs can identify promising technologies and influence their subsequent adoption.		•	•	
Chellappa and Saraf (2010)	An empirical study of the antecedents and outcomes of alliance formation of 69 firms in the enterprise system software (ESS) industry, a market that lacks a common standard	The alliance network in the ESS industry does not conform to the equilibrium structure as predicted by economics of network evolution. Rather, the relative structural position acquired by a firm and its alliance network is a reasonable proxy for its standards dominance and is an indicator of its performance. Compatibility considerations can trump rivalry concerns, and firms freely form alliances even with their rivals. Network prominence is more important for smaller firms.	•			
Smith et al. (2010)	An action research study of the power relationships during a centrally mandated national de jure information systems security standards adoption and accreditation process	A large-scale IS/IT project conducted across multiple government agencies and sites of varying sizes requires that the implementation be staggered and suited to agency size, thus breaking down the complexity of the tasks and enabling resources (people and budgets) to be put in place and allocated to future project phases. Adequate financial resourcing and management support and buy-in are also keys to effective implementation.		•		
Aggarwal et al. (2011)	An empirical event study of 299 IT standard-setting events between 1996 and 2005	In a capital market setting, establishing standards in a group does not decrease the total risk faced by an individual firm's shareholders; however, the market risk decreases and the idiosyncratic risk increases. Firms electing to participate in a large standardization group obtain a reduction in abnormal returns.	•		•	
Liu et al. (2011)	An analytical model of the impact of conversion technologies on market equilibrium in the context of sequential duopoly competition and proprietary technology standards	Unless network effects are very large, the subgame-perfect equilibrium involves firms agreeing to provide digital converters at a sufficiently low price to all consumers.		•		•
Steinfield et al. (2011)	A conceptual paper on interoperability and information transparency in interorganizational systems, illustrated through a case study in the automotive industry	Standards can help solve information transparency problems if they are complemented by hub-type architectures that are shared by organizations in the industrial field.	•	•		

Study	Context	Main Findings	Impact of Standards	Standard Diffusion	Standard Creation	Network Effects
Zhao et al. (2011)	A survey of e-business standards consortium participation of 232 firms from 7 consortia	In general, firms' consortium contribution levels are positively driven by their perceived process benefits, technical resources, and consortium management effectiveness. Vendors are more motivated by standard benefits, whereas users are more motivated by process benefits.			•	
Li and Chen (2012)	A formal model of whether to standardize on one product or to allow the users to make their own choices when companies purchase information technology (IT) products for their employees, departments, or divisions	The employer is more likely to commit to exclusive purchase from a single seller to enforce standardization when the competing products are compatible, less vertically differentiated, and/or more horizontally differentiated. The sellers agree to cooperate and invest in mutual compatibility only when the gap between their competitive advantages is moderate, but the availability of third-party converters that enable partial compatibility can induce more collaboration among the sellers.		•		•
Liu et al. (2012)	An empirical analysis of the effects of network externalities on the pricing of flash memory cards over 44 months (2003–2006)	Network effects are associated with a significant positive price premium for leading flash memory card formats. This premium is reduced by the availability of digital converters.	•	•		•
Venkatesh and Bala (2012)	A survey on the adoption of interorganizational business process standards (IBPS) of 248 firms (124 firm-client dyads) considering the adoption of RosettaNet-based IBPS in the high-tech industry	Process compatibility and technology readiness have a positive effect and standards uncertainty a negative effect on IBPS adoption. These effects are synergistic so that IBPS adoption is influenced by the relevant characteristics of both the focal firm and its trading partner. IBPS adoption decreases cycle time and increases partnering satisfaction, mediating the effects of process compatibility and technology readiness on cycle time and the effect of relational trust on partnering satisfaction.	•	•		
Zhao and Xia (2014)	Survey of interoperability and interorganizational systems (IOS) standards of 194 organizations in the geospatial industry	Firms' IOS standards adoption positively influences their standardized data infrastructure (SDI); SDI positively influences interoperability, which in turn positively influences firm performance. Network effects positively influence both IOS standards adoption and interoperability. Interoperability is found to be a valuable organizational capability.	•	•		•

Appendix B

Categories of Mechanisms Governing Technology Choice, Diffusion, and Lock-In

Key Concept(s)	Mechanism Leading Firms to a Potentially Suboptimal Technology Choice	Risk of Persistent Lock-in[1] to a Suboptimal Technology
Diffusion models based on a rational evaluation of benefits; S-curve models, epidemic models, probit models (e.g., Davies 1979; Geroski 2000; Rogers 1995)	None – while the diffusion may not be instantaneous and can be slowed down by, for example, the slow spread of information about the new technology or different firm abilities, all firms ultimately end up with the optimal technology.	None: Similar to the diffusion of the first technology, all firms ultimately switch to a more efficient alternative if such a technology becomes available.
Firm-level and individual-level determinants of IT adoption (e.g., Davis 1989; Grover 1993; Iacovou et al. 1995; Tornatzky and Fleischer 1990; Venkatesh et al. 2003)	The attributes of the firm and its members, in interaction with the attributes of the technology, determine whether a firm adopts a particular technology.	Moderate-low: While this literature generally does not consider factors locking firms to particular technologies, organizational inertia and unwillingness to adopt the new technology may inhibit the switch to a superior alternative.
Institutional pressures to adopt particular technologies (e.g., DiMaggio and Powell 1983; Liang et al. 2007; Teo et al. 2003)	Powerful institutional forces, such as regulatory pressures or legitimacy concerns, force the adoption of particular technologies regardless of their efficiency from the firm's perspective.	Moderate: The need to stay with the suboptimal technology tends to persist as long as the institutional forces are in effect, although this may not prevent the adoption of a superior alternative.
Herding through fads and information cascades (e.g., Abrahamson 1991; Banerjee 1992; Bikhchandani et al. 1992; Duan et al. 2009; Sun 2013; Walden and Browne 2009)	Uncertainty about the value of the technologies impels organizations to (either partly or fully) discount their own information and follow the example of other firms adopting a particular technology, leading to bandwagon dynamics.	Low: There is no mechanism preventing organizations from switching to a superior technology when its relative value becomes apparent, and incorrect herds are typically easily reversed.
Herding through managerial and information technology fashions (e.g., Abrahamson 1991, 1996; David and Strang 2006; Wang 2010)	External proponents of particular technologies, such as consultants, academics, and the media, prompt the adoption of technologies that may not be optimal for the firm.	Moderate-low: Managerial and IT fashions tend to be fleeting, although the need to maintain legitimacy may force the firm to maintain its commitment to suboptimal technologies as long as they are in fashion.
Switching costs (e.g., Farrell and Klemperer 2007; Fuentelsaz et al. 2012; Polites and Karahanna 2012)	A firm may choose a technology that is optimal at the time the choice is made, but a more efficient technology may emerge later on, and the firm would incur extra costs to switch to it because of technology-specific (e.g., contractual or learning-related) investments.	High: By definition, this literature generally considers costs that are sufficiently high to possibly prevent the switching to a superior alternative.
Network effects, i.e., network externalities (e.g., Gallaugher and Wang 2002; Katz and Shapiro 1986; Weitzel et al. 2006; Zhu et al. 2006)	The use value of a technology depends on the size of its network of adopters. Firms may choose an inferior technology when the benefits from joining a larger network surpass the loss due to lower technological quality.	High: Because membership in a larger network brings real economic benefits, individual firms have little incentive to switch to a superior alternative with a smaller network.

[1]By persistent lock-in, we refer to the inability of a firm to switch to an evidently superior alternative technology even after it becomes available to the firm.

Appendix C

Modeling Technological Search with the NK Model[2]

The NK model originated in biology, where Kauffman (1993), building on the work of Wright (1932), introduced a model of hill-climbing search in a fitness landscape to simulate adaptive evolution. Kauffman modeled an organism's fitness as determined by N genes, each of which is epistatically influenced by K other genes. The parameters N and K gave the NK model its name, and such a model can be used to simulate the evolution of populations of organisms that are described as strings of genes. Despite its origin in biology, the NK model was later adapted and extended to simulate the evolution of a broad range of complex systems that are characterized by the interplay of interdependent components, including technological systems (e.g., Fleming and Sorenson 2001; Frenken 2006; Tesfatsion and Judd 2006).

Central to the NK model is the notion of a fitness landscape. Such a landscape consists of one dimension for each component plus an additional dimension for the fitness of the system. In this landscape, each location represents a particular configuration of components, and each configuration is associated with a fitness value that indicates the performance or usefulness of that specific configuration. In an information system, the components might be elements of the hardware, the operating software, and the application software, or as in the Bluetooth example, they might represent the transmission frequency, transmission protocol, bandwidth, signal strength, and power consumption. The fitness value might then reflect the performance of the system.

Following Kauffman's approach, a technological system can formally be described as a binary string of N components.[3] To illustrate, a system of three components (N = 3) can assume eight different configurations (000, 001, 010, 011, 100, 101, 110, and 111) that correspond to different points in the fitness landscape. The calculation of the fitness value of each configuration depends on K, the second parameter in the model, which reflects the interdependence between the components and describes the system's inner structure. When components are interdependent, the overall fitness contribution of a component is dependent not only on its own state but also on the state of K other components.

Despite its striking simplicity as a model with only two parameters in its simplest formulation, the NK model can and has been used to model a broad range of complex systems. Its power arises because it captures the very essence of a complex system. Simon (1962, p. 468) defines a complex system as a system that is "made up of a large number of parts that interact in a nonsimple way." Therefore, in Simon's view, system complexity arises from the number of components and their interdependence. It is these two dimensions of complexity that the two parameters N (number of components) and K (degree of interdependence between components) of the NK model directly model.[4]

To characterize the effect of different levels of complexity, it is useful to compare the fitness landscapes arising from two extreme cases of interdependence: (1) K = 0 describes a case of no interdependence and (2) K = N – 1 describes the case of maximum interdependence. For K = 0, the fitness contribution of each component is solely dependent on that component's own state (0 or 1). Formally, the fitness value of each component is drawn randomly from a uniform distribution between 0 and 1. The overall fitness of the system P is then calculated simply as the mean value of the fitness contributions of each component, that is, $P = \frac{\sum_{i=1}^{N} p_i}{N}$, where p_i denotes the fitness value of component i. See Table C1 and Figure C1 for an illustration using the example above with N = 3. The arrows in Figure C1 flow from configurations of lower fitness to configurations of higher fitness and represent the direction of the hill-climbing search.

[2]This appendix is based on the work by Kauffman (1993) and Fleming and Sorenson (2001).

[3]The key characteristics of NK landscapes, in terms of hill-climbing search, do not depend on the number of possible values a particular component can adopt (Kauffman 1993) and, therefore, it is customary to limit the potential values for each component to 0 and 1 for analytic simplicity.

[4]While complexity arises from the combination of N and K, for purposes of simplicity, most research holds the number of components N constant and varies the parameter K to simulate landscapes with different levels of complexity (Frenken 2006).

Table C1. Fitness Values for a Landscape with N = 3 and No Interdependence (K = 0), Adapted from Kauffman (1993) and Fleming and Sorenson (2001)

Binary Values of the Components (123)	p_1	p_2	p_3	$P = \frac{\sum_{i=1}^{N} p_i}{N}$
000	0.529	0.447	0.088	0.355
001	0.529	0.447	0.506	0.494
010	0.529	0.950	0.088	0.522
011	0.529	0.950	0.506	0.662
100	0.253	0.447	0.088	0.263
101	0.253	0.447	0.506	0.402
110	0.253	0.950	0.088	0.430
111	0.253	0.950	0.508	0.570

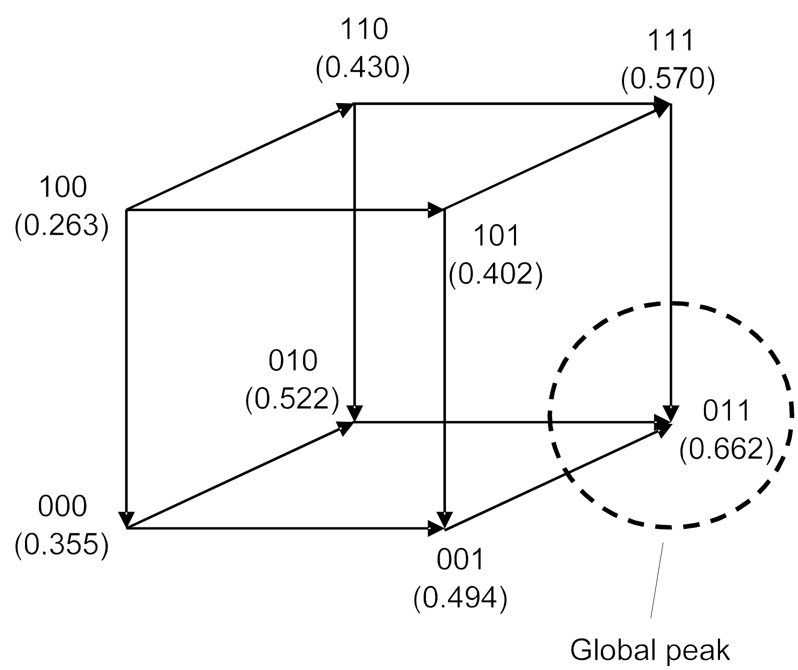

Figure C1. Landscape (N = 3) Without Interdependence (K = 0); Adapted from Kauffman (1993) and Fleming and Sorenson (2001)

By contrast, in the case of maximum interdependence (K = N – 1), the fitness contribution of each component depends on the states of all the other components. Thus, in the case of N = 3 and K = 2, a component can contribute any of eight potential values to the fitness of the system, depending on how the component itself and the other two components are configured. As a result, the fitness contribution of each component differs for each possible configuration. Formally, the fitness contribution of each component is drawn from a uniform distribution between 0 and 1 for each configuration separately. See Table C2 and Figure C2 for an illustration using (once again) the example in which N = 3.

Table C2. Fitness Values for a Landscape with N = 3 and Maximum Interdependence (K = 2), Adapted from Kauffman (1993) and Fleming and Sorenson (2001)

Binary Values of the Components (123)	p_1	p_2	p_3	$P = \frac{\sum_{i=1}^{N} p_i}{N}$
000	0.269	0.891	0.091	0.417
001	0.626	0.770	0.488	0.628
010	0.515	0.831	0.071	0.472
011	0.330	0.656	0.873	0.620
100	0.883	0.182	0.434	0.500
101	0.566	0.482	0.171	0.406
110	0.067	0.241	0.954	0.421
111	0.205	0.228	0.326	0.253

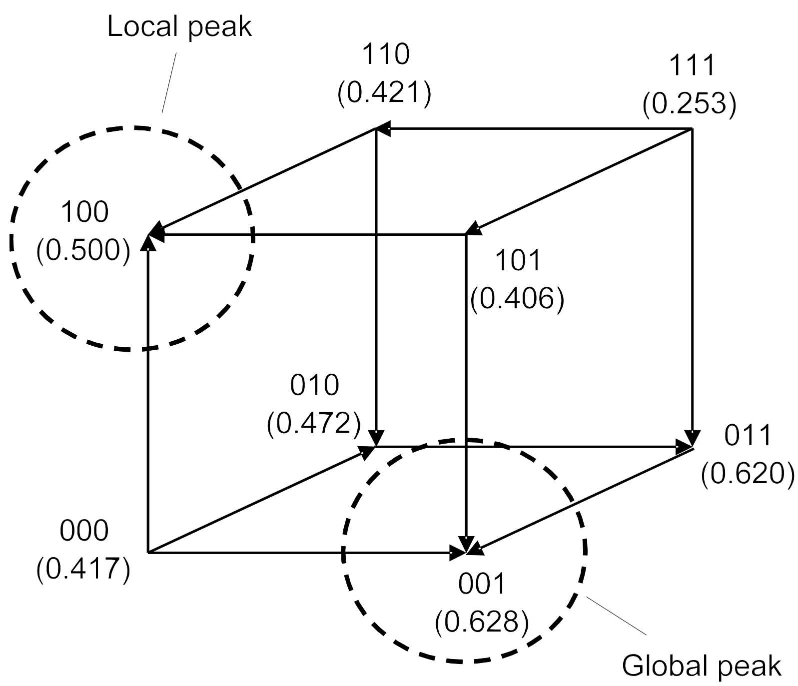

Figure C2. Landscape (N = 3) with Maximum Interdependence; Adapted from Kauffman (1993) and Fleming and Sorenson (2001)

NK models typically assume local search in the fitness landscape. In other words, the searching agent (e.g., organism, organization, or other actor) randomly changes one component at a time and assesses whether that change improves fitness. If fitness is improved, the agent retains the change; otherwise, it returns to the pre-change configuration. While this simple search process may seem simplistic and of low intelligence, it has been found to describe individual and organizational behavior in a broad variety of contexts (Fleming 2001; Fleming and Sorenson 2001; March and Simon 1958; Nelson and Winter 1982; Sørensen and Stuart 2000; Stuart and Podolny 1996).

One central insight arising from the NK model is that landscapes differ dramatically depending upon the interdependence of components and that these differences have important implications for the efficacy of local search. Landscapes with K = 0 exhibit one minimum, one maximum, and a high correlation of performance between adjacent points. In other words, the surface of the landscape is relatively smooth. Local search can identify the global maximum (i.e., the global peak) over time on such smooth landscapes by simply experimenting with one component at a time and selecting the option that leads to a better fitness contribution in each component. By contrast, landscapes with higher values of K have multiple local minima and maxima, and adjacent points exhibit low correlation in their fitness values. In other words, landscapes with high values of K are rugged (Levinthal 1997). Furthermore, the locations of local maxima become increasingly dispersed and unpredictable. On such rugged landscapes, local search may lead to the searching agent becoming mired in a suboptimal local peak (such as location “100” in Figure C2), in which any change of one component would lead to a configuration with a lower fitness value and, as a result, the agent may never reach the global maximum.

Research drawing on the NK model typically modifies the basic structure of the core model somewhat (Siggelkow and Levinthal 2003), adds extensions to the model (Lazer and Friedman 2007; Lenox et al. 2006, 2007; Rivkin and Siggelkow 2003), or modifies the search mechanism (Baumann and Siggelkow 2013; Gavetti and Levinthal 2000) to adapt the base NK model to the specific context to be modeled. In our paper, we follow this tradition by introducing a parameter c that reflects the strength of the supply-side network effects generated by other organizations occupying a particular position in the technological landscape, where each position represents a particular (tentative) technological solution to the technological problem underlying the emerging standard. Specifically, we make the attractiveness (i.e., the perceived fitness value) of a landscape position l (i.e., a particular combination of binary choices on the N components) dependent on the number of organizations occupying that landscape position. Formally, we define the attractiveness of a position l as $A(l) = P(l) + cn(l)$, where $P(l)$ is the stand-alone fitness value of position l in the NK landscape, $n(l)$ is the number of other organizations currently occupying landscape position l, and c is the adjustable parameter representing the number of compatibility benefits generated by one organization supporting a specific solution. In addition, we also extend the baseline model by allowing different organizations to potentially imitate others’ solutions, following the approach in the related NK literature (Ethiraj and Levinthal 2004; Levinthal 1997). The detailed pseudocode of our model, including the imitation algorithm, is described in Appendix D.

Appendix D

Pseudocode of the Baseline Simulation Model

An algorithm for determining a new IT standard through a coevolutionary technological search process of M supplier organizations in a technological landscape with N components, landscape complexity (the density of interactions between the components) set as K per each component, and the strength of network effects (compatibility benefits among the supplier organizations) set as c. The below algorithm is run 10,000 times for each value of M, K, and c, and the average technological quality over these 10,000 simulation runs is reported.

1. Initialization
   - 1.1. Create a technological landscape with 2^N possible landscape positions $l \in \{(0, 0, \ldots, 0), (0, 0, \ldots, 1), \ldots, (1, 1, \ldots, 1)\}$ as a performance function f that takes as its input the binary choices e_i on N components, $i \in \{1, 2, \ldots, N\}$, i.e., $f = f(l) = f(e_1, e_2, \ldots, e_N)$.
     - 1.1.1. For each component $i \in \{1, 2, \ldots, N\}$
       - 1.1.1.1. Randomly assign K other components $(i_1, i_2, \ldots, i_K)$ with which component i interacts, $i_j \in \{1, 2, \ldots, N\}$, $i_j \neq i$ $\forall j \in \{1, 2, \ldots, K\}$.
       - 1.1.1.2. Create a component performance contribution function f_i that takes as its input the binary choices e on component i and its K interacting components, i.e., $f_i = f_i(e_i; e_{i1}, \ldots, e_{iK})$.
       - 1.1.1.3. For each possible combination of $(e_i; e_{i1}, \ldots, e_{iK}) \in \{(0; 0, \ldots, 0), (0; 0, \ldots, 1), \ldots, (1; 1, \ldots, 1)\}$, initialize $f_i(e_i; e_{i1}, \ldots, e_{iK})$ with a random draw from U[0, 1].
     - 1.1.2. For each landscape position, i.e., for each of the 2^N possible combinations of choices in the N components $(e_1, e_2, \ldots, e_N) \in \{(0, 0, \ldots, 0), (0, 0, \ldots, 1), \ldots, (1, 1, \ldots, 1)\}$, set the performance value $f(e_1, e_2, \ldots, e_N)$ as the average of the component performance contribution functions given $(e_1, e_2, \ldots, e_N)$, i.e., $f\left(e_1, e_2, \ldots, e_N\right) = \frac{\sum_{i=1}^{N} f_i\left(e_i; e_{i1}, \ldots e_{iK}\right)}{N}$.
   - 1.2. Create a 2^N-dimensional vector L indicating the number of organizations in each landscape position l, initialized as $L(l) = 0 \; \forall \, l \in \{(0, 0, \ldots, 0), (0, 0, \ldots, 1), \ldots, (1, 1, \ldots, 1)\}$.
   - 1.3. For each organization $j \in \{1, 2, \ldots, M\}$
     - 1.3.1. Create the organization as an N-dimensional vector O_j of randomly initialized binary choices $O_j = (c_{j1}, c_{j2}, \ldots, c_{jN})$, with each c_{ji}, $i \in \{1, 2, \ldots, N\}$, given the value of either 0 or 1 with equal probability.
     - 1.3.2. Increase $L(O_j)$ by 1.
2. Coevolutionary technological search: for each time period, perform the following, until no organization has possible performance improvements available:
   - 2.1. For each organization $j \in \{1, 2, \ldots, M\}$
     - 2.1.1. Obtain the stand-alone performance value P_j of the organization's landscape position as $P_j = f(O_j)$.
     - 2.1.2 Taking into account network effects in terms of the compatibility benefits from other organizations (excluding organization j itself) occupying the same position, calculate the attractiveness A_j of the organization's landscape position as $A_j = P_j + c(L(O_j) - 1)$.
   - 2.2. Record the maximum attractiveness in the population as $A_{max} = A_h$ such that $h \in \{1, 2, \ldots, M\}$ and $A_h \geq A_j \; \forall \, j \in \{1, 2, \ldots, M\}$.
   - 2.3. Possible imitation: for each organization $j \in \{1, 2, \ldots, M\}$
     - 2.3.1. Calculate the relative difference d_j in attractiveness of the organization's landscape position A_j and A_{max} as $d_j = \frac{A_{\max} - A_j}{A_{\max}}$.
     - 2.3.2. With probability d_j, have the organization consider imitating another organization's landscape position as follows:
       - 2.3.2.1. Create a variable S_p as the sum of the attractiveness of all other organizations' landscape positions, i.e., $S_p = \sum_{k=1, k \neq j}^{M} A_j$.
       - 2.3.2.2. Create a variable x_{imit} as a random draw from U[0, S_p].
       - 2.3.2.3. Set the target organization for imitation as $m \in \{1, 2, \ldots, M\}$, $m \neq j$, such that $\sum_{k=1, k \neq j}^{m-1} A_j < x_{imit} < \sum_{k=1, k \neq j}^{m} A_j$.
       - 2.3.2.4. Compare the attractiveness of organization j's current position A_j with the attractiveness that can be achieved by imitating the target organization's landscape position, considering compatibility benefits, and if $P_m + cL(O_m) > P_j + c(L(O_j) - 1)$, decrease $L(O_j)$ by 1, set $O_j = O_m$, and increase $L(O_m)$ by 1.

- 2.4. Have all organizations conduct local search: for each organization, $j \in \{1, 2, \ldots, M\}$
  - 2.4.1. Create a random integer variable H such that H takes one of the values 1, 2, …, N with equal probability.
  - 2.4.2. Create a new vector of binary choices by changing organization j's choice c_{jH} from 0 to 1 or vice versa, and let O_{jnew} denote this new vector of choices and P_{jnew} its stand-alone performance value, i.e., $P_{jnew} = f(O_{jnew})$.
  - 2.4.3. Compare the attractiveness of the organization's current landscape position O_j and that of O_{jnew}, considering the compatibility benefits in both positions, and if $P_{jnew} + cL(O_{jnew}) > P_j + c(L(O_j) - 1)$, decrease $L(O_j)$ by 1, set $O_j = O_{jnew}$, and increase $L(O_{jnew})$ by 1.
- 2.5. Test whether equilibrium is reached: for each organization $j \in \{1, 2, \ldots, M\}$
  - 2.5.1. For each other organization $m \in \{1, 2, \ldots, M\}$, $m \neq j$, test whether imitating this organization's landscape position would improve attractiveness, as in 2.3.2.4.
  - 2.5.2. For each component $i \in \{1, 2, \ldots, N\}$, test whether changing component c_{ji} from 0 to 1 or vice versa would improve the attractiveness of the organization's landscape position, as in 2.4.3.
- 2.6. If a potential improvement is found for any organization in Step 2.5.1 or 2.5.2, proceed to the next time period and go back to Step 2.1; otherwise, end simulation run and go to Step 3.

3. Recording the results
   - 3.1. Find the vector of choices O_h with the maximum final attractiveness in the population, such that $h \in \{1, 2, \ldots, M\}$ and $A_h \geq A_j \; \forall j \in \{1, 2, \ldots, M\}$. (Note that in the baseline model, all M organizations will end up with this set of choices and therefore $A_i = A_j \; \forall i, j \in \{1, 2, \ldots, M\}$.)
   - 3.2. Record the technological performance of the newly set standard P_{std} as the stand-alone performance value of landscape position O_h, i.e., $P_{std} = f(O_h)$.
   - 3.3. Record the best possible stand-alone performance value achievable in the landscape as $P_{max} = \max f(l) : l \in \{(0, 0, \ldots, 0), (0, 0, \ldots, 1), \ldots, (1, 1, \ldots, 1)\}$.
   - 3.4. Record the worst possible stand-alone performance value achievable in the landscape as $P_{min} = \min f(l) : l \in \{(0, 0, \ldots, 0), (0, 0, \ldots, 1), \ldots, (1, 1, \ldots, 1)\}$.
   - 3.5. Calculate, and return as the output from the algorithm, the relative technological quality Q of the final standard as the percentage of optimum achieved, i.e., $Q = \frac{P_{std} - P_{min}}{P_{max} - P_{min}}$.

Appendix E

Example Game of the Baseline Simulation Model

An example simulation run of a coevolutionary technological search process conducted by $M = 3$ independently searching firms to set a new standard in a moderately complex technological landscape ($N = 7$ and $K = 3$) with moderately strong network effects ($c = 0.05$). See Appendix D for the pseudocode of the model.

	Firm 1	**Firm 2**	**Firm 3**	**Comments**
Initialization				
Assign starting landscape positions as random vectors of binary components	0100110 (0.450)	0110000 (0.469)	1001001 (0.333)	The first line denotes the landscape position (current solution) in terms of the binary choices on the N = 7 components; the stand-alone technological performance of this solution is given in parentheses
Time period 1				
Imitation	–	–	–	No firm considers the imitation of another firm's solution during this time period
Local search	Firm 1 evaluates whether changing component 3 from 0 to 1 would improve performance; it does and the component is consequently changed	Firm 2 evaluates whether changing component 4 from 0 to 1 would improve performance; it does and the component is consequently changed	Firm 3 evaluates whether changing component 4 from 1 to 0 would improve performance; it does and the component is consequently changed	
End position	0110110 (0.559)	0111000 (0.607)	1000001 (0.405)	Landscape position at the end of the time period; component(s) changed during the period underlined
Time period 2				
Imitation	–	–	–	
Local search	Component 2 evaluated and changed, as above	Component 5 evaluated and changed, as above	Component 3 evaluated, but performance of landscape position 1010001 (0.359) is lower than current performance and consequently the change is not made	
End position	0010110 (0.663)	0111100 (0.625)	1000001 (0.405)	

	Firm 1	Firm 2	Firm 3	Comments
Time period 3				
Imitation	–	–	–	
Local search	Component 5 evaluated, but performance of landscape position 0010010 (0.561) is lower than current performance; consequently, the change is not made	Component 1 evaluated, but performance of landscape position 1111100 (0.505) is lower than current performance; consequently, the change is not made	Component 4 evaluated, but performance of landscape position 1001001 (0.333) is lower than current performance; consequently, the change is not made	
End position	0010110 (0.663)	0111100 (0.625)	1000001 (0.405)	
Time period 4				
Imitation	–	–	Compares its performance to Firm 1, taking into account compatibility benefits (*c* = 0.05), and because 0.663 + 0.050 > 0.405, it imitates Firm 1's solution 0010110	Probability to imitate is proportional to performance difference; the high relative performance of Firm 1 made it a likely target of imitation, and the low performance of Firm 3 made it a likely imitator
Local search	Evaluates change in component 6, but performance of landscape position 0010100 (0.646) is lower than current performance plus the new compatibility benefits (*c* = 0.05) from Firm 3 (0.663 + 0.050), and the change is thus not made	Component 6 evaluated as above, no change made	Component 7 evaluated, but performance of landscape position 0010111 (0.644) is lower than the current performance plus the new compatibility benefits (*c* = 0.05) from Firm 1 (0.663 + 0.050), and the change is thus not made	
End position	0010110 (0.663)	0111100 (0.625)	0010110 (0.663)	Firm 3 imitated Firm 1's solution, changing 5 of the 7 components
Time period 5				
Imitation	–	–	–	
Local search	Evaluates change in component 1 with no change, as above	Evaluates change in component 7 with no change, as above	Evaluates change in component 7 with no change, as above	
End position	0010110 (0.663)	0111100 (0.625)	0010110 (0.663)	

	Firm 1	Firm 2	Firm 3	Comments
Time period 6				
Imitation	–	Compares its performance to Firm 3, taking into account compatibility benefits from Firms 1 and 3, and because 0.663 + 2×0.050 > 0.625, imitates Firm 3's solution 0010110	–	
Local search	Evaluates change in component 7 as above, no change made	Evaluates change in component 7 as above, no change made	Evaluates change in component 6 as above, no change made	
End position	0010110 (0.663)	0010110 (0.663)	0010110 (0.663)	
End of simulation run				No firm can further improve its position by either imitation or local search, as all possible changes at this point would lower performance

Final standard: 0010110 with stand-alone technological quality of 0.663
Best theoretically possible solution: 1000110 with stand-alone technological quality of 0.722
Worst theoretically possible solution: 0001110 with stand-alone technological quality of 0.263

Relative quality of the emerging standard $= \frac{0.663-0.263}{0.722-0.263} = 0.871.$

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