Paper to be presented at the

35th DRUID Celebration Conference 2013, Barcelona, Spain, June 17-19

INTER-GENERATIONAL HYBRIDS: SPILLBACKS, SPILLFORWARDS, AND SURVIVING TECHNOLOGY DISCONTINUITIES

Daniel C. Snow
Brigham Young University
Marriott School of Management
dsnow@byu.edu

Abstract
Although technology discontinuities represent one of the most challenging organization events, the micro-processes by which incumbent organizations adapt to such technology transitions remain remarkably opaque. Some prior research has observed that during such discontinuities incumbents develop hybrid recombinations of the old and new technology. Although some work implies that such inter-generational hybrids may be the result of organizational dysfunction, we propose that these hybrids may be sophisticated learning tools that shape organization adaptation to a technological discontinuity. In this paper we explore this tension, suggesting two ways in which inter-generational hybrids may impact organization adaptation: spillbacks and spillforwards. In an empirical test among the population of U.S. carburetor manufacturers during a technological discontinuity, we observe that, dependent on their knowledge investments, some organizations developing inter-generational hybrids capture spillback benefits: knowledge spillovers from a competing technology generation to the current generation. Furthermore, we find that these same organizations also capture spillforwards: spillover benefits from developing inter-generational hybrids that improve their survival chances and their product performance in the future technology generation. These results suggest that inter-generational hybrids may be a missing stepping stone, within boundary conditions, for organizations to learn about and adapt to a technology discontinuity.

Jelcodes:M13,M19

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Keywords: technology strategy, technology discontinuities, organization adaptation, knowledge recombination, innovation

*Authors listed in alphabetical order

ABSTRACT

Although technology discontinuities represent one of the most challenging organization events, the micro-processes by which incumbent organizations adapt to such technology transitions remain remarkably opaque. Some prior research has observed that during such discontinuities incumbents develop hybrid recombinations of the old and new technology. Although some work implies that such inter-generational hybrids may be the result of organizational dysfunction, we propose that these hybrids may be sophisticated learning tools that shape organization adaptation to a technological discontinuity. In this paper we explore this tension, suggesting two ways in which inter-generational hybrids may impact organization adaptation: spillbacks and spillforwards. In an empirical test among the population of U.S. carburetor manufacturers during a technological discontinuity, we observe that, dependent on their knowledge investments, some organizations developing inter-generational hybrids capture spillback benefits: knowledge spillovers from a competing technology generation to the current generation. Furthermore, we find that these same organizations also capture spillforwards: spillover benefits from developing inter-generational hybrids that improve their survival chances and their product performance in the future technology generation. These results suggest that inter-generational hybrids may be a missing stepping stone, within boundary conditions, for organizations to learn about and adapt to a technology discontinuity.

Technology discontinuities frequently displace older technologies, substituting new technologies in their place and often destroying the advantage of incumbents in the process (Tushman and Anderson 1986). Incumbents struggle to respond both because of organizational inertia and reluctance to abandon their existing resources (Agarwal and Bayus 2002; Agarwal and Tripsas 2011; Benner 2009; Gilbert 2005; Henderson 1993; Tripsas 2009), but also because technology discontinuities are often extended and uncertain, often failing to occur or taking years, even decades to transpire (Adner and Kapoor 2012; Agarwal and Bayus 2002; Anderson and Tushman 1990; Henderson 1995). As incumbents attempt to respond to the potential undermining of their existing technologies and resources, qualitative observation suggests that often incumbent organizations recombine the old and new technologies to create an inter-generational hybrid during this extended period of uncertainty. For example, when steam ships appeared, sailing ship makers integrated steam engines (threatening generation) into sailing vessels (defending generation) to improve performance while sailing in harbors. Similarly, when personal computers first emerged, electric typewriter makers integrated CRT displays and integrated memory circuits to create dedicated word processors. While inter-generational hybrids appear with surprising frequency in the interval between technology generations, in contrast to the more common intra-generational forms of recombination, inter-generational hybrids have received little study. As a result, we know little about the development of inter-generational hybrids and the effect of these hybrids on the efforts of incumbents to adapt to technological discontinuities.

What research does exist provides a potentially limited view of the role of inter-generational hybrids. Some accounts suggest that inter-generational hybrids are the physical manifestation of organizational inertia—the inability of an established organization to escape the limiting frame of its existing knowledge and the unwillingness to abandon existing resources and as such impede the organizations efforts to adapt to a technological discontinuity (Henderson and Clark 1990; Rosenbloom 2000; Sull et al. 1997). For example, when the photo-typesetting displaced the old hot metal architecture, Morgenthaler developed a hybrid between the two generations that in retrospect appears clumsily anchored in the old technology (Tripsas 1997b). There may be cases where hybrids are reflections of inertia and do appear insufficient in hindsight.

However, we suggest an alternate view: that inter-generational hybrids may actually be a sophisticated learning mechanism—a real option that provides insight and learning about an uncertain technical future that may impact organization adaptation to the discontinuity. Prior observation suggests that many threatening technologies never displace old technologies or, even when they do, these discontinuities can be misshapen or misinterpreted by incumbents leaping too early into a premature discontinuity, delays in the development of complementary assets, limited understanding of customer adoption, or institutional forces that delay a transition (Ansari and Garud 2009; Eggers 2012; Gilbert 2005; Tripsas 1997b; Utterback 1996). We propose that developing an inter-generational hybrid provides incumbents a mechanism to learn about the technology future and provide pathways for adaptation. If the threatening discontinuity fails to take hold, by investing in a hybrid, an organization may avoid wasting unnecessary resources, while potentially borrowing knowledge from another technological domain that improves their core products (Helfat and Eisenhardt 2005; Helfat and Raubitschek 2000). On the other hand, if the threatening technology does succeed, then the organization has developed knowledge about the new technology and how it differs from the older technology. This knowledge may help the organization adapt to the new technical regime (Brown and Eisenhardt 1997; Furr and Snow 2012). For example, 2.5G mobile networks allowed mobile operators to bridge the technical and market uncertainty during the long transition between voice-centric 2G networks and data-centric 3G networks (Ansari and Garud 2009).

Given our limited, even conflicting, understanding of how inter-generational hybrids impact organization learning about and adaptation to technological discontinuities, in this paper we ask two questions. First, how do different types of knowledge possessed by incumbents impact the development of inter-generational hybrids and, second, how do hybrids of the old and new technologies affect incumbent adaptation to and performance after a technological discontinuity. While we recognize that the occurrence and impact of inter-generational hybrids is bounded by certain conditions (modular components, substitutable architectures, and so forth), when they can occur they may play an important role in organizational adaptation to a technological discontinuity. Specifically, we propose two previously unexplored mechanisms, not applicable to more common intra-generational recombination, that affect the role of inter-generational hybrids in technology competitions: spillbacks and spillforwards. Spillbacks are the potential knowledge spillovers from a threatening technology regime that may provide benefits to an incumbent technology regime through an inter-generational hybrid. Spillforwards are the potential knowledge benefits from creating an inter-generational hybrid that may spill forward into a future technological regime, aiding incumbents in their efforts to adapt to a technology discontinuity.

We explore these questions in the setting of a technological discontinuity in the passenger automobile industry as carburetors were replaced by electronic fuel injection (EFI), using a dataset composed of the full population of manufacturers and every carburetor produced for the US automobile market between 1978-1992. In this setting, we examine how inventive knowledge in the extant regime and threatening regime, as well as more generalized inventive knowledge contribute to spillbacks, measured as the performance of inter-generational hybrid carburetors. We also explore how these hybrids contribute to spill-forward benefits, including survival and above average performance of an incumbent's products in the new generation after the technological discontinuity.

We find significant evidence of knowledge spillbacks as incumbents borrow from a future technology to improve their current technology. More surprisingly, we find that in spite of some interpretations of inter-generational hybrids as manifestations of organizational dysfunction, in this setting, inter-generational hybrids appear to play a critical role in helping organizations survive a technological discontinuity and even increasing performance relative to competitors in the post-discontinuity environment. In other words, our results support the idea that not only can creating a high-performing hybrid help incumbents to leap to the next generation, but once they cross the technological discontinuity their next-generation products have greater performance than do those of their competitors.

We believe these results make three contributions. First, this paper contributes to work on organizational adaptation by suggesting additional micro-processes, to those already identified, by which organizations learn about and adapt to technological discontinuities (Adner and Kapoor 2012; Benner 2009; Eggers and Kaplan 2009; Tripsas 1997b; Tushman and Rosenkopf 1996). Second, this work contributes to the innovation literature by identifying and developing a previously underappreciated form of recombination—inter-generational recombination—that has properties distinct from the more commonly studied intra-generational recombination (Eisenhardt and Santos 2006; Fleming 2001; Helfat and Raubitschek 2000). Third, this work contributes to the work on technology strategy (Adner and Kapoor 2012; Henderson 1995; Taylor 2010; Tripsas 2008) by clarifying an advantageous role of inter-generational hybrids, within boundary conditions, as stepping stones rather than stumbling blocks in surviving a technological discontinuity.

THEORY

Among the events to which organizations must adapt, the punctuated equilibrium nature of technologic discontinuities makes them one of the most challenging events to which incumbents must respond (Gersick 1991; Rosenkopf and Tushman 1994; Tripsas 1997a; Tushman and Anderson 1986). Despite these challenges, a growing body of literature has started to examine the factors that influence the ability of incumbents to adapt to such discontinuities. Research suggests that organizational processes (Benner and Tushman 2002; Henderson and Clark 1990), cognition (Eggers and Kaplan 2009; Furr et al. 2012; Tripsas 2009), resources and capabilities (Gilbert 2005; Rosenbloom 2000), complementary assets (Adner and Kapoor 2012; Tripsas 1997b), strategic commitments (Sull et al. 1997), and customer understanding (Ansari and Garud 2009; Christensen and Bower 1996) all affect organization adaptation to a discontinuity. One common thread among these many constructs is the role these elements play inhibiting or facilitating an organization's ability to learn about the technological discontinuity and the effect of this learning on subsequent adaptation. In such studies, scholars have at times observed that incumbents often appear to make a "half-step" between generations (Ansari and Garud 2009; Gilbert 2006; Tripsas 1997a; Utterback 1996), developing technology that recombines portions of extant technology with the threatening technology to create a hybrid technology—what we label an inter-generational hybrid.

Despite the limited research attention, inter-generational hybrids appear during a surprising number of technological discontinuities. The sail-steam, typewriter-PC, hot metal-phototypesetting, and celluar-data network hybrids mentioned earlier are but a small sampling of inter-generational hybrids. Other examples abound including the hybrid flash-hard disk bridging the storage and speed divide between flash memory and traditional hard drives; online backup services utilize 'snail mail' shipments of hard drives when bandwidth is limited; and anology-digital video camera hybrids. In short, we argue that the existence of hybrids between technology generations may be more the norm than the exception.

Such inter-generational hybrids (we use the term hybrid from this point forward as shorthand for inter-generational hybrid) are an important artifact of study because recombination across technical generations can affect organization adaptation to innovation in distinctly different ways than the more common forms of intra-generational recombination studied in the innovation literature (Fleming and Sorenson 2001; Hargadon and Sutton 1997; Henderson and Clark 1990; Nickerson and Zenger 2004). Whereas the recombination of contemporary industries has often been labeled innovation and interpreted as a positive organizational outcome, the limited extant observations of inter-generational hybrids depict the organizational implications of hybrids in a mixed light[1]. The undeveloped but implied view in much literature suggests that inter-generational hybrids are clumsy attempts to cross from one technical paradigm to the next and as such represent the physical manifestation of organizational rigidity. During technology discontinuities, not only are organizations' existing knowledge bases displaced (Anderson and Tushman 1990), but often the old knowledge base becomes a significant liability. Research suggests that the firms existing knowledge can lead them to overlook or misperceive the nature of the change (Henderson and Clark 1990) or lead to significant under-adaptation in the face of change (Holbrook et al. 2000; Kaplan et al. 2003; Tripsas and Gavetti 2000). From this perspective, organizations create hybrids that are limited by and protect their extant

[1] Recombination plays a fundamental role in innovation and technology strategy (Schumpeter 1934). Recombination has been defined as a new combination of elements or components. At times, the products of recombination have been labeled hybrids, to further emphasize the recombination of two or more well recognized components (Fleming and Sorenson 2001; Hargadon and Sutton 1997; Henderson and Clark 1990; Nickerson and Zenger 2004). Although hybrids have been discussed by organization theory (e.g. hybrid institutions, categories, governance, identity, structure, and so forth (DiMaggio 1995; Golden-Biddle and Rao 1997; Meyer et al. 2005; Ruef and Patterson 2009; Whetten 1989; Williamson 1991)) and strategy (e.g. hybrid strategy, resources, capability, knowledge, process and so forth (Anderson 1999; Baker and Nelson 2005; Gulati 1995; Kogut and Zander 1992; Nickerson and Zenger 2004; Snow and Hrebiniak 1980)), hybrids play a particularly fundamental role in innovation (Fleming 2001; Schumpeter 1934; Singh and Fleming 2010) and technology strategy (Ahuja and Katila 2001, 2004; Cooper and Schendel 1976; Fleming and Sorenson 2001; Levinthal 1998). However, most contemporary research focuses on hybrids that are recombinations of contemporary elements. In this paper we focus on the understudied case where innovations are the recombination of elements across technology discontinuities.

knowledge and therefore fail to fully adapt to the emerging technological paradigm (Christensen and Bower 1996; Gilbert 2005).

However, we propose a contrasting view, namely that that inter-generation recombination may actually be a sophisticated organizational response to technological uncertainty. Although many technologies often threaten an existing paradigm, often these technologies fail to materialize or may take years to overcome extant technology (Adner and Kapoor 2012; Agarwal and Bayus 2002; Anderson and Tushman 1990). As a result, leaping directly to a new technology prematurely can lead to substantial waste and disappointment (Gilbert 2005). By contrast, creating an inter-generational hybrid may represent a sophisticated option on an uncertain technical future (Brown and Eisenhardt 1997; Kogut and Kulatilaka 2001). It is sophisticated because it not only represents a 'placeholder' for the firm in the future market, but it also represents a source of learning today. On the one hand, if the threatening technology fails to take hold, by investing in an inter-generational hybrid, an organization may avoid wasting unnecessary resources while potentially borrowing ideas from another technology that improves its core products, perhaps even developing an advantage over competitors. On the other hand, if the threatening technology does succeed, then the organization has a potential learning advantage in the new technology by having integrated it into a hybrid. Furthermore, by developing a hybrid as an incumbent may learn when to adapt, avoiding the common incumbent mistakes of leaping too early or too late into a threatening technology (Christensen et al. 1998; Taylor and Helfat 2009).

As a relevant contemporary example, consider the choices Toyota, a manufacturer of traditional internal combustion engine (ICE) vehicles, faces with respect to the potential threat posed by electric vehicles. Toyota could choose to leap directly into electric vehicles, but electronic vehicles may take decades to replace combustion vehicles, if such a discontinuity occurs at all. Alternatively, Toyota could choose to wait until an electric vehicle future emerges, at which point it may be too late to respond effectively to the new technical generation. Toyota's mixed response was to create the Prius, an inter-generational hybrid between ICE and electric vehicles that effectively provides the organization an option on the future. If electric vehicles fail to emerge as a viable future, Toyota will have avoided the strategic misstep of investing heavily in electric vehicles, while at the same time creating a vehicle that has a significant performance advantage over existing combustion alternatives. But if electric vehicles emerge as the new dominant paradigm, Toyota will have developed significant knowledge and capability advantages in that domain (e.g. sourcing and manufacture of electronic components as well as consumer preferences) that will provide it an advantage in making the transition to an electric vehicle future relative to its competitors who, in their inertia, fixated on the ICE automobile. Furthermore, because Toyota has been involved with the hybrid, it may be more likely as an organization to recognize precisely the optimal time to leap into electric vehicles (Christensen et al. 1998).

Despite the depth of knowledge regarding recombination of contemporary elements, or intra-temporal recombination (Ahuja and Katila 2001, 2004; Fleming and Sorenson 2001), relatively little research has examined recombination over time, or inter-temporal hybrids. We define intra-generational hybrids as the combination of contemporary elements within or across technology generations, whereas we define inter-generational recombination as the combination of technology elements across generations (see figure 1). For example, digital SLR (DSLR) cameras are a recombination of the single-lens reflex camera shutter and lens system from an extant technical generation, with digital sensor and storage technology from what became the pure digital camera. Naturally, the possibility of inter-generational recombination has boundary conditions (see the discussion for an extended development of these boundary conditions). The possibility of inter-temporal recombination depends on the potential level of recombination across technology generations, most often in the form of modular components that can be borrowed between generations or in architectures that can be substituted or modified between generations (Baldwin and Clark 2000; Garud and Kumaraswamy 1995). As a result, inter-temporal recombination may be more likely to occur in products, especially assembled products, because they are more likely to have modular components or modifiable architecture[2].

(Insert Figure 1 about here)

[2] By contrast, inter-temporal recombinations are less likely to occur in non-assembled products such as chemicals and will not occur when technology generations have zero compatibility. Furthermore, the likelihood of occurrence of an inter-generational recombination may be affected by events and forces in the ecosystem in which the recombination would occur, specifically whether the product or its entire ecosystem is displaced by a technology discontinuity; we return to this subject in the discussion.

Inter-generational Hybrids and Technology Spillbacks

The view of inter-generational hybrids as learning mechanisms suggests two important elements of inter-generational hybrids that differ from intra-temporal hybrids and that may play an important role in organization adaptation during technology discontinuities: spillbacks and spillforwards. In respect to the former, inter-generational hybrids may create the opportunity for knowledge spillbacks from a threatening technology to an established technology. Spillbacks are defined in a technology setting as the longitudinal spillover of knowledge from a threatening technology generation to the extant technology regime. For example, Taylor (2010) observed in a field study of high technology organizations that often product development teams, motivated by internal competition, learned from and integrated new technology to improve their core product performance. In the context of a technology discontinuity, spillbacks may also occur when incumbents borrow elements from a threatening technology generation that actually improves the performance of the focal generation. For example, when Edison successfully introduced a light-bulb, gas-lighting organizations borrowed the idea of the filament to increase the efficiency of gas lighting five-fold—an improvement that threatened to destroy the nascent electric lighting industry and in turn render it difficult for Edison to commercialize electric lighting (it took Edison twelve years to turn a profit). Such spillbacks can contribute to performance boosts which result in a sudden improvement in the extant technology for the incumbent firm and for the technology generally—a "last gasp" in the technology S-curve (Tripsas 2008).

Spillbacks often result from the recombination of knowledge about an extant technology generation and a threatening technology generation in the form of a hybrid. Although knowledge in extant technology generations has sometimes been identified with inertia during a technology discontinuity (Henderson and Clark 1990; Rosenbloom 2000), many times incumbents eagerly engage in the development of hybrids because it leverages their existing knowledge[3]. Furthermore, often incumbents have developed inventive knowledge in the new domain that increases the potential for hybrids and spillbacks. Prior research differentiates between core and integrative knowledge as well as between operational and inventive knowledge. In terms of the first dimension, Helfat and Raubitschek (2000) argue integrative knowledge,

[3] Note, there are even times when incumbents actually develop the future generation, such as Kodak developing the first digital camera.

meaning knowledge of processes that span technical domains or value chains (such as how to optimize manufacturing operations or how to develop new products) differs from core knowledge which is relevant only to the focal domain. Similarly, knowledge may be operational, meaning knowledge applicable to standard operational procedures (such as the knowledge developed by running factory lines every day) (March and Simon 1958), or it may be inventive, meaning the creation of new knowledge such as occurs in patenting an invention (see Figure 2 for a summary). Such inventive capability has often been described as a higher-order capability (Moorman and Miner 1998), an architectural capability (Henderson and Cockburn 1994), or dynamic capability (Helfat and Peteraf 2003) that increases the ability of organizations to develop new knowledge, even if that capability has been developed in an "old" technology setting.

(Insert Figure 2 about Here)

When comparing operational and inventive knowledge, whereas operational knowledge may create inertia to organization adaptation, inventive knowledge may facilitate the development of inter-generational hybrids. Because operational knowledge in a domain tends to be highly routinized, structured, and embedded in resources and processes (Dosi et al. 2000; Nelson and Winter 1982), such knowledge may contribute to the rigidity observed by previous scholars (Benner and Tushman 2002, 2003; Gilbert 2005; Tripsas and Gavetti 2000). By contrast, when incumbent firms invent in an existing technological regime, they demonstrate a robust understanding of the technical area and a certain flexibility in the character of that knowledge by the very fact that they have altered the knowledge components to generate novel insights (Garud and Nayyar 1994). Not only do organizations often innovate for many years in an older technology after a new technology has been introduced (Adner and Snow 2010a; Cooper and Schendel 1976), but the very inventive capabilities developed in an incumbent technology may help organizations to invent in future generations (Sosa 2009, 2011; Tripsas 1997a). For example, Cohen and Tripsas (2012) studied traditional film-based camera manufacturers and found that an organization's inventive knowledge in film actually increased its ability to invent in the digital photography era. Therefore greater inventive knowledge, even if in the extant technology, may increase the ability of incumbents to recognize valuable elements of a future technology generation as well as integrate those technologies onto a broader platform in the extant technology.

H1: The greater an incumbent organization's inventive experience with the incumbent technology, the greater the performance of its inter-generational hybrid technology.

In addition to inventive knowledge in the old technology, inventive knowledge in the new technology may contribute to the development and performance of inter-generational hybrids. Often organizations invest in a technical domain in advance of actual entry in the domain (Cattani 2005). While these investments may help the organization cross to the new technical domain at a later date (Eggers and Kaplan 2009), before that time, investments in developing knowledge about a new domain may contribute to the development of inter-generational hybrids (Brusoni et al. 2001; Pisano 1996). Specifically, organizations learn new skills by recombining their current capabilities (Kogut and Zander 1992) and if organizations develop intimate knowledge about a new technology domain, the individuals within the organization are more likely to recognize components of that knowledge that could be recombined with their existing knowledge (Helfat and Raubitschek 2000). These novel components could be integrated with existing technology to increase the performance of extant products—a spillback from the novel technology to the current generation. Such spillovers from threatening technologies can create significant performance advantages for established technologies. For example, by developing knowledge of batteries and electric drive trains, Toyota's hybrid combustion-electric vehicle has successfully borrowed elements of electric cars to obtain a significant advantage over combustion vehicles in terms of higher MPG performance and differentiated customer appeal. Therefore, organizations with greater inventive experience in the threatening technology may have a greater likelihood of recognizing components from a threatening technology and understanding how to integrate these components to capture spillbacks that improve the performance of inter-generational hybrids.

H2: The greater an incumbent organization's inventive experience with the threatening technology, the greater the performance of its inter-generational hybrid technology.

Finally, in addition to inventive, specialized knowledge in a particular domain, it may be the case that some organizations are better at inventing and recombining knowledge and as a result, inventive knowledge developed outside the focal domain, may increase the ability of an incumbent to capture spillback benefits. Organizations increase their ability to recombine knowledge with practice (Grant 1996; Kogut and Zander

1992) and even organizations with experience inventing outside the focal domain, may have developed integrative inventive experience that increases their likelihood of recombining knowledge in the focal domain (Helfat and Raubitschek 2000) As evidence of this possibility, in her study of the petroleum industry, Helfat (1997) found that organizations investing in refining research and development were more likely to invest in complementary knowledge development in related areas, such as coal gasification. Related research on business recombination suggests that firms with greater recombination experience appear to develop knowledge and capabilities that increase the quantity and results of recombination efforts (Capron et al. 2001; Galunic and Eisenhardt 1996; Helfat and Eisenhardt 2005; Karim and Mitchell 2000, 2004).

It follows that if organizations have developed inventive capabilities in indirectly related technical areas, they may have developed general learning and recombination capabilities that could positively impact their ability to develop high-performing inter-generational hybrids (Helfat and Raubitschek 2000; Kogut and Zander 1992). Because these inventive organizations have practice at recombining knowledge even in areas not directly related to the knowledge domain in question, they will be more likely to capture spillbacks from threatening or alternative technology areas. Therefore organizations engaged in more inventive activities in indirectly related, advanced technology areas may more effectively combine two technology regimes during a technological discontinuity to develop inter-generational hybrids.

H3: The greater an incumbent organization's inventive experience advanced technology not directly related to the donor technology domains in question, the greater the performance of its inter-generational hybrid technology.

Inter-generational Hybrids and Technology Spillforwards

In addition to spillbacks, inter-generational hybrids may also create the opportunity for spillforwards (see Figure 3). We define "spillforwards" in a technology setting as the spillover of knowledge from an inter-generational recombination to a future technology generation. Spillforwards have rarely been investigated in the literature but may play a particularly important role in organizational adaptation to a technological discontinuity. There are several reasons why developing an inter-generational hybrid may allow an organization to learn about future technology in a manner that impacts its ability to adapt to it.

(Insert Figure 3 about Here)

First, because technology transitions frequently take many years incumbents frequently make the mistake of leaping into a new technology too early, too late, or with the wrong technology (Eggers 2012; Gilbert 2005; Taylor and Helfat 2009), incumbents developing hybrids may instead develop learning that increases their ability to correctly time entry into a new technical generation. Indeed, a closer examination of technology histories suggests that incumbents are sometimes the first to leap into a new technology, paying significant pioneering costs while making mistakes that cost them technology leadership (Markides and Geroski 2005). For example, manual typewriter manufacturers were some of the first to launch electric typewriters, traditional photography companies were some of the first to experiment in digital cameras, and major newspapers groups were some of the first to experiment with digital media portals (Cohen and Tripsas 2012; Gilbert 2005). However, because these firms made premature entries into the industry, these incumbents experienced significant disappointments that soured their view of the technology such that later, when the technological discontinuity actually *did* occur, these incumbents were among the laggards, having misjudged the real potential of the technology. Similarly, many incumbents leap into a threatening technology after a technology discontinuity and dominant design have already been established, decreasing their performance, such as Blockbuster's move into online DVD rentals or Nintendo's move from 8 to 16-bit video games—both late moves that cost those firms their dominant positions (and in Blockbuster's case its solvency) (see Eggers 2012 for a review of challenges to leaping early and leaping late).

To this end, correctly timing adaptation and technology choice during a technological discontinuity may be critical to survival and success (Anderson and Tushman 1990; Suarez and Utterback 1995). Christensen et al. (1998) suggested that the optimal time for incumbents to enter a new technology industry is not during the early era of ferment, but during the window of opportunity immediately before a dominant design emerges. By integrating two technology regimes in the form of an inter-generational hybrid, an organization may avoid the waste of leaping into a technology prematurely, while also developing an understanding of the potential, timing, and optimal entry mode for a future technology. Specifically, the managers in an incumbent experimenting with an inter-generational hybrid may more clearly see the transition points at which an extant technology has truly been exhausted and the threatening technology has begun to be adopted (Argyres et al. 2012). Learning about appropriate timing may be a critical knowledge spillforward that allows an organization to adapt to a technological discontinuity.

Second, by integrating the new technology in an inter-generational hybrid, the organization may learn both core knowledge and integrative capabilities related to the new technology that allow the organization to develop more successful new products in the future generation once a transition has been made (Helfat and Raubitschek 2000). While an organization may want to avoid committing fully to an uncertain future technology, an inter-generational hybrid may help the organization to learn about tomorrow's technology in today's time frame—not during a later time frame when adaptation efforts are too late. Specifically, by developing a hybrid incumbents can learn about how to develop, produce, optimize, distribute, and market a novel technology without "betting the farm" prematurely. Furthermore, during the process of learning with a hybrid, these same organizations may shape and legitimize customer preferences as the customers themselves learn what to expect from the technology.

In summary, developing an inter-generational hybrid may provide positive spillforwards in the form of product, customer, and timing knowledge that helps an organization to adapt. For example, when the electric typewriter industry was threatened by the distant threat of personal computers, rather than leaping directly into personal computers, several important incumbents in electric typewriters, including IBM and Olivetti, created hybrids called "word processors" which combined electric typewriter components with the monitors, disk drives, and other familiar components of the future personal computer. If these incumbents had leaped directly into personal computers they might have been disenchanted with lackluster sales—it took many years for the industry to transition from electric typewriters to personal computers. But once the personal computer industry did appear to emerging, IBM and Olivetti abandoned their hybrids and entered the PC industry in a manner that literally defined the dominant design of the industry, perhaps too well in the case of IBM (Utterback 1996). Notably, the roles of the typewriter, the correcting typewriter, and the hybrid word processor, are glaring in their absence from existing scholarly and popular narratives surrounding IBM's 'self-disruption' of its mainframe business with the PC. Such may also be the case for Toyota, that if an electric vehicle future emerges, they will have an advantage in knowledge about how to produce electric vehicles, customer preferences for electric vehicles, and when to leap to electric vehicles that other incumbents may lack.

Therefore, organizations that develop inter-generational hybrids may have adaptation advantages over incumbents who do not develop or underinvest in inter-generational hybrids. The potential product and timing knowledge spillforwards should increase the ability of an incumbent to survive a technology transition by allowing managers to select an optimal time to enter the industry and allow the incumbent to borrow from knowledge developed about the new technology to improve their technology performance relative to other incumbents who did not develop similar knowledge. Such knowledge spillforwards will likely be proportional to the effort invested—organizations developing higher performing inter-generational hybrids should have developed richer, more valuable knowledge, than more half-hearted incumbents who produced few or underperforming hybrids. Such benefits should be manifest in both survival and product performance as incumbents with high performing inter-generational hybrids are better able to determine the best entry path and apply their existing knowledge to the new technological regime.

H4: The greater an incumbent organization's inter-generational hybrid performance, the greater its product performance in the new technology relative to other incumbents.

EMPIRICAL CONTEXT AND METHODOLOGY

The context of our study is a technology discontinuity in automobile fuel delivery systems that occurred during the 1980s. In the early 1980s, in response to tightening government regulation as well as consumer demand, automobile manufacturers and their suppliers introduced a potential direct substitute (Electronic Fuel Injection (EFI)) for the existing fuel delivery technology, or the carburetor. Soon after the appearance of EFI, carburetor manufacturers began to adapt EFI's electronic sensors and controls for use on carburetors. The resulting hybrid carburetor, incorporating electronic controls, survived alongside standard carburetors and EFI through the late 1980s. By 1992, EFI achieved dominance and replaced both the standard and the hybrid carburetors.

This industry is an ideal setting in which to study the question of inter-generational hybrids and adaptation because we can observe the performance outcomes of knowledge investments and technology choices among the population of incumbents. Because of the regulated nature of the market, we can observe the full population of car models tested by the US Environmental Protection Agency (n=4374) from 1978 through 1992 (the entire period covering the transition from carburetors to EFI in the US market). Furthermore, during this period all carburetor firms produced carburetors but also offered a version of an inter-generational hybrid, the electronic carburetor. Therefore, because incumbents were engaged in inventive activity in both carburetors and EFI, we can observe how differing patterns of inventive activity and differing technology choices affected product performance in the old, hybrid, and new technologies as well as firm survival as a result of these choices.

To capture this data, the base unit of observation is a car model, which is defined as any available combination of model name, body type, engine size, transmission type, power output, and carburetor type (electronic or standard). The data contains results from EPA tests of each car model's physical attributes and tested performance. We then used carburetor repair manuals to identify the carburetor manufacturer for 3025 of the 4374 car models in the EPA data. These manufacturers and the counts of automobile models equipped with their carburetors are summarized in Table 1. Patent data to calculate measures of carburetor firm inventive activity from the National Bureau of Economic Research (NBER) and Harvard University (Hall et al. 2001; Lai et al. 2011). Table 2 reports the annual counts of firm-car pairs for which we obtained data and shows that carburetor manufacturers were identified successfully for most car models over the years of the study.

Variable definition

Dependent variable: MPG (Miles Per Gallon, car model attribute-adjusted)

The dependent variable is the imputed fuel consumption of a focal car model's carburetor, measured in miles per gallon, or *MPG*, obtained by the focal car model as measured by the EPA. *MPG* represents the critical carburetor/EFI performance metric that manufacturers strove to improve during this period. Fuel consumption has always been an economically significant dimension of an automobile's performance. Marginal improvements in fuel consumption have been found to command a sales price premium from customers (Kahn 1986) and are also rewarded by government regulators under the US Corporate Average

Fuel Economy (CAFE) program with the power to fine violators[4]. During the period of the study, due to increasing federal fuel economy standards and rising fuel prices, the contribution of a carburetor/EFI to MPG became the tantamount measure of product performance. We employ the most accurate and consistent measure of a carburetor MPG available which is to estimate the effect of carburetor-related variables of interest (e.g. carburetor technology type, carburetor manufacturer, lagged carburetor manufacturer patenting activity) after controlling for all other observable attributes of the car model.

Independent Variables

To test hypotheses1-3 about the contribution of different types of inventive knowledge to spillbacks in hybrid performance we construct measures based on patent data in the extant technology (carburetors), the new technology (EFI), and general inventive knowledge (semiconductors--a related technology area relevant for all firms). We measure *Patents* (and its subcategorizations such as *CarbPatentsHigh*) as the citation-weighted patenting activity associated with each individual carburetor model in the sample leading up to its sale in a focal car model. The *Patents* measure is constructed by associating individual automobile carburetors with patents that relate to the carburetor's technology. To do this, we identify the manufacturer of each carburetor in the sample. Carburetor manufacturers are then associated with patents through string searches in the "Assignee" field in the NBER Patent Citation File, verified by manual checks for false (negative and positive) matches. In the US automobile industry, the employee who invented the technology typically is listed as a patent's inventor, and the employer is listed as the patent's assignee[5].

The construction of *Patents* takes into account lead times in the automobile product development process. New car development begins five to seven years before launch whereas minor updates take as little as one year to complete. Our patenting measure captures this activity by counting patenting activity in the five

[4] In this program, excess fuel economy performance (e.g. exceeding the regulated minimum) is a fungible benefit that a manufacturer may transfer within firm from more fuel efficient models to less fuel efficient (and often higher-margin) ones in order to avoid serious fines. Also note, EPA testing regimes remain consistent during the study period.

[5] It is not possible with available data to separate such a case, for instance, from one in which an independent inventor has been contracted to perform research for General Motors. The inclusion of patents by independent inventors in the patent measure could then bias this as a measure of firm experience with a given future technology, because licensed independent inventions are less likely to accumulate as firm experience in the sense intended in this study. However, this bias would work against the hypothesized effects and lead to an underestimate rather than an overestimate of firm inventive experience.

years before the carburetor's sale to the public. For instance, the inventive activity and knowledge embodied in the Hitachi carburetor of a 1983 Mazda GLC is measured by patents applied for by (and subsequently granted to) Hitachi from 1978 until 1983. The patent's application date is used rather than the grant date to avoid the potential problem of patent grant times changing over the sample window for bureaucratic and legal reasons outside the firm's control. Each patent associated with a carburetor is then weighted for importance by counting the number of patents (granted to any inventor, inside or outside the firm) that subsequently cite it in the five years following its granting.

Patents is calculated for a given carburetor (through its manufacturer and model year) across three technology areas, standard carburetors, EFI, and semiconductors (*CarbPatents*, *EFIPatents*, and *ChipPatents*), using patent classes defined by the World Intellectual Property Organization (WIPO)'s International Patent Classification (IPC) system. From 1970 through 1999, the USPTO issued 9506 patents in the IPC classification entitled "supplying combustion engines in general with combustible mixtures or constituents thereof." Of those 9506 patents, 1844 are specific to carburetors and 887 are specific to EFI. In carburetors there are 274 assignees. The *Patents* measure for an individual carburetor firm j in a given year t is:

$$Patents_{jt} = \sum_{s=0}^{4}\sum_{k}\left[\mathbf{1}(pat\ k\ app\ for\ in\ t-s)\sum_{r=1}^{5}(count\ of\ cites\ of\ pat\ k\ in\ t-s+r)\right]$$

The *Patents* measures are summarized by carburetor firm in Table 5. For the measure of general inventive knowledge we chose semiconductor patents (*ChipPatents*), a related and technically sophisticated domain shared by most manufactures, because it suggests general inventive technical knowledge but is not directly required to produce EFI. To separate out the effect of inventive activity on hybrids from standard carburetors, we interact the binary variable *Hybrid,* equal to one when the car has a hybrid carburetor and zero if a standard carburetor, with the patent measure. Patents' shortcomings as measures of inventive activity and knowledge are well documented yet patents remain the best available measure of these constructs in large cross-section studies especially when they are properly weighted.

Independent variables: HybridPerf and StandardPerf

In order to test Hypothesis 4 that superior performance of a firm's hybrid carburetors will lead to subsequent improved performance in EFI, we construct *HybridPerf* and *StandardPerf*, measures of performance of a firm's hybrid and standard carburetors. Their construction starts with the most robust specification from the tests of Hypotheses 1 through 3 to obtain predicted values of MPG for each individual car model in the sample. This value represents the best prediction of MPG for a car model given its observable attributes. This predicted value is then subtracted from the car model's actual measured MPG, creating a measure of a car model's (and by connection its carburetor's) over- or underperformance given its observable attributes. These over- or under-performance values are averaged over model year by carburetor type (*Hybrid* or not) and by carburetor manufacturer. The later value provides a firm level measure of the annual under- or over-performance of a firm's hybrid and standard carburetors relative to those of their competitors. These values are calculated for a range of lags (e.g. *HybridPerfLag1* – the HybridPerf value one year before) for use in predicting subsequent *MPG* performance for the firm's EFI offerings. This *HybridPerf* value may be thought of as a measure of a firm's capability in executing the hybridization of the old and new technologies, relative to its competitors. The StandardPerf value may be thought of as a measure of a firm's capability in extracting performance from the existing technology. These measures are then used to predict performance in the disrupting technology, EFI

Control variables

To control for all other factors that could affect MPG, we construct a vector of observable attributes for each car model, including model year (*ModelYear*), measured curb weight (*Tons*), engine's displacement—a measure of the size of the engine—in liters (*Liters*), automatic or a manual transmission (*Autotrans*), and power output (*Horsepower*). Table 3 provides summary statistics and Table 4 provides a correlation matrix. The results are robust to alternate controls that we tested but reduced the sample size.

Estimation

For Hypotheses 1 through 3, we estimate the individual and joint (interacted) impact of the different types of carburetor firm knowledge and inventive experience (*Patents*) and of the *Hybrid* technology on the fuel economy (MPG) of an individual carbureted car model, controlling for other relevant car attributes. Testing of Hypotheses 1 through 3 begins with the base OLS specification

$$MPG_i = \alpha 1 + \beta 1(Hybrid)_i + \beta 2(CarbPatentsMedium)_i + \beta 3(Hybrid*CarbPatentsMedium)_I + \beta 4(CarbPatentsHigh)_i + \beta 5(Hybrid*CarbPatentsHigh)_i + \beta 6(EFIPatentsMedium)_i + \beta 7(Hybrid*EFIPatentsMedium)_I + \beta 8(EFIPatentsHigh)_i + \beta 9(Hybrid*EFIPatentsHigh)_i + \beta 10(ChipPatentsMedium)_i + \beta 11(Hybrid*ChipPatentsMedium)_I + \beta 12(ChipPatentsHigh)_i + \beta 13(Hybrid*ChipPatentsHigh)_i + \beta 14(ModelYear)_i + \beta 15(Tons)_i + \beta 16(Liters)_i + \beta 17(Autotrans)_i + \beta 18(Horsepower)_i + e_i$$

in which the fuel economy *MPG* of car model *i* is regressed on its attributes, its carburetor technology, and the *Patents* of its source firm . In order to address potential endogeneity and unobserved variable concerns, a series of increasingly restrictive firm, year, and car class, fixed effects is added to the regressions. Furthermore, because the relationship between the patent-based experience measures and *MPG* is not linear, we categorize the *Patents* measures into low, medium, and high categories (e.g. *EFIPatentsLow*, *EFIPatentsMedium*, *EFIPatentsHigh*) with cuts at the 33rd and 67th percentiles by year[6]. For all tests, the low patenting category is the omitted one. To test Hypothesis 4a we estimate the impact of *HybridPerf* and *StandardPerf* on subsequent performance of a firm's EFI-equipped car models using OLS. Finally, to test Hypothesis 4b, we present a table of firm outcomes following the transition to EFI.

To address criticisms that unobserved firm characteristics could be acting both on product performance and on patenting activity, leading to biased estimates of the effect of patenting on carburetor MPG, we estimate a second model that includes carburetor firm (*Carbco*) fixed effects (Regression 2, Table 6). In addition, if the rate of improvement in carburetors is non-linear over time then the linear *ModelYear* variable, which measures annual improvement in carburetor efficiency, may introduce bias. To address this concern, Regression 3 in Table 6 adds model year fixed effects to the specification in Regression 2. Finally, it may be possible that there are attributes of carburetor models that make them more or less suited to the addition of hybrid technology, and that these attributes are unobserved by the researcher but observable to automobile and carburetor firms. Based on the assumption that these attributes may be correlated with the class of car model (compact, sports car, station wagon, etc., hereafter referred to as *CarClass*) in which a

[6] The patenting measures contain extreme values that could bias the coefficient estimates in a standard linear OLS model. This non-parametric approach reduces the impact of extreme values and it provides insight into the any nonlinearities in these relationships.

carburetor is fitted, we add fixed effects that are interactions between *CarClass* and Carburetor Firm (*Carbco*), reported in Regression 4 of the Table 6.

RESULTS

To test Hypothesis 1, we examine whether knowledge and inventive experience with the old technology—carburetors—improves the performance a firm may extract from its hybrid offering. Accordingly, the coefficient estimates on the interactions between higher levels of carburetor-related patenting (*CarbPatentsMed* and *CarbPatentsHigh*) and *Hybrid* should be positive and significant. Results reported in the base specification in Regression 1, Table 6, do not support this, however. As a firm's level of carburetor-related patenting increases, there is no statistically significant impact on its *Hybrid* performance (i.e. *Hybrid*CarbPatentsMed* and *Hybrid*CarbPatentsHigh* are not significantly different from the omitted category *Hybrid*CarbPatentsLow*). Although these results do not support H1, carburetor patenting does have a positive impact on the performance of a firm's standard carburetors[7].

Hypothesis 2 argued that inventive knowledge in the new technology would improve hybrid performance. Regressions 1 through 4 in Table 6 show that an increased level of new-technology (EFI) patenting is associated with significantly better *MPG* performance of a hybrid carburetor. Specifically, the coefficient estimates on variables *Hybrid*EFIPatentsMedium* and *Hybrid*EFIPatentsHigh* are positive and significant in Regressions 3 and 4, the specifications with the most restrictive sets of fixed effects. Specifically, the move from a low to a medium level of EFI patenting (*Hybrid*EFIPatentsLow* [omitted] to *Hybrid*EFIPatentsMedium*) increases MPG between 1.2 and 2.5 MPG in the average hybrid carburetor, the move from low to high EFI patenting (*Hybrid*EFIPatentsLow* [omitted] to *Hybrid*EFIPatentsHigh*) is associated with gains of between 2.0 and 3.6 MPG in the average hybrid carburetor. Moving from a medium to a high level of EFI patenting (*Hybrid*EFIPatentsMedium* to *Hybrids*EFIPatentsHigh*) also significantly increases hybrid performance in regressions 3 and 4. These results provide confirmatory evidence for

[7] We point out the somewhat puzzling result that, in Regression 4, a high level of carburetor patenting (Hybrid*CarbPatentsHigh) appears to have a negative impact on hybrid carburetor performance; in the other regressions, it is merely indistinguishable from zero. This finding indicates that excessive inventive activity associated with the old portion of the hybrid may actually harm its performance. One possible explanation for this result is that inventive activity devoted to the old technology consumes firm resources that might otherwise be used to invest in and learn about the new technology.

Hypothesis 2. Furthermore, the estimates of the effects of *EFIPatents* interacted with *Hybrid* provides indirect evidence that the EFI patent results are not driven by unobserved firm characteristics that might increase product efficiency or the likelihood to patent: that sort of unobserved variation in firm resources would cause EFI and carburetor patenting to have the same sign. These results suggest that new-technology-related inventive experience is important to the successful adaptation of new-technology-derived components for use in extant technology products.

To test Hypothesis 3—a prediction that general inventive experience may be applicable and improve hybrid performance—we estimate the effect of firm inventive experience with an indirectly related advanced technology on hybrid performance. The results reported in Regressions 1 through 4 Table 6 provide mixed evidence, mostly running against this hypothesis. In these regressions, the general pattern is that elevated levels of semiconductor patenting (*Hybrid*ChipPatentsMedium* and *Hybrid*ChipPatentsHigh*,) are associated with *worse* performance of a hybrid carburetor, and elevated levels do not have a significant effect (i.e. they are indistinguishable from *Hybrid*ChipPatentsLow*, the omitted variable). Interpretation of these variables should be undertaken with care because the firm semiconductor patenting variables are characterized by a highly skewed distribution. Half of the carburetor firms in the sample did no patenting during the period of observation[8] (see Table 5 for descriptions). The most prolific patenter, Hitachi, had ten times the (citation-weighted) semiconductor patenting activity of its next closest competitor. So for a firm to move from *ChipPatentsLow* to *ChipPatentsHigh* would represent an unprecedented and not-inconsequential two-orders-of-magnitude increase in patenting activity. With that caveat, it appears that a move from low to medium semiconductor patenting (*Hybrid*ChipPatentsLow* to *Hybrid*ChipPatentsMedium*) leads to a diminution of between 1.7 and 2.4 MPG for an average hybrid carburetor in Regressions 1 though 4. A move from low to high semiconductor patenting (*Hybrid*ChipPatentsLow to Hybrid*ChipPatentsHigh*) has a significantly negative effect in Regression 1 that disappears with the addition of fixed effects in Regressions 2 through 4. Most theoretically interesting is the notion that inventive experience with indirectly related advanced technologies is not enough to drive performance improvement in a hybrid. In other words, a general technological

[8] The citation-weighted measure for a patent that receives no citations is given a value of 1 – essentially getting credit for citing itself. Therefore, a value of 0 indicates a complete lack of patents by the firm.

orientation towards new and high technologies is not enough – a connection between the functions of the old and the new is required in order for experience to have a meaningful impact on the hybrid's performance.

In Hypothesis 4, we predict that a firm's superior hybrid performance could create learning that leads to superior subsequent performance in the future technical generation—a spillforward effect. To test for potential spillforwards, we create a series of variables *HybridPerf* and *StandardPerf* to measure the effect of a manufacturer's hybrid carburetor performance on the average annual over- or under-performance of a firm's EFI offerings relative to the expected average performance. We regress the MPG of EFI-equipped car models on these variables and on a set of controls identical to those found in Regressions 1-4. In Regressions 6 and 7, a firm's previous over-performance in hybrids predicts improved performance in its EFI offerings two and three years later (ie *HybridPerfLag2* and *HybridPerfLag3* are positive and significant)[9]. In Regression 6, the estimates suggest that over-performance of 1 MPG in a carburetor firm's fleet of hybrid offerings will result, two years later, in an increase of .243 MPG in a firm's EFI offerings. Over- and under-performance in hybrid carburetors does not seem to have a short-term effect (ie *HybridPerfLag1* is not significant), and its effect is attenuated with time (ie *HybridPerfLag4* is not significant). A firm's over-performance in standard carburetors (StandardPerf) does not significantly help or hurt subsequent EFI performance for any range of time. These results provide support for H4. Although we explore these results in one industry, we would point to qualitative examples in related industries that suggest the potential generalizability of the effect.

These are surprising results when considered in the context of previous research on incumbents and inertia which qualitatively implies that efforts focused on extant technology impede a firm's ability to perform in the new generation (Utterback 1996). These results seem to suggest that, at least in this setting, it is not performance in the old technology that matters for success or failure following the transition—rather it is the learning that occurs during hybrid stage that matters most to performance in the future generation. This finding is supported by the observation that in the sample of incumbents manufacturing carburetors, that the incumbents who developed the highest performing hybrids survived for five years or more after the EFI

[9] It should be noted that this sample is significantly reduced from the previous sample because it includes only those car models that contain EFI systems supplied by former carburetor companies. In other words, products from de novo EFI entrants are not included, and neither are (the nonexistent) products from carburetor firms that eventually failed during the technology transition.

technological discontinuity (~50% of the population) whereas those incumbents who developed the lowest performing hybrids (or did not develop hybrids) either failed during or shortly after the EFI discontinuity.

DISCUSSION

Within the boundary conditions outlined, our results suggest that inter-generational hybrids can play an important role in organization adaptation and the progression of a technological discontinuity. In particular, we investigated the types of knowledge that may contribute to a high-performing inter-generational hybrid and found that inventive knowledge in the incumbent technology had a positive but insignificant effect on capturing spillback benefits whereas inventive knowledge in the new technology had a positive and significant effect on capturing spillback benefits. Our interpretation of this result is that a base level of inventive knowledge in the incumbent technology (possessed by most incumbents) is necessary as a grafting point for the new technology but only inventive knowledge in the new technology actually led to capturing spillback benefits. These results are some of the first pieces of evidence, of which we are aware, of how different knowledge types contribute to inter-generational hybrids and spillback benefits.

Our work also contributes to the work on organization adaptation to technology discontinuities (Adner and Kapoor 2012; Eggers 2012; Henderson and Clark 1990; Tripsas and Gavetti 2000; Tushman and Anderson 1986). Prior work has observed inter-generational hybrids but has viewed them both as organizational dysfunctions and as learning opportunities (Taylor 2010; Tripsas 1997a). This work, although constrained to observation of a single industry, suggests that an inter-generational hybrid can serve as a real option on learning: allowing an organization to learn about the future today including potentially product and timing knowledge about the technology discontinuity that helps in adaptation. We found initial evidence of these positive outcomes, in the form of increased organizational survival and spillforward benefits: creating higher-performing hybrids increased the ability of incumbents to develop high-performing technologies in the future generation. Although in hindsight such discontinuities are often perceived as short, punctuated equilibriums, in the moment technology discontinuities are often lengthy, uncertain periods. Inter-generational hybrids may help organizations to effectively span this uncertainty without making the mistake of leaping too early, leaping too late, or ignoring the threat altogether.

Lastly, our work contributes to the work on technology strategy that has begun to explore the forces that shape technological evolution and organization response (Agarwal and Bayus 2002; Agarwal and Tripsas 2011). Work has begun to more fully explore the evolution of technology discontinuities, both in terms of the many forces shaping the emergence of new technologies and the significant substitution uncertainty constraining incumbent responses{Ansari, 2009 #1520}{Adner, 2012 #1477}. This work contributes a more nuanced view on how organizations manage the long period of uncertainty during a potential discontinuity and how the actions of these organizations may reshape the emergence of the new technology paradigm.

Clearly significant theoretical and empirical work is needed to more fully develop the idea of inter-generational hybrids. First, the boundary conditions that allow for the development of inter-generational hybrid needs greater definition. Products that have modular components that can be grafted onto existing architectures, such as the carburetors grafting electronic controls or sailing ships grafting steam engines, are the most likely candidates for inter-generational hybrids. Products that have substitutable architectures, such as tablets based on Microsoft operating architecture, may also be candidates for inter-generational hybrids but occurring less frequently with potentially lower spillback benefits than products with modular components. By contrast, innovations that are process-based or rely heavily on complex or expensive processes may be the least likely to have or benefit from an inter-generational recombination. For example, in Eggers (Eggers 2012) study of the flat-panel industry, which relies heavily on manufacturing process, he observed no evidence of inter-generational hybrids but instead a technology contest between two replacement technologies. The reason may be that the knowledge of a "hybrid" process, once blended, results not in knowledge of both the old and new technologies but of a third, different, blended technology (much like a mule blends a donkey and horse) that may require significant investment but not actually produce learning about the new technology.

Second, the conditions under which an inter-generational hybrid results in a temporary technology versus an enduring technology deserves further development. Some inter-generational hybrids come and go, such as the hybrid carburetor or gas light, but others have enduring value, such as the digital SLR camera. Whether a hybrid acts as temporary stepping stone or enduring new technology depends on one of several factors. First, if components have non-substitutable value, such as the reflective lens of a digital SLR camera, then inter-generational hybrid will be more likely to endure. Second, if customers have non-substitutable preferences, then a hybrid may endure. For example, although not a hybrid, dot matrix printers have endured in some customers segments, such as repair shops, that prefer the impact printing of dot-matrix over laser jet printing (Adner and Snow 2010a, b). Third, hybrids may endure when they perform a unique, unfulfilled purpose not served by either the prior or later technology generations (e.g. the DSLR camera case)

Further development is also needed to understand the conditions under which inter-generational hybrids are effective stepping stones versus stumbling blocks versus exit options? The answer depends on one of several variables. One variable may be where innovation occurs at the product or system level. In cases where the technology discontinuity replaces a product but leaves the system intact, an inter-generational hybrid likely acts as a stepping stone, as was the case in the EFI industry. By contrast, if an innovation replaces a product and the larger ecosystem surrounding the product, an inter-generational hybrid may delay a technology discontinuity as suggested by prior work (Furr and Snow 2012) but may not be sufficient as a stepping stone. For example, when the gas lighting industry borrowed the filament from electric lighting, the inter-generational hybrid increased the efficiency of gas lighting five times. This spillback benefit severely delayed the transition to electric lighting and probably would have bankrupted Thomas Edison if he had not been so well-funded (it took 12 years for Edison to turn a profit) (Utterback 1996). However, to be successful in electric lighting required not just filaments but in the broader system, including high-power generators, low-cost copper wiring, and so forth. Creating a hybrid did not help the gas companies innovate in the larger system but it did buy them sufficient time to profitably exit to the adjacent heating and power industries. Therefore, when a technology discontinuity disrupts an innovation system rather than a product, an inter-generational hybrid may defer the technology discontinuity providing time for incumbents to find alternate paths but the hybrid may not generate sufficient learning to survive in the next technology generation.

Another variable affecting the value of inter-generational hybrids as stepping stones in a technology discontinuity may be the timing of the hybrid. Technology discontinuities normally progress through periods of initially high uncertainty when a new technology poses a threat, followed by an era of ferment and experimentation, closing with a dominant design and a shift from product to process innovation (Anderson and Tushman 1990; Tushman and Anderson 1986). The evolution of a discontinuity may closely model this pattern or be distorted by institutional factors surrounding the emergence of a technology (Ansari and Garud 2009). In either case, the timing of an inter-generational hybrid relative to the progression of the technology affects whether the hybrid acts as a stepping stone, driven largely by the value of the learning generated by an inter-generational hybrid. Inter-generational hybrids developed after a dominant design has been established are likely to provide too little learning too late. For example, Blockbuster developed a hybrid brick-and-morter/online rental model only after Netflix had already established the dominant design and market dominance. At the other extreme, it may be possible that the value of developing an inter-generational hybrid too early may be limited by the incorporation of under-developed, inferior components at the very emergence technology threat or the decay of learning during a long technology emergence. For example, it appears that early attempts to develop hybrid autos suffered from grossly inferior battery and the length of the technology emergence. Perhaps the optimal learning approach would be to develop inter-generational hybrids not at the time of threat invention but at the time of threat emergence (i.e. commercialization experiments at market boundaries) or when relevant components or architectures are within reach of reasonable investments.

Conclusion

Although technology discontinuities represent a crucial event for innovation, organization, and strategy scholars alike, the micro-processes of technology transitions remain remarkably opaque. Recently research has begun to unpack the uncertainty, interactions, and processes that characterize the waves of creative destruction commonly associated with technology discontinuities (Adner and Kapoor 2012; Adner and Snow 2010b; Henderson 1995; Tushman and Anderson 1986). This paper makes several contributions to our understanding of the micro-processes of innovation, recombination, and organizational adaptation to the disruption that characterizes technology discontinuities. We suggest that the topic of hybrids, particularly inter-generational hybrids deserves further development as a source of innovation and an adaptation strategy.

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Figure 1. Intra-Generational versus Inter-Generational Knowledge Recombination

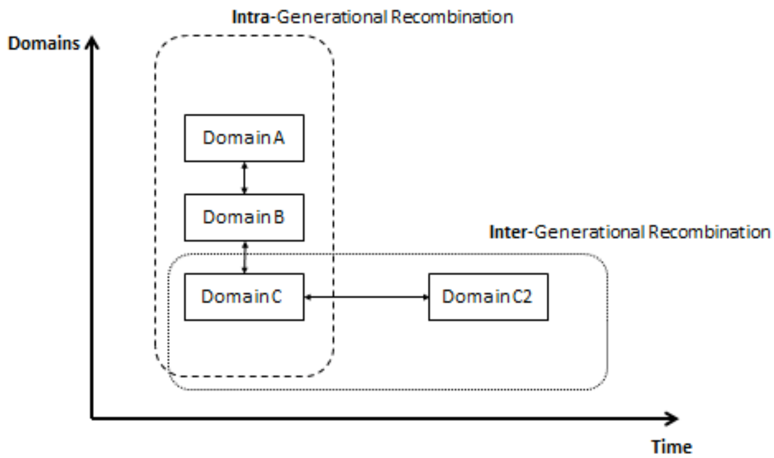

Figure 2. Knowledge Types and Recombination

	Core Knowledge	Integrative Knowledge
Inventive Knowledge	Inventive knowledge and capabilities in core domain Ex: Inventive capabilities in cancer medicines	Inventive knowledge and capabilities across domains Ex: Inventive capabilities in cancer medicines, cardio medicines, and medical devices
Operational Knowledge	Operational knowledge and capabilities in core domain Ex: Manufacturing knowledge in cancer medicines	Inventive knowledge and capabilities in core domain Ex: Manufacturing knowledge for small and large molecule medicines and medical devices

Figure 3. Representation of Spillback and Spillforward

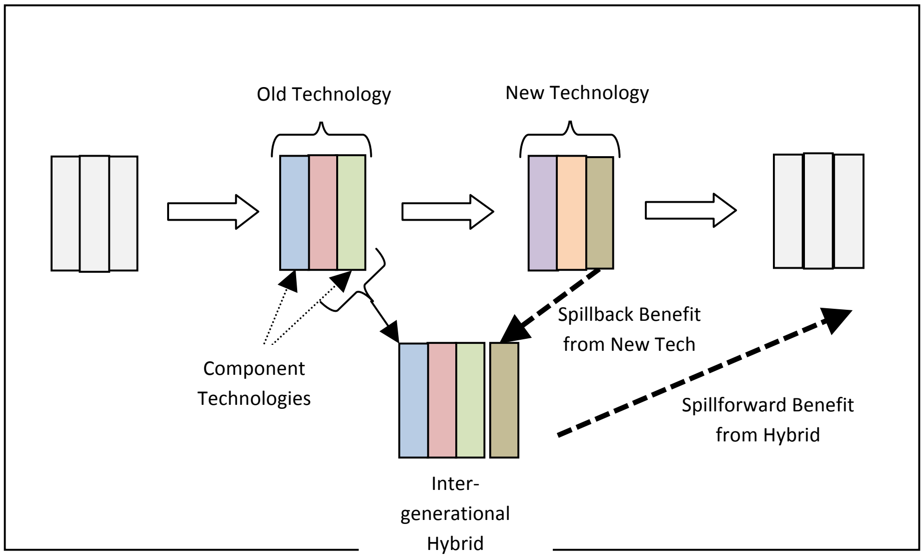

Table 1: Automobile Model Carburetor Observations by Carburetor Manufacturer

Carburetor Manufacturer	N in Manuals & in EPA Data	Percent
Aisan	259	8.6
Carter / ACF	750	24.8
Ford / Motorcraft	129	4.3
Hitachi	321	10.6
Holley / Colt	94	3.1
Weber	215	7.1
Keihin	140	4.6
Mikuni	205	6.8
Nikki	6	0.2
GM / Rochester	907	30.0
Total	3,026	100.0

Table 2: Automobile Model Observations by Model Year

Model Year	N in EPA Data	N in EPA & in Patent Data
1979	438	228
1980	564	370
1981	542	415
1982	633	480
1983	637	453
1984	378	279
1985	448	330
1986	322	217
1987	207	140
1988	96	64
1989	59	31
1990	24	12
1991	15	3
1992	11	4
Total	4374	3026

Table 3: Summary statistics

Variable	Mean	Std. Dev.
Dependent variable		
MPG	23.44	7.66
Independent variables		
(1) *CarbPatents*	53.1	40.4
(2) *EFIPatents*	17.5	25.1
(3) *ChipPatents*	149.7	391.5
(4) *Electronics*	0.41	
(5) *Tons*	1.80	0.45
(6) *Liters*	3.55	1.55
(7) *Autotrans*	0.51	
(8) *Horsepower*	114.0	

Table 4. Pairwise correlation matrix of independent variables

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
(1)	1.00							
(2)	0.31	1.00						
(3)	0.08	0.26	1.00					
(4)	-0.22	0.17	0.13	1.00				
(5)	0.36	0.16	-0.27	-0.23	1.00			
(6)	0.42	0.11	-0.29	-0.20	0.91	1.00		
(7)	0.17	0.09	-0.13	0.01	0.25	0.29	1.00	
(8)	0.40	0.23	-0.26	-0.17	0.83	0.90	0.28	1.00

Note: Variable numbers correspond to Table 3 variable numbers

Table 5: Citation-Weighted Patents by Carburetor Manufacturer and Category, Summed Over Years

Carburetor Manufacturer	Carburetor Category	EFI Category	Semiconductor Category
Aisan	358	119	131
Carter / ACF	306	0	0
Ford / Motorcraft	549	125	2406
Hitachi	662	542	25,751
Holley / Colt	211	78	0
Weber	117	114	6
Keihin	3	0	0
Mikuni	111	21	0
Nikki	0	0	0
GM / Rochester	860†	860	1780

1978-1992 annual counts summed. Annual counts include citation weighted patents in five-year window of interest. †GM's EFI patent citations coincidentally sum to the same number as do its carburetor patents.

Table 6: OLS: Inventive Activity's Effect on MPG of Hybrid and Standard Carburetors

Dep. Var.: MPG	(1)	(2)	(3)	(4)
Hybrid	211.1	111.9	2.154*	1.965**
	(176.4)	(186.6)	(1.012)	(0.721)
CarbPatentsMedium	0.991**	1.760**	1.185**	1.670**
	(0.196)	(0.231)	(0.250)	(0.227)
Hybrid*CarbPatentsMedium	-0.308	-0.495	-0.153	-1.295**
	(0.323)	(0.365)	(0.379)	(0.362)
CarbPatentsHigh	2.044**	1.499*	1.400*	1.752*
	(0.620)	(0.605)	(0.640)	(0.747)
Hybrid*CarbPatentsHigh	0.288	0.489	0.352	-1.281
	(0.940)	(0.931)	(1.011)	(0.997)
EFIPatentsMedium	0.0158	-0.522+	-1.036**	-1.424**
	(0.289)	(0.273)	(0.285)	(0.316)
Hybrid*EFIPatentsMedium	0.505	0.123	1.223+	2.516**
	(0.629)	(0.653)	(0.708)	(0.729)
EFIPatentsHigh	0.204	-1.430*	-1.274	-2.604**
	(0.598)	(0.632)	(0.792)	(0.834)
Hybrid*EFIPatentsHigh	1.865*	1.514*	2.045*	3.620**
	(0.758)	(0.696)	(0.812)	(1.054)
ChipPatentsMedium	0.0249	0.970	0.535	0
	(0.555)	(0.914)	(1.015)	(0)
Hybrid*ChipPatentsMedium	-2.378**	-1.698**	-2.413**	-2.296*
	(0.660)	(0.579)	(0.611)	(0.963)
ChipPatentsHigh	0.680*	0	0	-2.166*
	(0.320)	(0)	(0)	(1.062)
Hybrid*ChipPatentsHigh	-0.895+	-0.486	-0.792	-0.0512
	(0.523)	(0.535)	(0.538)	(0.499)
Tons	-10.97**	-9.819**	-9.809**	-8.855**
	(0.390)	(0.340)	(0.329)	(0.389)
Liters	0.00465	0.484**	0.425**	0.489**
	(0.153)	(0.158)	(0.155)	(0.157)
Autotrans	-1.374**	-1.339**	-1.382**	-2.021**
	(0.106)	(0.101)	(0.102)	(0.0975)
Horsepower	-0.0508**	-0.0604**	-0.0580**	-0.0453**
	(0.00471)	(0.00486)	(0.00480)	(0.00447)
ModelYear	0.656*	0.693*		
	(0.239)	(0.243)		
Constant	-1,253**	-1,329**	42.42**	38.73**
	(123.0)	(115.6)	(0.557)	(0.727)
Fixed Effects	-	Carbco	Carbco Model Year	Carbco x CarClass Model Year
Observations	3025	3025	3025	3025
R-squared	0.835	0.613	0.630	0.554

Robust standard errors in parentheses are clustered by carburetor firm;
+ significant at 10%; * significant at 5%; ** significant at 1%.

Table 7: OLS: Firm Performance in Hybrid and Standard Carburetor MPG and its Effect on EFI MPG

Dep. Var.: MPG	(5)	(6)	(7)	(8)
HybridPerfLag1	0.027			
	(0.069)			
StandardPerfLag1	0.042			
	(0.185)			
HybridPerfLag2		0.243**		
		(0.106)		
StandardPerfLag2		-0.192		
		(0.176)		
HybridPerfLag3			0.167**	
			(0.072)	
StandardPerfLag3			-0.142	
			(0.116)	
HybridPerfLag4				-0.110
				(0.090)
StandardPerfLag4				-0.202
				(0.321)
Tons	-9.699***	-9.542***	-8.858***	-8.020***
	(2.318)	(2.135)	(1.895)	(1.528)
Liters	0.118	0.126	0.130	0.0952
	(0.451)	(0.446)	(0.474)	(0.410)
Autotrans	-1.080**	-1.077**	-1.044**	-1.011**
	(0.342)	(0.339)	(0.338)	(0.329)
Horsepower	-0.0460***	-0.0458***	-0.0473***	-0.0466***
	(0.006)	(0.006)	(0.007)	(0.007)
Constant	46.10***	50.33***	48.88***	45.19***
	(4.106)	(3.264)	(2.857)	(2.357)
Fixed Effects	Model Year	Model Year	Model Year	Model Year
	Carbco x CarClass	Carbco x CarClass	Carbco x CarClass	Carbco x CarClass
Observations	1,379	1,353	1,288	1,203
R-squared	0.598	0.602	0.595	0.614

Robust standard errors in parentheses are clustered by Caburetor / EFI firm;
*** p<0.01, ** p<0.05, * p<0.1