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Thinking about Technology: Applying a Cognitive Lens to Technical Change

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Abstract: We apply a cognitive lens to understanding technology trajectories across the life cycle by developing a coevolutionary model of technological frames and technology. Applying that model to each stage of the technology life cycle, we identify conditions under which a cognitive lens might change the expected technological outcome predicted by purely economic or organizational models. We also show that interactions of producers, users and institutions shape the development of collective frames around the meaning of new technologies. We thus deepen our understanding of sources of variation in the era of ferment, conditions under which a dominant design may be achieved, the underlying architecture of the era of incremental change and the dynamics associated with discontinuities.

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1. Introduction

Evolutionary models of technical change invoke a life cycle metaphor to depict technological progress in an industry over time. Within this literature, the basic model posits that early on, following a technological discontinuity, high levels of technical variation characterize an era of ferment. Next, selection among competing technologies leads to the retention of a dominant design – a set of technologies and associated problem-solving heuristics embodied in a particular product design. Convergence on a dominant design is followed by a period of incremental progress that is ultimately disrupted by another technological discontinuity as the cycle repeats itself in a highly path-dependent process. Associated with each stage of this cycle are technical outcomes that the literature has addressed: Where does technical variation originate? Under what conditions does a dominant design emerge (or not)? What determines which design will become "dominant?" What drives the rate and direction of technological change during periods of incremental progress? When does a technological discontinuity occur? A long-standing research tradition grounded in both economics (Dosi, 1984; Nelson & Winter, 1982; Sahal, 1981) and organizations (Tushman & Anderson, 1986; Tushman & Rosenkopf, 1992; Utterback, 1974) has examined these questions. For the most part, however, the technology life cycle literature, including such recent papers as Murmann and Frenken (2006) and Suarez (2004), has neglected cognitive factors, factors that we argue are essential to understanding the dynamics of technology evolution.

Given the inherent unpredictability and equivocality of technologies (Nightingale, 2004; Weick, 1990), one might expect that cognitive processes should shape their evolution. Neither the nature of a new technology nor its trajectory is obvious *ex ante*. When a technology first emerges, actors – be they producers, users or institutions – are unsure about what it is or how it will perform. In such ambiguous circumstances, actors need to make sense of the situation before they can act (Weick, 1995), implying that cognitive explanations should be central to understanding technology evolution. Yet, while cognition has received increasing attention in the broader field of organizational theory (DiMaggio, 1997; Huff, 1990; Lant, 2002; Walsh, 1995), research on the technology life cycle has been largely silent about cognition's role. One view of innovation has underscored the cognitive underpinnings for translating scientific discoveries into technologies within organizations (Nightingale, 1998), and in this paper we extend these types of insights by developing a model of technology evolution that explicitly considers the role of cognitive dynamics across organizations.

The model we develop focuses on how the technological frames (Acha, 2004; Orlikowski & Gash, 1994) of a wide array of actors shape the technological trajectory over the life cycle. We propose that diverse technological frames are a source of variation in the era of ferment, that framing activities help drive the achievement of a dominant design when one emerges, and that the intertwining of technological frames and organizational architecture in the era of incremental change can explain why transitions are so difficult.

We use the word "technology" in the tradition of the technology life cycle literature, to mean technology as applied in a particular product context and as embodied in a physical artifact. So technology is not just the knowledge from which products are elaborated, but also includes the physical manifestation of that knowledge within a product. For instance, empirical studies of the technology life cycle have examined products such as automobiles, typewriters, television sets, and calculators (Suarez & Utterback, 1995).

Our theoretical exploration of the relationships among technology, technological frames and actors' interpretive processes leads to two important contributions to the literature on technological change. We first use cognitive factors to refine our understanding of why technologies evolve along a particular path over the course of the life cycle. For each stage of the technology life cycle, we identify conditions under which applying a cognitive lens might change the expected technological outcome predicted by purely economic or organizational models. Because cognitive dynamics may not be fully aligned with the kinds of economic or behavioral forces previously identified in the technology life cycle literature, we argue that models of technological progress that ignore cognitive factors may result in spurious conclusions. Even when economic, organizational and cognitive factors all work in the same direction, our model provides an alternative explanation for commonly observed phenomena, improving our depth of understanding.

Second, applying such a cognitive lens to technological change foregrounds the importance of interactions among the frames of multiple sets of actors in the process. We suggest that the technological frames of producers, users, and institutional actors all need to be considered in understanding technology evolution. Because their frames are likely to be diverse, interactions among these actors may be conflictual. Actors may therefore act purposefully to shape which frame comes to predominate in the field. Thus, we argue that the emergence of a collective technological frame is a contested process. Such diversity and contestation amongst frames can help explain why (and which) alternatives appear during the era of ferment. It also shows why dominant designs are not always achieved. Only when this process culminates in a predominant collective frame can a dominant design emerge. A collective technological frame is an essential dimension of the dominant design, and it structures further developments in the field. This model thus provides a co-evolutionary perspective on the interpretive dynamics that contribute to the direction a technology takes.

In the following sections, we first develop our cognitive model of technology trajectories, building upon prior research in the area of managerial cognition. We then apply the model to each stage of the technology life cycle. We examine how the mechanisms at work and the expected outcomes might differ from previously established economic or organizational arguments. We conclude with implications for research and practice suggested by this cognitive model of technical change.

2. A cognitive model of technology trajectories

2.1 The underpinnings of a cognitive model of technology trajectories: technological frames and interpretive processes

The examination of cognition in the managerial arena goes back at least to March and Simon (1958), who argued that everyone in an organization brings a certain cognitive foundation, a set of givens, to any management decision – assumptions about the future, knowledge about alternatives and a view of the consequences of pursuing each alternative. Confronted with a highly complex and uncertain environment that does not transmit clear and easily recognizable signals, actors use these givens, or frames, to form simplified representations of the information environment. By frame, we mean the lens through which actors reduce the complexity of the environment in order to be able to focus on particular features, make context-specific interpretations, decide, and act (Goffman, 1974).

In the context of understanding technology evolution, we focus on what Orlikowski and Gash (1994: 178) call a "technological frame," which captures how actors make sense of a technology (see also, Acha, 2004). Specifically, technological frames shape how actors categorize a technology relative to other technologies and which performance criteria they use to evaluate the technology. Said differently, a technological frame guides the actor's interpretation of what a technology is and whether it does anything useful.

Actors' technological frames do not spring up randomly, but rather are the encoding of their prior history, including both idiosyncratic organizational experiences and industry affiliations. Within an organization, the common experiences of members creates a shared understanding of technology – an understanding that is unique to the firm given its distinctive history (Prahalad & Bettis, 1986). This shared logic is rooted in experience with existing products and technologies. Even start-up firms with no history have founders whose unique perspectives become imprinted in the firm (Beckman, 2006; Burton *et al.*, 2002). In addition to internal dynamics, an actor's external affiliations – with industry associations, customer sets, competitive groups, user groups, etc. – affect how a new technology is framed. For example, producers have a mutually agreed upon set of rivals that they attend to (Baum & Lant, 1995; Porac *et al.*, 1995). That competitive group develops common norms about how firms operate. These "industry recipes" are often a powerful source of frames, in particular when they influence the commonsense understanding of a given technology (Spender, 1989: 56). In this way, actors' histories create knowledge accumulations that are the source of the technological frames each brings to any situation.

In order to understand the evolution of technology, it is crucial to pay attention to the technological frames of the multiple sets of actors who are implicated in this process – not just producers, but also users and institutions.[1] Most research on technical change has focused primarily on the role of producers' actions in shaping the direction a technology takes (e.g., Utterback, 1994). Even Garud and Rappa (1994), who explicitly examine the effect of researcher beliefs on technical artifacts, focus mainly on producer organizations. When users are recognized as an important factor in the literature, they are typically portrayed as making an exogenous, passive choice about whether or not to adopt the new technology (Rogers, 1995). Only in rare instances are users given a more active and purposeful role in shaping technological outcomes (Tripsas, Forthcoming; von Hippel, 1986). Even less has been done to understand their interaction with producers. The one important exception is Clark's (1985) analysis of the development of design hierarchies, which suggests that producer and user

[1] Because we focus the discussion on the interactions of producers, users and institutional actors, we often treat these organizations as unitary actors, but this should not be seen as a reification of the organization as a cognizer. We assume that the frames of each organization are the product of interactions of individuals and groups within the organization that produce a collective organizational frame (Kaplan, Forthcoming-b; Spender, 1998; Weick & Roberts, 1993), but we bracket these dynamics for the sake of focusing on the technology level of analysis.

interactions inform the paths that technology development takes, but this aspect of Clark's work has not been picked up in subsequent scholarship.

Where the role of institutional actors (such as government agencies, the media, user groups, standards bodies, industry associations and other like groups) in influencing technology evolution has been discussed (Garud & Rappa, 1994; Rosenkopf & Tushman, 1998; Van de Ven & Garud, 1993), the focus has been on the legitimizing role that institutions play in providing "an industrial system that embodies the social, economic, and political infrastructure that any technical community needs" (Van de Ven & Garud, 1993: 2). In addition, Suarez (2004) emphasizes the more active role that institutions can take in, for instance, explicitly endorsing a particular technology through regulatory action. We extend this work by focusing on the role of institutions in framing processes. We thus argue that a more complete understanding of the evolution of technology requires us to consider the technological frames of producers, users, and institutions, and their interactions with each other.

Technological frames do not influence technologies directly but rather through the interpretive processes of these actors. Managerial cognition research has conceptualized organizations as interpretive systems that notice, interpret, decide and act in response to the environment (Daft & Weick, 1984; Gioia, 1986; Ocasio, 1997). We argue that in the case of technology evolution it is the technological frames that shape what is noticed, how actors attribute meaning to the information and how these interpretations are translated into decisions and action. Thus, the interpretive process is the mechanism that connects technological frames to technological outcomes.

The most compelling empirical evidence we have on this front is on the producer side, where research has shown that cognition can shape firm strategic choice and action during periods of environmental change (e.g., Barr, 1998; Cho & Hambrick, 2006). A few studies have focused specifically on responses to technical change. For instance, in the transition to digital imaging, Polaroid's choice of commercialization strategy was driven by beliefs resident in the analog photography business model (Tripsas & Gavetti, 2000). Similar effects have been found in the shift from print to online newspapers (Gilbert, 2006), in pharmaceutical firms' responses to the emergence of biotechnology (Kaplan *et al.*, 2003), and in communications technology firms' responses to fiber optics (Kaplan, Forthcoming-a). Each of these studies of producers shows that frames shape interpretations and organizational outcomes. While less empirical evidence exists regarding these dynamics for users and institutional actors, we suggest that similar processes are enacted by each.

Thus, the underpinnings of a cognitive model of technology trajectories are the technological frames of multiple sets of actors – producers, users and institutions – and the interpretive processes that connect these frames to actions. In the next section, we examine how the interactions of these actors with each other and with the technology itself shape the direction the technology takes.

2.2 Technological frames and technology evolution

Using the building blocks we have established so far, we propose a cognitive model of technology trajectories. We focus on the reciprocal and mutually constituting dynamics among three components: actors' technological frames and interpretive processes, a collective technological frame, and the evolution of a technology (Figure 1). In our model, actors' interactions both shape and are shaped by the emerging collective technological frame (arrows [a] and [b]). Similarly, technology evolution is shaped by actors' choices and actions (arrow [c]), but the technology also constrains and enables the actions such actors can take (arrow [d]). As a result, a collective technological frame co-evolves indirectly with the technology itself through the actions and interactions of actors (arrow [e]). This co-evolutionary process provides a cognitive and interactional underpinning to the dynamics of technology evolution.

-- Insert Figure 1 about here --

Our conceptualization of frames is multi-level – we distinguish between the actor's frame and the collective technological frame that is the product of the interaction among producers, users and institutional actors' interpretive processes. The idea of a collective technological frame is akin to field frames, which are seen as field-level meaning systems that guide the development of an industry (Lounsbury *et al.*, 2003), or to Kuhn's (1962) notion of a scientific "paradigm," which represents general agreement about what a scientific field is. The collective technological frame guides the development of a technology.

Collective technological frames do not emerge fully formed – and sometimes do not emerge at all. We argue that they are the product of interactions among the various actors' competing technological frames (arrow [a]). Given the different backgrounds of salient actors and the high levels of uncertainty a new technology poses, actors' technological frames are likely to be varied and conflicting. As a result, actors' interactions can be highly political as they attempt to get their own technological frame to predominate in the industry. These kinds of political struggles resemble those identified in social movements research in which framing processes are a means to foment collective action around a particular set of ideas (Benford & Snow, 2000; McAdam *et al.*, 1996). Contestation is an essential part of the process by which collective technological frames emerge and shape the evolution of the technology.

The relationship between the actors' technological frames and the emergence of a collective frame is reciprocal (arrow [b]). Actors' interactions affect which collective frame will emerge, but the emerging collective frame also influences which frames individual actors apply. To the extent that a dominant collective technological frame emerges, actors are more likely to evoke it when making decisions and taking action (Spender, 1989). By implication, when a collective technological frame occurs, it is achieved over time during the evolution of a technology, being diffuse during the era of ferment, solidifying in conjunction with the achievement of a dominant design, structuring inquiry during the era of incremental change and eventually breaking down in the context of a new discontinuity.

Technological frames influence actors' technical choices, which are the direct mechanism by which the technology evolves (arrow [c]). Producers invest in a particular technology or not. Users adopt the technology or not. Institutional actors support one technology or another. Each of these actions has an effect on the direction of a technology's evolution by providing more effort, investment, legitimacy or scale economies for one particular variant over others. For instance, in the case of cochlear implants, researchers' beliefs about the technology, embodied in their evaluation routines, were shown to influence technical choices (Garud & Rappa, 1994). The technological frame that actors apply to the situation will thus shape these choices, and it is in this way that the frame influences outcomes.

At the same time, the technology itself both constrains and enables possible interpretations (arrow [d]). Certain understandings of a technology may lead to greater support for a particular direction, but if the realities of the technology do not ultimately play out in the way anticipated (e.g., if certain performance criteria are not achievable), then that incongruity will force actors to shift away from the original technological frame to a new understanding of what the technology is and what performance criteria should be applied. For instance, the failure of biotechnology to satisfy pharmaceutical firms' initial efforts to create large molecule drugs caused those firms to reframe biotechnology as a research method for locating small molecule drugs (Kaplan & Murray, Forthcoming). Technological evolution may also enable users to discover other applications for the technology (Dowell *et al.*, 2002; von Hippel, 1986; Yates, 1993), resulting in new interpretations by other actors.

The interactions among the various actors may eventually construct a collective frame (Porac *et al.*, 2001) as well as shape technological evolution. The achievement of a dominant design and evolution along a particular trajectory will thus involve both the resolution of competing technological frames and of competing technologies (arrow [e]). Conversely, if a collective technological frame does not emerge (e.g., if political processes cannot resolve competing actors' frames), a dominant design is less likely to emerge. Technological frames and technological evolution are tightly intertwined. A technology trajectory is therefore representative of both a technology and a collective frame about the technology.

3. Applying a cognitive model of technology trajectories to understanding stages in the technology life cycle

Having laid the groundwork for an interpretive explanation of technology evolution in the previous section, we now show how these processes construct outcomes over the technology life cycle. We define the technology life cycle in terms of the four standard stages: an era of ferment (variation), a dominant design (selection), an era of incremental change (retention) and a technological discontinuity, which sparks a new era of ferment (Anderson & Tushman, 1990; Tushman & Smith, 2002; Tushman & Rosenkopf, 1992) (see Figure 2). The initial stage of variation, the era of ferment, is characterized by high turbulence and uncertainty, since both the market and the technology are early in their development. Potential users have unclear preferences given their lack of experience with the technology. They don't know what features they want or how to value different characteristics. In addition, it is unclear how well different technical variants will work. The rivalry among competing technologies is eventually resolved, and both technical and market uncertainty decrease with the selection of a dominant design. Once a dominant design emerges, a period of retention – the era of incremental change – ensues, during which incremental technological progress occurs, improving performance across a stable set of user preferences. Finally, a technological discontinuity disrupts the period of stability, resulting in a new era of ferment. The empirical robustness of this basic model has been documented in a broad array of industries including watches (Landes, 1969), automobiles (Abernathy, 1978; Utterback & Suarez, 1993), facsimile machines (Baum *et al.*, 1995), typesetters (Tripsas,

1997) and many more. (See Murmann & Frenken, 2006, for an extensive listing of empirical technology life cycle studies).

-- Insert Figure 2 about here --

For each stage of the technology life cycle, we next identify specific technological outcomes of interest and then contrast existing economic and organizational explanations of the driving mechanisms and predicted outcomes with those illuminated by our model (Table 1). We propose that the influence of technological frames and interpretive processes varies across the life cycle. In some cases, our model provides an alternative explanation for the same observed outcome. In other cases, taking cognitive dynamics into account substantively changes expected outcomes.

-- Insert Table 1 about here --

3.1 The era of ferment

The outcomes of interest in the first stage of the technology life cycle – the era of ferment – are the degree and type of technical variation. Empirical work has clearly documented that variation is highest early in the life cycle. For example, in their longitudinal study of cochlear implants, Van de Ven and Garud (1993) found that technically novel events were more predominant in the early stages of the industry, and historical research on the automobile industry documents early variation including competition among steam, electric and internal combustion engines and tillers vs. steering wheels (Abernathy, 1978; Basalla, 1988). Yet, while high variation is observed empirically, the underlying origins of that variation are not well understood. We know little about what might lead to different degrees of variation or what types might occur.

Economic explanations are limited, since variation as an outcome variable is not generally examined. Technical breakthroughs and thus variation are assumed to come from exogenous events (Dosi, 1982). Similarly, in the organizations literature, the source of technical variation is undertheorized. It is generally attributed to “stochastic technological breakthroughs" (Anderson & Tushman, 1990: 605; Tushman & Rosenkopf, 1992: 6). More recent studies have suggested that these breakthroughs come from creative recombinations of knowledge (Fleming, 2001; Fleming, 2002), but these still do not tell us much about the degree and type of variation. By applying a cognitive lens to the problem, we suggest that differing technological frames of industry actors are a critical source of technical variation.

In the era of ferment, actors must make sense of the new technologies, yet technological frames in the new domain are still being created. In their absence, actors draw on their prior frames, categorizing the new technology based on its perceived similarity to existing technologies and applying performance criteria borrowed from the old frame (Rindova & Petkova, 2007). Building on the two broad sources of technological frames described earlier (an organization's idiosyncratic history and its prior industry affiliation), we examine the mechanisms by which frames affect our outcomes of interest looking first at producers, then at users and institutions.

The influence of a producer's prior frames on a new context is evident in the example of the nascent personal digital assistant (PDA) industry (Kaplan & Tripsas, 2003). In the early days of the industry, entering firms tended to develop products that were similar in design and functionality to their previous products. Hewlett Packard, with its history of experience in producing sophisticated calculators, introduced an early PDA that looked very much like a calculator. Similarly, the word processor company NEC made a PDA that looked like a word processor. The underlying technological components used by these two firms were similar (Bayus *et al.*, 1997), but the ways that they were combined and the functionality assigned to them differed quite dramatically depending on the history of the firm that developed the product.

In negotiating new environments, producers also look at the activities of firms in their cognitive competitive set for input (Peteraf & Shanley, 1997; Porac *et al.*, 1995; Reger & Huff, 1993), often mimicking the behaviors of competitors or using competitive behavior to signal the legitimacy of change (Greve & Taylor, 2000). These inter-organizational comparisons influence decisions such as what products and services to offer and how to price them. When the environment shifts, however, firms are slow to change their cognitive frames about which firms constitute their competition. In the financial intermediary industry, for instance, managers used outdated frames that reflected old industry boundaries even after deregulation transformed the industry (Reger & Palmer, 1996). In the context of new technology, we argue that managers will continue to pay attention to the technical developments of firms that have been historically part of their competitive set as opposed to developments of more distant firms. Drawing again on the example of the PDA industry, we see that firms' initial products resembled those with whom they shared a prior industry affiliation. Firms with a computer hardware background, such as Compaq or Atari, introduced products that were more similar to each other than to products of firms with a communications background, such as Motorola and Bell South.

We next explore the process by which actors' different technological frames result in variation. Clark (1985) proposes that technological choices are conditioned by the solution spaces (what he terms a design hierarchy) that actors define. For instance, having chosen a steam engine over an internal combustion engine, a set of choices within the domain of steam engines is then made. But Clark fails to address how the delineation of the solution spaces is done in the first place – a process in which we propose technological frames matter. We argue that firms with different technological frames will map different solution spaces. In the process of identifying possible technological solutions, firms scan multiple technical domains, and frames influence what gets noticed, how what gets noticed is evaluated and ultimately what technologies are considered in the set of possibilities. So, at a fundamental level, the origins of technical variation reside within different framing of the potential solution space.

Users also develop different interpretations of new technology as they implement it in practice, driving additional variation. Since potential users do not have the experience needed to evaluate or understand the attributes of a new product (von Hippel, 1986), they make interpretations based on their existing technological frames and on comparisons with the interpretations being made by other users. For instance, Orlikowski and Gash (1994) show that in adopting Lotus Notes, users imposed their assumptions about familiar technologies on the new product, making comparisons with word processing and spreadsheet programs. Even within the same firm, variation in framing resulted in different Lotus Notes implementations. Users that do have experience – what have been called "lead users" – may also find different functions for a technology than those initially intended by the producer, thus shaping subsequent technology development in yet another direction (Urban & von Hippel, 1988).

Clark's (1985) analysis of the development of design hierarchies suggests that it is not just producers but rather the interaction between producers and users that inform the direction of technology development. At the same time that producers develop technologies based on their technological frame, users' preferences about the technology also take shape. Producers track and interpret those developments as input to their own technical choices. But producers may not all "read the context in exactly the same way" (Clark, 1985: 238). Technological frames influence estimates of the performance trajectory of different technologies, what attributes users will value and what performance criteria are relevant. In making decisions about which technology to pursue, firms thus incorporate their interpretations of the technology, of user needs, of their own capabilities and of the competition. Thus, one extrapolation of Clark's (1985) work is that variation is produced by the interaction between producers' and users' technological frames and interpretive processes.

Above and beyond the producers and users, we also add the role of institutional actors who may also shape the degree and direction of variation in the era of ferment directly or indirectly. The direct effect of institutions' interpretations can be felt in the way that industry associations promote a particular technology or regulatory agencies define standards that favor one version of a technology over others. Their indirect effect is through how institutional affiliations of producers and users shape their own interpretations. When actors are trying to make sense of an emerging technology, they rely on industry associations to perform market research and develop forecasts of technological performance, market size and the supply/demand balance. Producer firms depend upon these services to guide assumptions behind technology investments and product development efforts. From the user perspective, user communities provide a forum for sharing solutions to problems and for exchanging ideas about innovative ways to use a technology. Just as cognitive maps of competition are slow to be updated, we propose that institutional affiliations are also slow to change, leading to inertia around the common beliefs of industry affiliates. The more actors can break away from these previous affiliations, the more likely they are to see anomalies and apply new technological frames to the situation.

In aggregate, this evidence suggests that variation in the era of ferment is not purely stochastic, nor is it based on varying capabilities and resources alone, but rather comes from the interpretations and actions of different actors with differing technological frames. In an era of ferment, the idiosyncratic historical experiences and affiliations of actors will influence their framing and interpretation of the new technology, resulting in greater degrees of technological variety than would be expected if only other differences (e.g., in capabilities, resources or incentives) were considered. Specifically, producers with similar technical capabilities, but different technological frames, are likely to develop different technologies. And, users with different technological frames adopting the same technology are likely to implement the technology differently. Producers are more likely to develop technologies that are similar to those of their past competitors than to those of other entrants, and users are more likely to implement the technology in a manner similar to users with which they have been affiliated in the past. Thus, the higher the level of variation in the prior affiliation of actors entering an industry, the greater the degree of technological variation. In an era of ferment, prior histories and affiliations will guide actors' framing and interpretation of the technology, which will in turn affect the type of technological variation.

3.2 Convergence on a dominant design

In the next stage of the life cycle – convergence on a dominant design – we seek to explain two outcomes: whether convergence occurs and, if so, which technical variant becomes dominant. Both economists and organizational scholars have examined these issues extensively. Economists attribute the emergence of a dominant design to the presence of increasing returns to scale resulting from network externalities or economies of scale (Arthur, 1988; David, 1985; Klepper, 1996). A vast literature on competing technologies and standards has demonstrated the theoretical and empirical importance of these effects in driving a market to consolidate on a single or multiple standards. These same forces determine which particular variant wins, and strategic actions such as first mover status, licensing and penetration pricing are recommended to start early bandwagons around a given firm's product (Farrell & Saloner, 1986; Katz & Shapiro, 1985; Khazam & Mowery, 1994).

Organizational scholars, on the other hand, have proposed that "social, political and organizational dynamics select … dominant designs" (Anderson & Tushman, 1990, p.605). While there is no explicit discussion of interpretive processes, this stage of the technology life cycle is the domain where organizational scholars are most likely to acknowledge the role of shared understandings.[2] Theoretical models in this stream of research have argued that selection among technologies is adjudicated through a complex process that involves non-technical factors such as competing coalitions and communities that span firms, universities, professional societies and government (Rosenkopf & Tushman, 1998; Suarez, 2004; Tushman & Rosenkopf, 1992; Van de Ven & Garud, 1993). Empirical work has substantiated

[2] Though even here some (c.f., Rosenkopf & Tushman, 1994) suggest that social forces only apply for complex products. They argue that dominant designs in simple products will emerge out of a technological, optimizing logic.

the importance of these social processes. For example, Rosenkopf and Tushman (1998) show how the coevolution of technology and associated community networks resulted in the eventual dominance of one type of flight simulator – flight training devices – over the alternative. Pinch and Bijker (1987) trace the early evolution of the bicycle and show how the problems of different social groups such as women users or anticyclists affected the evolution of the artifact.

Other scholars have examined how actors use social mechanisms to get their preferred variation to win (Anderson & Tushman, 1990; Utterback & Suarez, 1993). This dynamic is demonstrated by the emergence of VHS as the dominant videotape standard. While increasing returns from manufacturing scale and network externalities from video rentals are certainly part of the story, Matsushita's strategic maneuvers in defining the product differently helped it to beat out Sony and its Betamax technology (Cusumano *et al.*, 1992). While these descriptions acknowledge the role of social processes in shaping the dominant design, they are rarely explicitly cognitive.

In contrast to the existing literature, which focuses on the resolution of *technical* variation in the life cycle, we also consider the resolution of *cognitive* variation. We argue that negotiating a collective technological frame is a necessary part of the process of convergence on a dominant design. Divergent frames will be embodied in divergent technological solutions. In explaining the emergence of a dominant design, we focus first on explaining the emergence of a collective technological frame.

As suggested earlier in our discussion of Figure 1, interactions are a key element of the process. The resolution of competing technologies and technological frames occurs through the interaction of the technological frames and interpretive processes of the various actors in the market. These interactions can simply be passive, involving data gathering and interpretation with no intent to modify the behavior or understanding of other actors. For instance, in decentralized market exchanges, producers offer a set of products on the market, infer users' interpretations of the technology from observed purchase behavior, modify the product, release it and repeat the cycle. This series of arms-length interactions results in both learning about user preferences and a common conceptualization of what the technology is and should do. These interactions may also be strategic (Hargrave & Van de Ven, 2006; Oliver, 1988). Purposeful, often political, action occurs when competing technological frames exist. Such actions represent participants' efforts to create a collective technological frame favorable to their own interests, in particular because this collective technological frame will then shape how other actors select among technology alternatives (Dowell *et al.*, 2002).

Producers frequently take an active role in communicating to other actors how to make sense of new technology. Senior management teams in particular can have a significant influence in shaping the perceptions of a range of relevant constituents (O'Reilly & Tushman, In Press). Formal relationships, such as strategic alliances for the development of a new product, enable purposeful interactions, as do some forms of joint experimentation. For instance, in lead user studies or rapid prototyping (von Hippel, 1986), interpretive processes become joint activities, leading to coherence in the technological frame. Thus, through an interactive process of joint learning and experimentation, actors influence one another's framing of a new technology and move the industry toward a particular collective technological frame associated with a dominant design. While data on the performance implications of this type of interaction are still limited, in their study of the evolution of wind turbines in the U.S. and Denmark, Garud & Karnoe (2003) found that Danish firms, which used a "bricolage" process of joint experimentation, were much more successful than U.S. firms, which had limited interaction with users and instead focused on discovering breakthrough technologies.

Producers and other actors can also have influence through the media (Pollock & Rindova, 2003). For example, IBM in the 1980s reinforced its dominant position in mainframes by controlling its "strategic projections" very tightly. These messages to the outside world influenced the understanding of the industry structure and IBM's competitive advantage (Rindova & Fombrun, 1999). Firms also engage the media in "technological dramas" in order to influence the perceptions of a range of actors regarding a new technology (Lampel, 2001). These dramas often take the form of theatrical product announcements or demonstrations, such as Thomas Edison's announcement of his illumination system (David, 1992) or the speed-typing contests that drew attention to the QWERTY keyboard design (David, 1986). The goal is to shape the technological frames of important constituents regarding the new technology.

Producers can also influence the categorization of the technology and the determination of the salient performance criteria through advertising. When interpreting data about a new technology, users develop taxonomies based on analogies with existing products to help categorize novel products (Gregan-Paxton & John, 1997). By using advertising messages to influence what analogies are formed, producers can shape the performance criteria applied in the new domain (Moreau *et al.*, 2001). Producers can also influence new product categories to their advantage. In their study of the evolution of minivan categories, Rosa et al. (1999) show that once a category label stabilized (through a consensus among producers and users), minivan models that fit within that label had greater market acceptance, even with no material changes to the models. In particular, under conditions of ambiguity and uncertainty, advertising influences how users make sense of what product analogies to draw, how to use new products, what features to value, how to judge quality and how to interpret evidence (Hoch & Ha, 1986).

Institutional actors play a critical role in shaping which technological frame will come to predominate. Institutional endorsements confer legitimacy upon new technologies, product markets and firms participating in those markets (Baum & Oliver, 1991; Rao, 1994; Zuckerman, 1999). The press, as an example, has been portrayed as "editors of product categories" (Lounsbury & Rao, 2004: 991). Institutions can also be an arena through which producers and users (and other institutions) attempt to shape each others' understandings in an effort to achieve stabilization around a particular technological frame or category (Rosa & Porac, 2002; Rosa *et al.*, 1999). Standard-setting bodies and technical committees are a common example of institutions performing this function. Different firms join the standards groups in order to be able to influence the interpretations of what the technology is and what performance criteria should be applied. Such industry institutions are particularly useful for facilitating knowledge exchange among actors for whom direct interaction is not feasible (Rosenkopf *et al.*, 2001). The emergence of institutions associated with a new technology creates a space in which competing technological frames can be resolved, thus increasing the likelihood of convergence.

In sum, we suggest that the interactions of the interpretive processes of producers, users and institutions will shape the emergence of a collective technological frame. Increased levels of interaction among diverse actors increases the likelihood that such a frame (and thus a dominant design) emerges. This process can be enabled by the presence of a focused set of institutional arenas that can increase the level of interaction. In these contexts, the technology promoted by actors who purposefully attempt to shape technological frames will more likely become the dominant design.

If a collective technological frame does not emerge, we would not expect a dominant design to emerge. Instead multiple technological frames, each with a corresponding design might co-exist, each appealing to a subset of producers, users and institutions that share a common understanding within their community. In fact, even when a dominant design does emerge, small peripheral groups that utilize an alternative technology may persist.

3.3 Era of incremental innovation

The era of incremental innovation is portrayed in the literature as a period of inertia in which the dominant design is difficult to displace and technological improvements are minor, constrained by limits of the dominant design (Utterback, 1994). We are interested in what drives this inertia.

Economists have argued that the presence of strong network externalities combined with user learning can result in "excess inertia" where movement to a superior, socially optimal technology is thwarted (Farrell & Saloner, 1985). The quintessential example of this lock-in to what we now regard to be an inferior standard is the QWERTY keyboard (David, 1985). Organizational scholars, on the other hand, attribute inertia to routines. Once the dominant design is achieved, actors in the market no longer reexamine the underlying design choices about what the technology is or how it should be evaluated. To the extent that actors focus on change, it is to refine and elaborate existing components in the context of a relatively stable architecture (Henderson & Clark, 1990). This process has also been characterized in behavioral terms as guided by path-dependent learning (Levinthal & March, 1993; Levitt & March, 1988/1996). Actors engage in local search, constrained by organizational routines and problem-solving heuristics associated with the dominant design (Nelson & Winter, 1977, 1982). For instance, Dosi (1982) defines movement along the technological trajectory as "the pattern of 'normal' problem solving activity (i.e., of 'progress') on the ground of a technological paradigm" (p. 152), and Rosenberg (1969: 4) describes technical improvements as progressing in one "painfully obvious" direction.

We argue that there is also a cognitive element of inertia that causes the era of incremental change to persist; however, this element is deeply intertwined with the overall system. We propose that both organizational inertia and technological limits are the product of the tight linkages among the collective technological frame, the institutions that embody norms and taken-for-granted beliefs, the interpretive processes of producers and users, and the technology itself. The dominant design embodies the predominant collective frame. That frame gets embedded in day-to-day routines and communication patterns, and constrains actors' choices. In the era of incremental change, producers focus on improvements and line extensions, mainly for their most significant customers (Christensen & Bower, 1996). User preferences and usage patterns become relatively fixed, in line with the collective technological frame. Institutional actors, such as the press or trade associations, focus on the needs of and inputs from the most dominant actors, thus further reinforcing the status quo. The role of institutions as arenas provides a stable forum for ongoing interactions that reinforce existing ways of doing business.

The stability of this period results in a tightly linked system, with capabilities, routines, incentives and technological frames all working in a common direction (Kaplan & Henderson, 2005). Thus frames matter, not distinctively, but as an essential part of this self-reinforcing system. During an era of incremental change, technological frames become intertwined with the overall organizational and industry architectures such that these frames are one of the essential but not separately distinguishable elements contributing to organizational and industry inertia. Inertia can only be broken to the extent that technological frames are challenged and changed. It will not be sufficient to change incentives or build new capabilities.

3.4 Technological discontinuity

In the final stage of the life cycle, this system breaks down when new, discontinuous technologies are introduced into the industry. The outcome of interest in this stage is whether a new technology breaks the period of stability. Economists have focused on the size and strength of the new technology's network, as well as the cost advantages of a new technology in predicting whether it will displace the old one. Coordination of actors can help them to overcome the excess inertia associated with an existing technology's network, facilitating movement to the new technology (Farrell & Saloner, 1988).

Organizational scholars have not studied the drivers of a discontinuity extensively. As with the era of ferment, new technologies are assumed to be exogenously determined and the dominant empirical finding is that they are introduced into the industry by outsiders with different capabilities and resources (Cooper & Schendel, 1976; Tushman & Anderson, 1986).

Some have argued that this disruption is triggered when the old technology reaches its natural limits (Fleming, 2001; Sahal, 1981), causing actors to search for solutions in new technological domains. The implicit assumption here is that superior performance of a new technology will result in its adoption. But, others have demonstrated that technology's performance limits are more cognitive than purely technical (Henderson, 1995). This claim is supported by the substantial evidence that prior accepted limits have often been exceeded when incumbent firms respond to the emergence of a new technology that could threaten their own business (Utterback, 1994). One alternative explanation for the timing of technological discontinuities are radical shifts in user preferences – what Tripsas (Forthcoming) calls preference discontinuities. This work argues that during the era of incremental change, users continue to learn, grow, and potentially develop new preferences that are so different they trigger the invasion of radically new technology.

We argue that emergence of discontinuous new technologies has an important cognitive aspect. The sources of variation described in our discussion of the era of ferment are precisely the forces that cause old technological frames and technologies to lose their salience. New entrants with different technological frames might be able to visualize opportunities that established firms miss. Startup firms in particular have been seen as the source of discontinuous technologies and threats to incumbent firms. While this is often attributed to their inherent flexibility as small firms (e.g., Aldrich, 1999), we argue that the advantage that new entrants have – both *de novo* startups as well as *de alio* established players coming from other industries – is not just that they are unencumbered by inertia but rather that they see the world through different lenses. Hounshell (1975) illustrates this vividly in his comparison of the early development of the telephone in which the telegraph "expert" – Elisha Gray – developed early telephone technology but could not see its practical application and argued that it was a "scientific toy," while the outsider – Alexander Graham Bell – pursued the technology's commercial potential. User experience can also result in unique framing, with users not only engaging in ongoing innovation (von Hippel, 1986), but user entrepreneurs commercializing those innovations through firm formation (Shah & Tripsas, 2007).

New technologies are often ignored, at least early on, by existing players in the industry because they do not fit the predominant collective frame. Evidence of this dynamic is found in Christensen and Bower’s (1996) study of disk drives. They argue that resource dependence is responsible for established firms’ commitment to the needs of existing customers – and the subsequent lack of interest in new technologies on the part of incumbent disk drive producers. While resource dependence is certainly important, we would argue that cognitive forces were also at play. The new technology was not recognized as competing in the same market as current technologies due to existing technological frames: it was perceived as inferior to current approaches, since it excelled on a new and different set of performance criteria. Thus technological discontinuities are more likely to be introduced by industry outsiders or peripheral actors who possess not only different capabilities but also different technological frames from those of existing industry participants.

4. Discussion

In this paper we set out to explore the relationship between cognition and technology evolution, developing a model of how the technological frames and interpretive processes of producers, users and institutional actors interact in shaping technology trajectories over the life cycle. This model suggests that technological change is cognitively embedded and as such falls under the general project to endogenize the relationship of organizations and their environments (Dacin *et al.*, 1999). We argue not only that technological frames engrain themselves in technologies, but also that technologies constrain and enable the use of frames. Our model is therefore a way to conceptualize the loose coupling between the actor and the environment. This perspective gives us a new way to think about technology evolution and also suggests an agenda for future research.

While many scholars have previously proposed research agendas related to managerial cognition in general (Huff, 1997; Meindl *et al.*, 1994; Stubbart, 1989; Walsh, 1995), cognition's role in explaining the dynamics of technical change has not yet been comprehensively explored. While there is empirical evidence, if limited in some cases, for each of the separate effects in the model we develop in this paper, there is little work that takes into account the linkages across the interpretive processes of producers, users and institutional actors. If we understand technical change to involve interactions between the technology and the interpretive processes of these different actors, we raise a whole host of new research questions. The development of the model in this paper suggests that it would be useful to expand our understanding of framing processes themselves, reexamine notions of path dependence, explore the relationships between the interpretive processes of multiple actors and link research methods more closely to the nature of the problem.

4.1 Cognition matters

The first job of our model was to argue that adopting a cognitive lens can provide us with alternative explanations for the outcomes we observe in examining technology trajectories. Our explanation, however, allows us to show not just that cognition matters separately from economic or organizational explanations, but that it matters differentially across the technology life cycle. And, while the interpretive process may be more or less visible across the life cycle, we suggest that there is a cognitive element at each stage.

In the era of ferment, the disparate histories of multiple actors result in divergent frames and, therefore, different interpretations of new technology. Thus, while much of the management of technology research has focused on the role of competencies in developing new technologies (e.g., Tushman & Anderson, 1986), our model proposes that framing processes are equally key in producing initial variations. One implication is that we should consider not only whether a new technology requires radically new capabilities, but whether it requires new frames (Tripsas & Gavetti, 2000). With regard to the next stage of the life cycle, there has been disagreement in the management of technology literature about whether a dominant design will necessarily emerge in all cases (Klepper & Simons, 1997; Utterback, 1994). Our model suggests that a dominant design will only emerge to the extent that a collective technological frame is achieved.

While technological frames are most evident in shaping outcomes in the era of ferment and in the achievement of the dominant design, they also play an essential role during the era of incremental change. Once a collective technological frame is achieved and becomes embedded in the technology, constraints on further development may be associated not only with technical but also with cognitive limits. The collective technological frame becomes more deeply embedded in the industry and in each organization. It becomes implicated in incentive systems, capabilities and the mutual understanding of how things are done. These features collectively can be thought about as the "architecture" of the organization or industry (Henderson & Clark, 1990). Radical or architectural innovations will therefore require not only a break in the existing technology but an unraveling of the interconnection between the technological frames and other features of that architecture (Kaplan & Henderson, 2005).

By examining the role of cognition across the technology life cycle, we enrich our understanding of the mechanisms by which technological frames affect outcomes. In particular, the notion of a system with interactions forces us to expand our concept of cognition. In this interlinked set of interpretive processes, we suggest that cognition is not just about technological frames, but rather is an interactive process of framing. The importance of this framing process is especially evident in the contestation over a collective technological frame. In the context of emerging technologies, it is therefore relevant to examine the relationship to outcomes of both the content of frames and the framing process itself.

4.2 History matters

A cognitive model of technology trajectories also implies that path dependence, to the extent it is observed, is an accomplished result rather than a deterministic driver of outcomes. Trajectories have been traditionally described as “compulsive sequences” (Rosenberg, 1969) in which one change then makes the next appear obvious, and path dependence as the effect of chance actions that become determinative (David, 1992; Stinchcombe, 1968). This literature proposes that the mechanism of entrainment is a rational cost benefit analysis based on the current situation at any one point in time. *Ex ante*, the outcomes are indeterminant. Outcomes may be seen as suboptimal *ex post*.

Consistent with recent research on “path creation” (Garud & Karnøe, 2001), we suggest, however, that actors are capable of purposeful actions that affect the direction of evolution by shaping the technological frames of other actors. From this perspective, there is no historical accident but rather “mindful deviation” from existing ways of doing things. This process produces new technological frames that guide further action and thus make particular steps appear obvious after the fact. History matters, but in different ways than those attributed to it in current evolutionary theories. And, as such, the past is more appropriately seen as a source of potential frames rather than a deterministic driver of outcomes (Flaherty & Fine, 2001). It is the manner that history gets drawn upon by the actors as they construct their technological frames that affects the path of development. It may therefore be useful to think of cognition in the way that Swidler (1986) talks about culture, where the past accumulates in a repertoire (or “tool kit”) of frames that get activated depending on context and interactions. The multiplicity of technological frames within a field makes alternative paths possible. In our model, the “path” is shaped by the ways in which interactions among the interpretive processes of multiple actors plays out over time.

4.3 Multiple actors matter

Our model thus emphasizes that it is the interaction of the cognition of multiple actors in the market that shapes the evolution of technology. Most research on technical change has examined either producers (e.g., Utterback, 1994) or sometimes users (e.g., von Hippel,

1986) and only infrequently their interaction (Clark, 1985, being an important exception). While the role of institutions in technology evolution has been explored (e.g., Garud & Rappa, 1994; Rosenkopf & Tushman, 1998; Van de Ven & Garud, 1993), their interaction with producers and users in shaping technological frames is not emphasized. Separately, the institutional literature has shed light on the role of institutional actors as shapers of outcomes (e.g., Lounsbury, 2001), but this has not been integrated with producer and user perspectives. Our model emphasizes the need to consider the interlinked nature of these actors. All three sets of actors matter as they interact with each other.

Such an interactional view would suggest, first, that it is risky to examine how producing firms react to technical changes without acknowledging that their reactions also shape the very nature of the change itself or that user interpretations of the technology might move it in directions entirely unanticipated by the producer. Thus, harkening back to the debate about the relative merits of demand-pull or technology-push theories (Mowery & Rosenberg, 1982), we suggest that both market pull and technology push have independent roles in technology evolution and that this occurs through the interaction of the interpretive processes of producers (push) and users (pull) and is mediated by institutional actors.

Second, this model sheds new insight on user innovation. While existing theory suggests that users innovate due to a combination of economic incentives and a deep knowledge of needs (von Hippel, 1986), this paper suggests a complementary perspective. Users may also innovate when their frame for understanding a new technology differs significantly from that of its producers. In these situations, users may be in the best position to create products that are consistent with their vision of how the technology should develop.

Third, we emphasize the role of institutions as both actors and arenas in which the interactions of other actors can take place (e.g., through standards bodies). Because collective technological frames only emerge from interactions, the presence of various industry institutions that draw actors together can accelerate or amplify these efforts. Actors may purposefully create institutions (e.g., user groups or industry associations) precisely to have a forum for their framing activities.

Our analysis suggests that each of the different actors brings different technological frames to the table as they interpret the nature of a technology, make choices and act. These frames may often be in conflict. Further research could unpack the different ways in which these conflicts can be resolved, which types of interactions are most productive at different stages of the technology life cycle, to what extent actors can shape others' frames and under what conditions purposeful action might be possible.

The study of cognitive mechanisms for shaping technical outcomes could be extended to multiple levels of analysis. Depending on the level of analysis, different designations of the actor and the collective would be salient. For example, in a study of framing inside one organization, the actor would be an individual, team or functional group, and the collective frame would occur at the organizational level (Kaplan, Forthcoming-b). In studying top management teams, the actor would be the individual executive and the collective would be the team. Further research could explore the ways that the mechanisms that we propose in our cognitive model of technical change would manifest themselves at these different levels of analysis.

4.4 Methodological implications

The model also suggests that researchers in this area may have to rethink methodological approaches. Approaches that are simultaneously longitudinal and cross-sectional (at least paired comparisons) are most likely to shed light on cognition and technical change. The most problematic aspect of studying technological frames is the risk of retrospective reconstruction. The uncertainty during eras of ferment and the achievement of clarity only after the fact mean that *ex post* efficiency explanations are inappropriate. This concern has two methodological implications: the need to present a "symmetric account of different paths irrespective of whether or not they were eventually successful" (Garud &

Rappa, 1994: 348) and the importance of using contemporary data sources. These requirements, coupled with the desirability of a longitudinal approach, put stringent demands on the researcher. Future research along these lines could be aimed at understanding how technological frames are formed (antecedent conditions such as experience and routines) and how they evolve over time, at modeling multidirectional forces of macro and micro co-evolution, and at taking into account the endogenous and emergent nature of the phenomenon (Volberda & Lewin, 2003).

Answers to the kinds of questions posed by cognition and technical change may also lie in understanding the practices of real-time decision making: the day-to-day perspectives and events that shape outcomes. It is in these micro-processes that one can observe how framing of the industry context and the technological change can affect choices. To get at the specific ways that these interpretive processes play out in practice, researchers would need to exploit in greater depth methodological approaches that allow us to study "cognition in the wild" (Hutchins, 1995). Such a focus on practice is a particularly powerful way to explore a co-evolutionary model of technological frames and technical change because its underpinnings presuppose actors as knowledgeable agents who enact structures (technological frames) that shape their emergent and situated interpretive processes (Feldman, 2003; Orlikowski, 2000). Using a practice lens would allow the researcher to integrate macro and micro approaches to understanding technology evolution, emphasizing the complementarity of these perspectives.

4.5. Managerial and policy implications

Finally, our cognitive model of technology trajectories may give us power on the normative front. If we can understand how interpretive processes work in relation to technical change, there is potential to influence framing strategically. Such a perspective could help answer many questions about how firms can navigate the "gales of creative destruction" associated with technical change (Schumpeter, 1942). For example, how can firms manipulate users' technological frames in order to improve adoption or actively manage the manner in which customers make sense of new technologies in order to optimize their own positions? Similarly, how can firms be more effective at managing cognitive change inside their own organizations? Should they actively manage shifts in technological frames the same way they manage shifts in capabilities? Does it make sense to hire people with different frames in order to promote innovation? What are the implications for organizational and top team demography?

Policy makers should also attend to cognitive factors. When developing regulations for emerging technologies, framing of that technology can have radical consequences. For instance, if the Segway, an innovative motorized scooter, were framed as a motor vehicle, its use would be severely restricted because it could only travel on roads and not pedestrian areas. The framing of technology-based industries can also have serious antitrust implications. Industry definition is subject to interpretation, so in addition to economic factors, regulators might add cognitive considerations to their deliberations about industry boundaries. Such examples suggest that policy makers would be usefully served by taking the time to examine their own cognitive frames about technology and understand the assumptions about the nature of the technology or of competition might shape regulatory frameworks. They might also consider exercises, such as country comparisons or open forum discussions with multiple stakeholders, which might help challenge existing ways of thinking. The cognitive model of technical change raises these kinds of questions. We believe that further empirical research into how producers, users and institutional actors think about technology can bring greater theoretical, managerial and policy-level insight to the understanding of technical change.

References

Abernathy WJ. 1978. *The productivity dilemma: roadblock to innovation in the automobile industry*. Johns Hopkins University Press: Baltimore

Acha V. 2004. Technology frames: the art of perspective and interpretation in strategy, *SPRU Working paper series, #109*:

Aldrich H. 1999. *Organizations evolving*. Sage Publications: London ; Thousand Oaks

Anderson P, Tushman ML. 1990. Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change. *Administrative Science Quarterly* **35**(4): 604-633

Arthur B. 1988. Competing Technologies: an Overview. In G Dosi, C Freeman, R Nelson, G Silverberg, L Soete (Eds.), *Technical Change and Economic Theory*: 590-607. Pinter: London

Barr PS. 1998. Adapting to unfamiliar environmental events: A look at the evolution of interpretation and its role in strategic change. *Organization Science* **9**(6): 644-669

Basalla G. 1988. *The evolution of technology*. Cambridge University Press: Cambridge

Baum JAC, Korn HJ, Kotha S. 1995. Dominant designs and population dynamics in telecommunications services: Founding and failure of facsimile transmission service organizations, 1965-1992. *Social Science Research* **24**(2): 97

Baum JAC, Lant TK. 1995. Cognitive sources of socially constrained competitive groups: examples from the Manhattan hotel industry. In WR Scott, S Christensen (Eds.), *The institutional construction of organizations : international and longitudinal studies*. Sage Publications: Thousand Oaks, Calif.

Baum JAC, Oliver C. 1991. Institutional Linkages and Organizational Mortality, *Administrative Science Quarterly*: 187 132 pages.: Ithaca

Bayus BL, Jain S, Rao AG. 1997. Too little, too early: Introduction timing and new product performance in the personal digital assistant industry. *JMR, Journal of Marketing Research* **34**(1): 50-63

Beckman CM. 2006. The influence of founding team company affiliations on firm behavior. *Academy of Management Journal* **9**(4): Forthcoming

Benford RD, Snow DA. 2000. Framing processes and social movements: An overview and assessment, *Annual Review of Sociology*: 611-639: Palo Alto

Burton MD, Sorensen J, Beckman CM. 2002. Coming from good stock: career histories and new venture formation. In M Lounsbury, MJ Ventresca (Eds.), *Research in the Sociology of Organizations*, Vol. Social Structure and Organizations Revisited: 229-262. JAI Press

Cho TS, Hambrick DC. 2006. Attention as the Mediator Between Top Management Team Characteristics and Strategic Change: The Case of Airline Deregulation. *Organization Science* **17**(4): 453-469

Christensen CM, Bower JL. 1996. Customer power, strategic investment, and the failure of leading firms. *Strategic Management Journal* **17**(3): 197-218

Clark KB. 1985. The Interaction of Design Hierarchies and Market Concepts in Technological Evolution. *Research Policy* **14**: 235-251

Cooper AC, Schendel D. 1976. Strategic Responses to Technological Threats. *Business Horizons* **19**(1): 61-69

Cusumano MA, Mylonadis Y, Rosenbloom RS. 1992. Strategic maneuvering and mass-market dynamics: The triumph of VHS over Beta, *Business History Review*, Vol. 66: 51 44 pages.

Dacin MT, Ventresca MJ, Beal BD. 1999. The embeddedness of organizations: Dialogue & directions. *Journal of Management* **25**(3): 317-356

Daft RL, Weick KE. 1984. Toward a Model of Organizations as Interpretation Systems. *Academy of Management Review* **9**(2): 284-295

David P. 1986. Understanding the necessity of Qwerty: the necessity of history. In W Parker (Ed.), *Economic history and the modern economist*: 30-49. Blackwell: London

David PA. 1985. Clio and the Economics of QWERTY. *American Economic Review* **75**(2): 332-337

David PA. 1992. Heroes, herds and hysteresis in technological history: Thomas Edison and "The Battle of the Systems" reconsidered. *Industrial and Corporate Change* **1**(1): 129-180

DiMaggio PJ. 1997. Culture and cognition. *Annual Review of Sociology* **23**: 263-287

Dosi G. 1982. Technological Paradigms and Technological Trajectories: A Suggested Interpretation of the Determinants and Directions of Technical Change. *Research Policy* **11**(3): 147-162

Dosi G. 1984. *Technical change and industrial transformation*. St. Martin's Press: New York

Dowell G, Swaminathan A, Wade JB. 2002. Pretty Pictures and Ugly Scenes: Political and Technological Maneuvers in High Definition Television. *Advances in Strategic Management* **19**: 97-133

Farrell J, Saloner G. 1985. Standardization, Compatibility, and Innovation. *The Rand Journal of Economics* **16**(1): 70

Farrell J, Saloner G. 1986. Installed Base and Compatibility - Innovation, Product Preannouncements, and Predation. *American Economic Review* **76**(5): 940-955

Farrell J, Saloner G. 1988. Coordination Through Committees and Markets. *The Rand Journal of Economics* **19**(2): 235

Feldman MS. 2003. A performative perspective on stability and change in organizational routines. *Industrial and Corporate Change* **12**(4): 727-752

Flaherty M, Fine G. 2001. Present, past, and future - Conjugating George Herbert Mead's perspective on time. *Time & Society* **10**(2-3): 147-161

Fleming L. 2001. Recombinant uncertainty in technological search. *Management Science* **47**(1): 117-132

Fleming L. 2002. Finding the organizational sources of technological breakthroughs: the story of Hewlett-Packard's thermal ink-jet. *Industrial and Corporate Change* **11**(5): 1059-1084

Garud R, Karnoe P. 2003. Bricolage versus breakthrough: Distributed and embedded agency in technology entrepreneurship. *Research Policy* **32**(2): 277-300

Garud R, Karnøe P. 2001. Path Creation as a Process of Mindful Deviation. In R Garud, P Karnøe (Eds.), *Path dependence and creation*: 1-38. Lawrence Erlbaum Associates: Mahwah, N.J.

Garud R, Rappa MA. 1994. A socio-cognitive model of technology evolution: The case of cochlear implants. *Organization Science* **5**(3): 344-362

Gilbert CG. 2006. Change in the Presence of Residual Fit: Can Competing Frames Coexist? *Organization Science* **17**(1): 150-167

Gioia D. 1986. Symbols, scripts and sensemaking: creating meaning in the organizational experience. In HPJ Sims, DA Gioia (Eds.), *The Thinking Organization*: 49-74. Jossey-Bass Publishers: San Francisco

Goffman E. 1974. *Frame Analysis: An Essay on the Organization of Experience* (2nd (1986) ed.). Northeastern University Press

Gregan-Paxton J, John DR. 1997. Consumer learning by analogy: A model of internal knowledge transfer. *Journal of Consumer Research* **24**(3): 266-284

Greve HR, Taylor A. 2000. Innovations as catalysts for organizational change: Shifts in organizational cognition and search. *Administrative Science Quarterly* **45**(1): 54-80 30 pages.

Hargrave TJ, Van de Ven AH. 2006. A Collective Action Model of Institutional Innovation. *Academy of Management Review* **31**(4): 864-888

Henderson R. 1995. Of life cycles real and imaginary: The unexpectedly long old age of optical lithography. *Research Policy* **24**(4): 631-643

Henderson RM, Clark KB. 1990. Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms. *Administrative Science Quarterly* **35**(1): 9-30

Hoch SJ, Ha YW. 1986. Consumer Learning: Advertising and the Ambiguity of Product Experience. *Journal of Consumer Research* **13**(2): 221

Hounshell DA. 1975. Elisha Gray and the Telephone. *Technology and Culture* **16**(2): 133-161

Huff AS. 1990. *Mapping strategic thought*. John Wiley and Sons: Chichester, New York

Huff AS. 1997. A current and future research agenda for cognitive research. *Journal of Management studies* **34**(6): 947-952

Hutchins E. 1995. *Cognition in the wild*. MIT Press: Cambridge, Mass.

Kaplan S. Forthcoming-a. Cognition, capabilities and incentives: assessing firm response to the fiber-optic revolution. *Academy of Management Journal*

Kaplan S. Forthcoming-b. Framing contests: strategy making under uncertainty. *Organization Science*

Kaplan S, Henderson R. 2005. Inertia and incentives: bridging organizational economics and organizational theory. *Organization Science* **16**(5): 509-521

Kaplan S, Murray F. Forthcoming. Technology, Organizations and Institutions in the Construction of Economic Value: The Case of Biotechnology. In D Griffiths, N Phillips, G Sewell (Eds.), *Research on the Sociology of Organizations*. Elsevier

Kaplan S, Murray F, Henderson RM. 2003. Discontinuities and Senior Management: Assessing the Role of Recognition in Pharmaceutical Firm Response to Biotechnology. *Industrial and Corporate Change* **12**(4): 203-233

Kaplan S, Tripsas M. 2003. The Interaction of Cognition and Technology in New Industry Emergence: The Case of the Personal Digital Assistant (PDA), *Industrial Performance Center Working Paper Series*:

Katz ML, Shapiro C. 1985. Network Externalities, Competition, and Compatibility. *The American Economic Review* **75**(3): 424

Khazam J, Mowery D. 1994. The commercialization of RISC: Strategies for the creation of dominant designs. *Research Policy* **23**(1): 89

Klepper S. 1996. Entry, exit, growth, and innovation over the product life cycle. *American Economic Review* **86**(3): 562-583

Klepper S, Simons KL. 1997. Technological Extinctions of Industrial Firms: An Inquiry into their Nature and Causes. *Industrial and Corporate Change* **6**(2): 379-460

Kuhn TS. 1962. *The Structure of Scientific Revolutions* (1996 ed.). University of Chicago Press: Chicago

Lampel J. 2001. The core competencies of effective project execution: The challenge of diversity. *International Journal of Project Management* **19**(8): 471-483

Landes D, S. 1969. *The Unbound Prometheus: Technological change and industrial development in Western Europe from 1750 to the present*. Cambridge University Press: Cambridge

Lant TK. 2002. Organizational cognition and interpretation. In JAC Baum (Ed.), *Companion to Organizations*: 344-362. Blackwell Publishers: Malden, MA

Levinthal DA, March JG. 1993. The myopia of learning. *Strategic Management Journal* **14**(Special Issue): 95

Levitt B, March JG. 1988/1996. Organizational learning. In MD Cohen, L Sproull (Eds.), *Organizational learning*: 516-540, (Originally appear in Annual Review of Sociology, Vol. 514, 1988). Sage Publications: Thousand Oaks

Lounsbury M. 2001. Institutional sources of practice variation: Staffing college and university recycling programs. *Administrative Science Quarterly* **46**(1): 29-56 29 pages.

Lounsbury M, Rao H. 2004. Sources of durability and change in market classifications: A study of the reconstitution of product categories in the American mutual fund industry, 1944-1985. *Social Forces* **82**(3): 969-999

Lounsbury M, Ventresca MJ, Hirsch PM. 2003. Social movements, field frames and industry emergence: a cultural-political perspective on US recycling. *Socio-Economic Review* **1**(1): 71-104

March JG, Simon HA. 1958. *Organizations*. Wiley: New York,

McAdam D, McCarthy JD, Zald MN. 1996. *Comparative perspectives on social movements: political opportunities, mobilizing structures, and cultural framings*. Cambridge University Press: Cambridge England New York

Meindl JR, Stubbart C, Porac JF. 1994. Cognition within and between organizations: five key questions. *Organization Science* **5**(3): 289-293

Moreau CP, Markman AB, Lehmann DR. 2001. "What is it?" Categorization flexibility and consumers' responses to really new products. *Journal of Consumer Research* **27**(4): 489-498

Mowery D, Rosenberg N. 1982. The influence of market upon innovation: a critical review of some recent empirical studies. In N Rosenberg (Ed.), *Inside the black box: technology and economics*: 193-241 (originally published in 1979 in Research Policy, 1978: 1103-1953). Cambridge University Press: New York

Murmann JP, Frenken K. 2006. Toward a systematic framework for reserach on dominant designs, technological innovations, and industrial change. *Research Policy* **35**: 925-952

Nelson RR, Winter SG. 1977. In search of a useful theory of innovation. *Research Policy* **6**: 36-76

Nelson RR, Winter SG. 1982. *An evolutionary theory of economic change*. The Belknap Press of Harvard University Press: Cambridge, MA

Nightingale P. 1998. A cognitive model of innovation. *Research Policy* **27**(7): 689-709

Nightingale P. 2004. Technological capabilities, invisible infrastructure and the un-social construction of predictability: the overlooked fixed costs of useful research. *Research Policy* **33**(9): 1259-1284

O'Reilly CA, Tushman ML. In Press. Ambidexterity as a Dynamic Capability: Resolving the Innovator's Dilemma. *Research in Organizational Behavior*

Ocasio W. 1997. Towards an attention-based view of the firm. *Strategic Management Journal* **18**: 187-206

Oliver C. 1988. The Collective Strategy Framework **-** an Application to Competing Predictions of Isomorphism. *Administrative Science Quarterly* **33**(4): 543-561

Orlikowski WJ. 2000. Using technology and constituting structures: A practice lens for studying technology in organizations. *Organization Science* **11**(4): 404-428

Orlikowski WJ, Gash DC. 1994. Technological Frames: Making Sense of Information Technology in Organizations. *ACM Transactions on Information Systems* **2**(2): 174-207

Peteraf M, Shanley M. 1997. Getting to know you: A theory of strategic group identity. *Strategic Management Journal* **18**(Special Issue): 165-186

Pinch TJ, Bijker WE. 1987. The social construction of facts and artifacts: or how the sociology of science and the sociology of technology might benefit each other. In WE Bijker, TJ Pinch (Eds.), *The social construction of technological systems*: 17-50. MIT Press: Cambridge, Mass.

Pollock TG, Rindova VP. 2003. Media legitimation effects in the market for initial public offerings. *Academy of Management Journal* **46**(5): 631-642

Porac JF, Thomas H, Wilson F, Paton D, Kanfer A. 1995. Rivalry and the industry model of Scottish knitwear producers. *Administrative Science Quarterly* **40**(2): 203-227

Porac JF, Ventresca MJ, Mishina Y. 2001. Interorganizational cognition and interpretation. In JAC Baum (Ed.), *Blackwell companion to organizations*: 579-598. Blackwell Publishers: Malden, MA

Prahalad CK, Bettis RA. 1986. The Dominant Logic: A New Linkage Between Diversity and Performance. *Strategic Management Journal* **7**(6): 485-501

Rao H. 1994. The social construction of reputation: Certification contests, legitimation, and the survival of organizations in the American automobile industry: 1895-1912, *Strategic Management Journal*: 29: Chichester

Reger RK, Huff AS. 1993. Strategic groups: A cognitive perspective. *Strategic Management Journal* **14**(2): 103-123

Reger RK, Palmer TB. 1996. Managerial categorization of competitors: Using old maps to navigate new environments. *Organization Science* **7**(1): 22-39

Rindova VP, Fombrun CJ. 1999. Constructing competitive advantage: The role of firm-constituent interactions. *Strategic Management Journal* **20**(8): 691-710

Rindova VP, Petkova AP. 2007. When is a new thing a good thing? Technological change, product form design, and perceptions of value for product innovations. *Organization Science* **18**(2): 217-232

Rogers EM. 1995. *Diffusion of innovations* (4th ed.). Free Press: New York

Rosa JA, Porac JF. 2002. Categorization bases and their influence on product category knowledge structures. *Psychology & Marketing* **19**(6): 503-531

Rosa JA, Porac JF, Spanjol JR, Saxon MS. 1999. Sociocognitive dynamics in a product market. *Journal of Marketing* **63**: 64-77

Rosenberg N. 1969. The direction of technological change: inducement mechanisms and focusing devices, *Economic Development and Cultural Change*: 1-24. University of Chicago Press: Chicago

Rosenkopf L, Metiu A, George VP. 2001. From the bottom up? Technical committee activity and alliance formation. *Administrative Science Quarterly* **46**(4): 748-772

Rosenkopf L, Tushman M. 1994. The coevolution and technology and organizations. In JAC Baum, JV Singh (Eds.), *Evolutionary dynamics of organizations*: 403-424. Oxford University Press: New York

Rosenkopf L, Tushman ML. 1998. The coevolution of community networks and technology: lessons from the flight simulation industry. *Industrial and Corporate Change* **7**: 311-346

Sahal D. 1981. *Patterns of Technological Innovation*. Addison-Wesley: London

Schumpeter JA. 1942. *Capitalism, socialism, and democracy* (3d, 1950 ed.). Harper: New York

Shah SK, Tripsas M. 2007. The Accidental Entrepreneur: The Emergent and Collective Process of User Entrepreneurship. *Strategic Entrepreneurship Journal* **1**: 123-140

Spender JC. 1989. *Industry recipes : an enquiry into the nature and sources of managerial judgement*. Blackwell: Oxford, UK ; New York, NY, USA

Spender JC. 1998. The dynamics of individual and organizational knowledge. In C Eden, J Spender (Eds.), *Managerial and organizational cognition*: 13-29. Sage Publications: London

Stinchcombe AL. 1968. *Constructing social theories*. Harcourt Brace & World: New York,

Stubbart CI. 1989. Managerial Cognition: A missing link in strategic management research. *Journal of Management Studies* **26**: 325-347

Suarez FF. 2004. Battles for technological dominance: an integrative framework. *Research Policy* **33**(2): 271-286

Suarez FF, Utterback JM. 1995. Dominant designs and the survival of firms. *Strategic Management Journal* **16**(6): 415

Swidler A. 1986. Culture in Action: Symbols and Strategies. *American Sociological Review* **51**(2): 273

Tripsas M. 1997. Unraveling the process of creative destruction: Complementary assets and incumbent survival in the typesetter industry. *Strategic Management Journal* **18**(Special Issue): 119-142

Tripsas M. Forthcoming. Customer preference discontinuities: a trigger for radical technological change. *Managerial and Decision Economics*

Tripsas M, Gavetti G. 2000. Capabilities, cognition, and inertia: Evidence from digital imaging. *Strategic Management Journal* **21**(10/11): 1147-1161

Tushman M, Smith WK. 2002. Organizational Technology. In J Baum (Ed.), *Companion to Organizations*: 386-414. Blackwell: Malden, MA

Tushman ML, Anderson P. 1986. Technological Discontinuities and Organizational Environments. *Administrative Science Quarterly* **31**(3): 439-465

Tushman ML, Rosenkopf L. 1992. Organizational Determinants of Technological-Change - toward a Sociology of Technological Evolution. *Research in Organizational Behavior* **14**: 311-347

Urban GL, von Hippel E. 1988. Lead User Analyses for the Development of New Industrial Products. *Management Science* **34**(5): 569

Utterback JM. 1974. Innovation in Industry and the Diffusion of Technology. *Science* **183**(Feb 15th): 658-662

Utterback JM. 1994. *Mastering the Dynamics of Innovation*. HBS Press: Cambridge, Mass.

Utterback JM, Suarez FF. 1993. Innovation, competition, and industry structure. *Research Policy* **22**(1): 1-21

Van de Ven AH, Garud R. 1993. Innovation and industry emergence: the case of cochlear implants. In RS Rosenbloom, R Burgelman (Eds.), *Research on technological innovation, management, and policy*, Vol. 5: 1-46. JAI Press: Greenwich, CT

Volberda HW, Lewin AY. 2003. Guest Editor's Introduction: Co-evolutionary Dynamics Within and Between Firms: From Evolution to Co-evolution. *The Journal of Management Studies* **40**(8): 2111-2136

von Hippel E. 1986. Lead Users: A Source of Novel Product Concepts. *Management Science* **32**(7): 791

Walsh JP. 1995. Managerial and organizational cognition: Notes from a trip down memory lane. *Organization Science* **6**(3): 280-321

Weick KE. 1990. Technology as equivoque. In P Goodman, L Sproull (Eds.), *Technology and Organizations*: 1-44. Jossey-Bass: San Francisco

Weick KE. 1995. *Sensemaking in organizations*. Sage Publications: Thousand Oaks

Weick KE, Roberts KH. 1993. Collective mind in organizations: Heedful interrelating on flight decks. *Administrative Science Quarterly* **38**(3): 357-381

Yates J. 1993. Coevolution of Information-Processing Technology and Use - Interaction between the Life-Insurance and Tabulating Industries. *Business History Review* **67**(1): 1-51

Zuckerman EW. 1999. The categorical imperative: Securities analysts and the illegitimacy discount. *American Journal of Sociology* **104**(5): 1398-1438

Figure 1
A cognitive model of technology trajectories

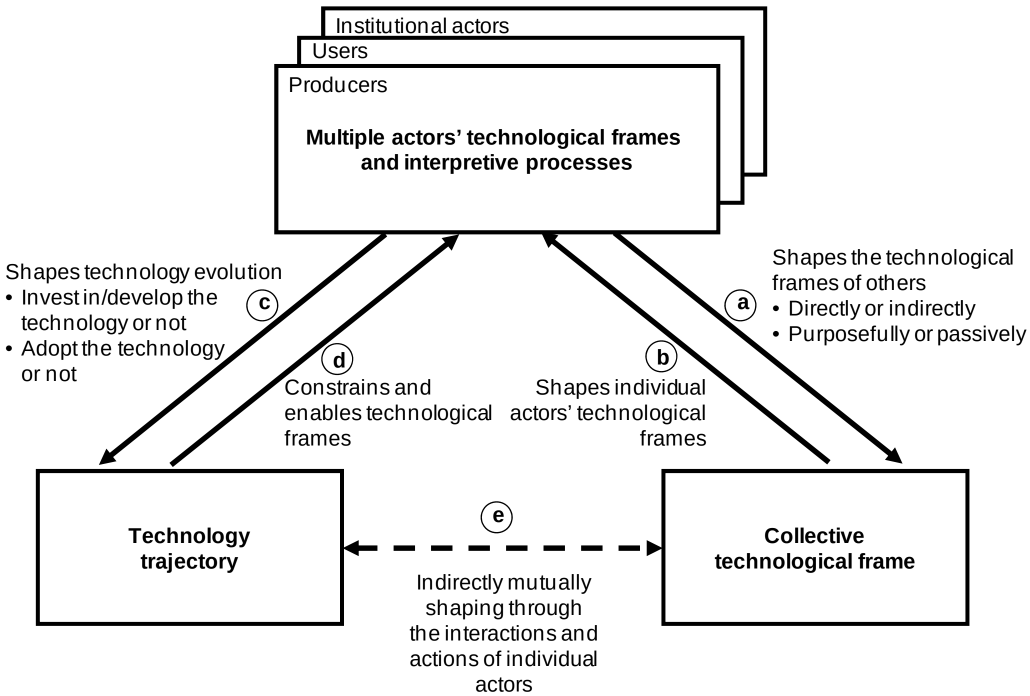
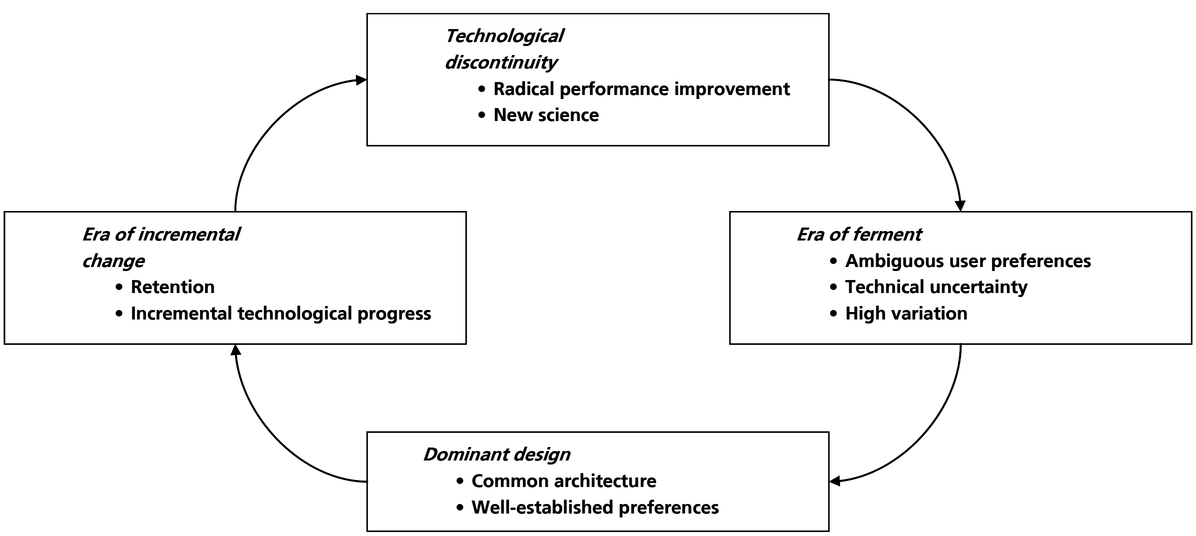


Figure 2
The technology life cycle



Adapted from Tushman and Rosenkopf, 1992.

Table 1: A cognitive model of technology evolution over the technology life cycle

	Era of ferment	Dominant design	Era of incremental change	Discontinuity
Technological outcomes to be explained	• Greater or lesser variation takes place • Specific variants are introduced	• A dominant design is achieved or not • A particular technology becomes the dominant design over others	• Inertia develops around the dominant design	• A new technology emerges or not
Economic perspective	**Mechanism:** • Technical variety is driven by exogenous stochastic technological advances **Predicted outcome**: • No prediction – variation is random	**Mechanism:** • Emergence of a dominant design is driven by increasing returns to scale (network externalities and economies of scale) **Predicted outcomes:** • A dominant design will occur when increasing returns to scale (network externalities and economies of scale) are strong • The first technology to reach critical mass will have an advantage	**Mechanism:** • Excess inertia results from network externalities **Predicted outcomes:** • When network effects are strong, the existing technology will be difficult to displace	**Mechanism:** • New technologies emerge because existing technologies reach definable limits **Predicted outcome:** • When the existing technology reaches diminishing returns, a new technology will emerge
Organizational perspective	**Mechanism:** • Technical variety is driven by exogenous stochastic technological advances **Predicted outcome**: • No prediction – variation is random	**Mechanism:** Emergence of a dominant design is driven by: • Institutional isomorphism: firms imitate the actions of similar firms (bandwagons) • Social construction: organizations are influenced by social affiliations **Predicted outcomes:** • No strong predictions about whether a dominant design will occur or not • If one occurs, the technology sponsored by a dominant social community is likely to become the dominant design.	**Mechanism:** • Inertia results from local technological search, driven by existing behavioral routines and procedures **Predicted outcome:** • Technological progress will be incremental, elaborating on the dominant design	**Mechanism:** • Industry outsiders bring different capability endowments to bear **Predicted outcome:** • New technologies will emerge if industry outsiders with different capabilities will introduce them
Cognitive perspective (our model)	**Mechanisms:** Technical variation is driven by: • Idiosyncratic differences in actors' frames • Prior affiliations, which guide actors' framing and interpretation of the technology **Predicted outcomes:** • Producers with similar technical capabilities, but different technological frames, are likely to develop different technologies • Users with different technological frames will implement the same technology differently • The higher the level of variation in the prior affiliation of firms entering an industry, the greater the technological variation • Producers and users are more likely to develop and implement technologies similar to producers/users with which they have been affiliated in the past.	**Mechanisms:** • The resolution of conflicting technological frames into a collective frame is a prerequisite for achievement of a dominant design • Higher levels of interaction among diverse actors increases the likelihood they will converge on a collective frame • Actors may act purposefully to get their own technological frame to predominate **Predicted outcomes:** • The technology promoted by actors that strategically attempt to get their own technological frame (not just technology) to predominate in the collective is more likely to become the dominant design • If a focused set of institutional arenas emerges, it provides a forum for interaction, increasing the likelihood that a collective technological frame (and thus a dominant design) emerges.	**Mechanism:** • Collective frames solidify and become intertwined with other systems within firms and within industries • Change is difficult because these links must be broken apart in order to do things differently **Predicted outcome:** • Technological progress will be incremental, elaborating on the dominant design	**Mechanisms:** • Entrepreneurial action outside of the collective frame can break the existing frame • Continuous problem-solving that highlights an increasing number of anomalies can break the frame **Predicted outcome:** • New technologies will emerge if industry outsiders with different technological frames will introduce them • Incumbent firms can introduce radically new technologies only if they break the links between their own technological frames and the rest of the organizational architecture