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COMPLEMENTARY ASSETS AS PIPES AND PRISMS: INNOVATION INCENTIVES AND TRAJECTORY CHOICES

BRIAN WU,[1] ZHIXI WAN,[2] and DANIEL A. LEVINTHAL[3]*
[1] *Stephen M. Ross School of Business, University of Michigan, Ann Arbor, Michigan, U.S.A.*
[2] *College of Business, University of Illinois at Urbana-Champaign, Champaign, Illinois, U.S.A.*
[3] *Wharton School, University of Pennsylvania, Philadelphia, Pennsylvania, U.S.A.*

The issue of the failure of incumbent firms in the face of radical technical change has been a central question in the technology strategy domain for some time. We add to prior contributions by highlighting the role a firm's existing set of complementary assets have in influencing its investment in alternative technological trajectories. We develop an analytical model that considers firm heterogeneity with respect to both technological trajectories and complementary assets. Complementary assets play a dual role in incumbents' investment behavior toward radical technological change: they are not only resources (pipes) that can buffer firms from technology change, but also prisms through which firms view those changes, influencing both the magnitude of resources that should be invested and the trajectory to which these resources should be directed.

INTRODUCTION

A long-standing interest in the technology strategy domain has been the question of the failure of incumbent firms in the face of radical technical change (Christensen, 1997; Henderson and Clark, 1990; Tushman and Anderson, 1986). In explaining such failure, early work within economics, such as Arrow (1962) and Reinganum (1983), stressed the incentives established firms face with respect to innovations that might replace their existing products or services. The strategy literature, such as Tushman and Anderson (1986), and work on evolutionary economics, such as Dosi (1982) and Nelson and Winter (1982), emphasized the distinct capabilities that alternative technologies may require.

An innovation is radical in the economic sense if the new technology is a preferred substitute for the old technology (Arrow, 1962; Reinganum, 1983); for such innovations, the incumbent's investment in innovation will cannibalize its existing products.[1] The incumbent's marginal benefit of investment is lower than that of the entrant and hence it will have less incentive to invest than the entrant. Thus, the economics literature explicitly suggests that the incumbent failure stems from an underinvestment in radical technologies. An innovation is viewed as radical in the organizational sense

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*Correspondence to: Daniel A. Levinthal, Wharton School, University of Pennsylvania, 3209 Steinberg-Dietrich Hall, Philadelphia, PA 19104–6370, U.S.A. E-mail: dlev@wharton.upenn.edu

[1] Germane to the current work, Dew, Goldfarb, and Sarasvathy (2006) extend the Arrow (1962) and Reinganum (1983) analyses to include the effect of complementary assets on an incumbent's incentives in a patent race.

if the innovation is competence destroying with respect to a firm's technical capabilities (Tushman and Anderson, 1986). With their existing capabilities rendered obsolete, incumbent firms are less likely to introduce radical innovations compared to new entrants equipped with the relevant technical capabilities (Tushman and Anderson, 1986). Consistent with this implication, Henderson shows that 'incumbent firms appear to have rationally anticipated less productive research efforts when they invested in innovation that was radical in the organizational sense, and thus to have invested no more than entrants' (Henderson, 1993: 264). That is, the destruction of capabilities is likely to lead to a reduction in investment in the associated new technologies. In this explanation, incumbent firms' lower investment in radical innovations is not the cause of incumbent failure; rather, both lower investments and incumbent failure are driven by the obsolescence of underlying capabilities.

Contrary to the association between lower investments and incumbent failure, however, some in-depth case studies point out a puzzling divergence: incumbent firms often invest significant amounts in radical innovations, but develop inferior versions of the new technology (Rosenbloom, 2000; Tripsas, 1997; Tripsas and Gavetti, 2000). Tripsas (1997) shows that a lack of investment in R&D was not responsible for incumbent failure within the typesetter industry, which went through three generations of radical transformations. Incumbents actually invested heavily in the new product generations: 'qualitative data from interviews with both management and development engineers indicate that the level of investment by incumbents was at least equivalent to that of new entrants' (Tripsas, 1997: 130). However, the technical performance of products developed by incumbents during each new technology period was inferior to the performance of the entrant's products. Relatedly, Tripsas and Gavetti (2000) show that Polaroid committed substantial investments to digital imaging technologies when such technologies first emerged as a potential threat to its instant camera business: 'An electronic imaging group was formed in 1981, and as part of this effort work began on a microelectronics laboratory. The microelectronics laboratory opened up in 1986 after a capital investment of about $30 million, and with an operating budget of about $10 million/year. By 1989, 42 percent of [Polaroid's] R&D dollars were devoted to exploring a broad range of digital imaging technologies' (Tripsas and Gavetti, 2000: 1152). Despite such significant efforts, Polaroid declared bankruptcy in 2001. Rosenbloom (2000) shows that National Cash Register Company (NCR) was among the pioneers seeking to make a transition to electronics from mechanical cash registers. NCR began to engage in in-house electronics research activities as early as 1938 and entered the computer industry in 1953 by acquiring Computer Research Corporation (CRC), one of the first computer companies. While NCR eventually survived the technological change after decades of restructuring, it encountered a deep crisis in the early stages of this transition.

This gap between the theoretical literature and empirical observations is further illustrated by Kodak's investment behavior vis-à-vis digital photography (Benner, 2010; Benner and Tripsas, 2012). Digital photography appears to represent a radical technological change in both an economic and organizational sense. First, from an economic perspective, digital imaging can displace traditional film-based imaging. As Kodak entered the digital imaging field, it had to cannibalize its own traditional film sales. In contrast, the entrants from the computer and consumer electronics industries, such as HP and Sony, did not face the same problem. Thus, other things being equal, this cannibalization effect should have decreased Kodak's incentive to invest in the digital imaging field.

Perhaps a more fundamental factor in determining Kodak's investment behavior, however, is the shift away from the chemistry-based technology domain of silver halide film to the electronic-based digital technology domain of digital cameras. R&D initiatives along the new technology domain rendered obsolete the skills and knowledge that Kodak accumulated in the chemistry-based domain. In contrast, new entrants, including both new ventures and *de alio* entrants coming from electronic and computer industries, had a capability set consonant with the new technology domain. Thus, existing theories of both economic substitutes and competence-destroying change would predict that Kodak would lag behind in investing in digital photography.

However, in spite of these considerations, Kodak made aggressive investment very early on in digital (Benner, 2010) and, indeed, invented the first digital camera in 1975. More generally, Kodak had one of the highest patenting rates in digital technology (Benner and Tripsas, 2012) and by the early 1990s, 40 to 50 percent of Kodak's patents were already directed at digital.[2] Despite these early, enormous efforts, Kodak did not achieve commercial and technical success in the digital camera market. Indeed, Kodak filed for bankruptcy protection in January 2012.

One explanation for this paradox is agency behavior: managers in incumbent firms may squander their retained earnings on new technologies in which they should not have invested in an attempt to sustain ultimately unsustainable competitive positions. As a consequence, these incumbents may spend enormous amounts of capital on such technologies without obtaining adequate returns for their shareholders. From this perspective, such incumbent firms would better serve their shareholders by returning cash via dividends or share buybacks (Jensen, 1993). We do not disagree with this possibility. In this study, however, we ask whether there is an economic rationale for incumbents' substantial investments in radical innovations, even in a setting in which these investments yield little in the way of competitive success. By doing so, we believe we contribute to a more complete understanding of the various mechanisms underlying incumbent firm strategic reorientation processes (Agarwal and Helfat, 2009).

A PERSPECTIVE ON COMPLEMENTARY ASSETS AND TECHNOLOGICAL TRAJECTORIES

Theoretical basis

To address the puzzling divergence between investment efforts and innovation outcome, we suggest that it is important to examine not only the impact of a firm's existing capabilities on the magnitude of its investments in new technologies, but also the qualitative nature of those investments and, in particular, the specific technological trajectories the firm pursues. The direction of technological change is a central element in Christensen's (1997) argument that established firms pursue technological trajectories that are consonant with the firms' existing consumers. Christensen's (1997) important contribution pointed to the critical role of firms' resource allocation processes and to the strong claim that existing customers and market segments served might have on such processes. He argues that incumbent disk drive manufacturers did not lack in resource commitments to research and new product development or in underlying capabilities but, as a result of being embedded in a particular set of customer relations, were led to continue to invest in the established market segment and to largely ignore promising new technological approaches. In a similar vein, Adner and Snow (2010) highlight the role of demand heterogeneity on incumbent firms' strategic reorientation. The arrival of the new technology reveals heterogeneous consumer preferences on the demand side. While incumbent firms can choose to compete head-to-head with new entrants on the new technology, they may also choose to strategically retreat to a smaller niche where their old technologies are still applicable or possibly redeploy their old technologies to a new market. As a result, it might appear that the incumbent failed in the mainstream market, although it could have strategically chosen to exit the market or create a hybrid product, melding the old and new technology to serve the mainstream market.

This loose coupling between the magnitude of investment and commercial outcome is also addressed by recent work that takes a cognitive perspective on firms' technology strategies (Benner and Tripsas, 2012; Gilbert, 2005; Tripsas and Gavetti, 2000). Incumbent firms may choose to invest in radical innovations because they believe in the importance of major inventions, somewhat independent of their technological capabilities to pursue these innovations. For instance, Polaroid decided to invest in digital innovation, not because it is similar to instant photography in terms of capability requirements, but because digital innovation was viewed as another 'major invention' like instant photography (Tripsas and Gavetti, 2000) and consistent with the firm's, and in particular Edwin Land's (Polaroid cofounder and president) sense of identity as an 'innovator.' In general, cognitive frames, often formed in incumbents' antecedent competitive contexts, may work as road maps in the face of high uncertainty during periods of technological discontinuity (Benner and Tripsas, 2012). However, such beliefs can also hinder the commercialization of the research output if

[2] This figure is based on Kodak's patent data from the NBER Patent Data Project (https://sites.google.com/site/patentdataproject/Home/downloads) and uses the digital camera patent classes defined by Benner and Tripsas (2012).

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the business model underlying commercialization conflicts with the firm's prior belief, such as the case of Polaroid's effort to impose the razor/razor blade business model on the commercialization of the digital camera (Tripsas and Gavetti, 2000). Such a cognitive bias may manifest itself via the introduction of a hybrid product to the market, which melds elements of the old product technology even though consumers may prefer a pure play new product unencumbered by this prior history.

The explanation put forth here follows in the spirit of these explanations, examining both the magnitude and direction (technological trajectory) of an established firm's investment in new technologies in the face of possible technological change and the threat of new entrants. We offer a supplemental perspective based on forward-looking rational calculations on the part of firms and incorporating a fundamental asymmetry between established incumbent enterprises and new entrants. Clearly, as early arguments by Dosi (1982) and Tushman and Anderson (1986) suggest, incumbents and entrants may differ in their technological capabilities, with incumbent firms developing distinct technological capabilities along specific technological trajectories. However, even if one puts this factor aside, there is another basis of asymmetry, which is that established firms are likely to have an array of complementary assets in manufacturing, distribution, marketing and the like (Teece, 1986). While Teece points to the important role that complementary assets have on the ability of firms to appropriate the returns to innovative efforts, Mitchell (1989) and Tripsas (1997) demonstrate the importance of complementary assets in buffering incumbent firms from technological transitions. Perhaps because the original motivation for considering complementary assets was the issue of an innovator's ability to appropriate value from R&D investments conditional on a successful R&D outcome (Teece, 1986), the previous literature on complementary assets tends to focus on the effect of complementary assets on the *ex post* performance of incumbent firms (Hill and Rothaermel, 2003).

We wish to build on these important prior contributions regarding the role of complementary assets and examine the *ex ante* investment incentives created by the presence (or absence) of complementary assets. In particular, we examine both how a firm's choice of technological trajectory and how its level of investment along the chosen trajectory may be influenced by the magnitude of its complementary assets. Incumbent firms may choose technological trajectories that are arguably less promising, but comprise technological approaches that are compatible with, and leverage, its existing array of complementary assets. This observation suggests a further refinement in what is meant by a 'radical' technological change. In this regard, a change is viewed as radical if it disrupts the relation between the firm's existing set of complementary assets and the new technological trajectory. We examine the conditions under which a firm's complementary assets may cause it to choose to invest in what is viewed *a priori* as an inferior technology. Further, we consider the competitive consequences of the choice of technological trajectory and the magnitude of investment on the part of an established and entrant firm in view of their differential levels of complementary assets.

Complementary assets and trajectory choices

The prototypical setting one might imagine is an established firm with a substantial stock of complementary assets (e.g., substantial downstream resources with regard to distribution and brand name), but having its old technical basis negated by the emergence of a radical technological change and facing a decision as to which technological trajectory along which to invest. We use the term 'technological trajectory' to connote the particular class of technologies the firm is building upon and the nature of the technological performance attributes it is attempting to enhance (Dosi, 1982). For simplicity, we consider two trajectories: a trajectory that may have lower inherent promise to be preferred by the market but allows the incumbent to leverage its existing complementary assets or a trajectory that has higher inherent promise but would diminish the value of its complementary assets. We term the former as a complement-preserving trajectory and the latter as a complement-disrupting trajectory. In contrast, potential entrants, lacking complementary assets, face no such trade-off and will favor the complement-disrupting approach. Our analysis recognizes that the link between investments, trajectory choices, and market outcomes is influenced by the presence of complementary

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assets. Central to this perspective is the heterogeneity along different dimensions of the firm's capabilities and the interdependence among them (Helfat, 1997; Mitchell, 1989; Sosa, 2009; Taylor and Helfat, 2009; Teece, 1986; Tripsas, 1997).

Specifically, complementary assets can have a dual role in affecting incumbents' R&D investment. On the one hand, complementary assets, if fungible, amplify returns on R&D investments for incumbent firms, thereby increasing incumbent firms' economic incentive to invest in the new technical domain. Specifically, given the same R&D efforts, a larger stock of complementary assets allows a firm to appropriate more of the returns from its R&D investments (Teece 1986, Arora, Fosfuri, and Gambardella, 2001; Girotra, Terwiesch, and Ulrich, 2007). This implies a higher marginal benefit from R&D investment and, thus, a higher investment incentive. The empirical findings of Mitchell (1989) and King and Tucci (2002) that experience in prior subfields is positively associated with a firm's likelihood of entering new, related subfields is consistent with this argument. Even more directly supportive of this argument is Helfat's (1997) work that indicates that firms are more likely to develop technologies that can utilize existing complementary technologies.

On the other hand, complementary assets may also bias incumbents' choice of technological trajectories. As Teece (1986) notes, complementary assets may be cospecialized to a specific technology and, therefore, complementary assets can be trajectory specific in the sense that they are valuable in conjunction with a certain trajectory but much less valuable in conjunction with others. Therefore, incumbents endowed with complementary assets may have an incentive to choose a technological trajectory along which they can leverage their complementary assets, even if such a trajectory has lower inherent promise to be preferred by the market.

Combining these two perspectives, we examine the dual role complementary assets play with respect to incumbents' investment behaviors toward radical technological change: complementary assets are not only resources—in the context of network ties Podolny (2001) refers to as 'pipes,' that can buffer firms from technology change—but are also 'prisms' through which they view those changes, in terms of both the magnitude of resources that should be invested and the trajectory to which these resources should be directed. When complementary assets are specific to a less promising technological trajectory, the incumbent is faced with a trade-off between fully leveraging its complementary assets and choosing a more promising technological trajectory.

To illustrate this trade-off, reconsider the case of NCR noted earlier. After NCR acquired an early leader in the computer industry (CRC), NCR integrated CRC's research activities in computer technology into the framework of NCR's 'overall product development program' to leverage NCR's extensive sales force—one type of complementary assets (Rosenbloom, 2000: 1087). The technological trajectory choice was also modified. 'The binary arithmetic and limited input–output (I/O) capabilities of the 102-A [a general purpose computer] were well suited to scientific use, but appeared to the people in Dayton [where NCR's headquarters is located] as obstacles to business application. As a senior engineer commented, 'when you talked about a binary machine, you scared our salesmen' (Rench, 1984: 26) . . . Under pressure from Dayton, CRC designed the 102-D, using decimal arithmetic . . . '(Rosenbloom, 2000: 1089).

Likewise, while Polaroid invested a significant amount in digital photography very early on, their digital efforts were ' . . . guided by a desire to eventually develop an instant digital camera/printer product termed 'PIF' for Printer In the Field . . . The 1984 Annual Report's Letter to shareholders stated, 'We believe that there is considerable potential in developing new hybrid imaging systems that combine instant photography and electronics' . . . Since the output was to be on instant film, [the PIF concept] leveraged the firm's strong film-manufacturing capabilities. It was also, however, consistent with the firmly held belief in a razor/blade model' (Tripsas and Gavetti, 2000: 1152).

Similarly, much of Kodak's early investment in digital photography derived from its attempt to leverage complementary assets accumulated around films, from film production to photo finishing. Kodak was able to design high-quality films using its film capabilities and manufacture them at a low cost based on mass production. Further, Kodak developed strong relationships with retailers by providing services and supplies to those with photofinishing facilities and wholesale services to those without processing facilities.

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In addition, Kodak built an extensive network of Kodak Express franchises.[3]

Photo CD and Advanced Photo System are two hybrid products embodying Kodak's 'film-based digital imaging strategy' (Eastman Kodak Company, 1991: 3) in the early 1990s.[4] After the image is captured with an analog camera, the Photo CD system allows photofinishers to scan consumers' 35 mm negatives to a digital format and store them on a compact disc (Benner, 2010). These images can be shown on TV through a special CD player or on a computer using a CD-ROM. Consumers can further edit the pictures, transfer them, and print them. The Advanced Photo System (APS) adds to the film a transparent magnetic coating, which can store data such as the level of brightness and the use of flash when the picture was taken. Such data can help photofinishers enhance the quality of the print (Cohen and Tripsas, 2012).

Ex ante, such a hybrid approach may be a rational choice given the uncertain technological path (e.g., the low home PC adoption rate and narrow Internet bandwidth at the time, which might limit the diffusion of digital cameras). By blending digital technologies with traditional film technology and processes, this approach leveraged Kodaks' film-based complementary assets. Consumers would still want to buy films, particularly when films still offered higher resolution than the digital images available at the time. In this way, Kodak was able to leverage its capabilities in film production. Using their relationships with retailers, Kodak was able to persuade many retailers to add the Photo CD system to their photofinishing facilities, offering digitization, editing, and additional features, such as printing greeting cards. The digital information stored through the APS system also allowed Kodak-related photofinishing facilities to produce higher-quality prints. The APS system also permitted Kodak to more effectively introduce self-service kiosks. With this approach, Kodak would still be able to make money from consumables like photo paper and services. This hybrid approach is in contrast to a pure digital approach, where pictures are taken through digital camera, do not need to be processed and printed out, and can be viewed on a computer and transmitted through the Internet. Such a pure digital approach would deprive Kodak of its film-based complementary assets and force Kodak to compete head-to-head with consumer electronics firms. Thus, a hybrid approach had appeal to Kodak, as it allowed the firm to try to retain its advantage along part of the value chain, while introducing some digital features to enhance the performance of the product and services it offered. At a minimum, such efforts might delay consumers' switch to digital and might even influence consumers' behavior in using digital products in the future by setting a new industry standard.

Ex post, however, hybrid products tended to look clumsy due to rapid technological advances. In particular, with the further development of the Internet, Internet bandwidth quickly reached a point where it was sufficiently high for image transmission. In addition, households widely adopt personal computers, the price of digital cameras dropped, and the quality of digital cameras improved. Ultimately, the convenience of taking and sharing pictures through products like smart phones and Facebook greatly reduced the need to print images.

In considering these examples, it is important to bear in mind that while the probability with which the technological trajectory chosen by the incumbents will ultimately be preferred by the market might have been lower than that for alternative technological trajectories, the probability was not zero (Furr and Snow, 2012). Should the chosen trajectory ultimately be preferred by the market, the incumbent would be better able to fully leverage its existing complementary assets and gain greater market success. Therefore, for a given range of complementary assets, it may be optimal for the incumbent to choose the less promising technological trajectory. Moreover, these complementary assets may provide an incentive for the incumbent to invest more than the entrant *ex ante*. *Ex post*, however, should the trajectory chosen by the incumbent prove to be an ineffective way to engage the market, either as a result of the limits of technical progress along the performance dimensions pursued by the firm or the market's valuation of those performance dimensions, the incumbent may experience an inferior market outcome under

[3] Kodak also has other complementary assets, such as distribution channels, to sell films. However, such complementary assets were fungible to the new technological trajectory, since digital cameras can be sold through many of the same channels. In an analysis of the model, we examine how our results are influenced by the degree of fungibility of complementary assets.

[4] We thank an anonymous reviewer for suggesting these aspects of Kodak's efforts.

certain conditions despite its higher investments. The incumbent firm bets on the trajectory that yields, in expectation, the greatest profits; however, due to the impact of its existing stock of complementary assets, this is a different calculation than choosing the technological trajectory that is most likely to prove promising. As a consequence, we should observe at times incumbent firms making what appear to be *ex post* bad 'bets.' The dual role of complementary assets can help explain situations such as Kodak's investment behavior and resulting market outcomes in digital photography. Kodak's stock of relevant complementary assets in the imaging industry created strong economic incentives to invest in the new technical domain. However, in order to leverage its complementary assets, Kodak chose a technological trajectory that engaged digital technology in a manner that facilitated the firm linking this new technology to its existing assets and ways of competing.[5]

Complementary assets are an asset to be leveraged, but at the same time, they bias a firm's strategic choices. As a result of this dual effect, firms may rationally invest large sums in technology efforts that yield a relatively modest rate of technical advance. The incumbent may invest heavily but achieve a lower likelihood of technical leadership than similar investments yield for new enterprises established to pursue these new technological opportunities. It is important to recognize that the incumbent may choose different technological trajectories and, therefore, it is critical to distinguish between the magnitude of the investment and its qualitative nature (i.e., the particular technological trajectory pursued). The ultimate consequences or outcomes that stem from such investments (relative distance from the technology frontier, product market success, and the like) will be a function of the firm's investments, technical capabilities, complementary assets, competitors' actions, and what emerges to constitute consumer preferences.

An important backdrop to these arguments is the degree of imperfection in the market for complementary assets and technology. To the degree that these markets do not function well, the entrant cannot gain access to complementary assets (e.g., through contracting) and the incumbent may not gain access to external technology (e.g., through licensing). It is likely to take time for the entrant to internally develop complementary assets because the adjustment costs of developing complementary assets in a short period of time are prohibitive (Dierickx and Cool, 1989; Pacheco-de-Almeida and Zemsky, 2007). Furthermore, as Teece (1986) argues, the market for complementary assets is imperfect, because such assets tend to be cospecialized or specialized to the firm, creating high transaction costs. In the absence of these properties, the competitive supply of complementary assets would cause the asymmetry between the incumbent and the entrant to disappear or certainly dissipate. An analogous set of issues holds for the markets for technology (Arrow, 1962; Nelson, 1959). How well markets for technology are able to function depends on a number of factors, including the nature of knowledge, intellectual property rights regime, and related institutions (Arora *et al.*, 2001; Dushnitsky, 2010; Dushnitsky and Lenox, 2005; Dushnitsky and Shaver, 2009; Elfenbein, 2007; Goldfarb, 2008). We discuss possible extensions that include such issues in the discussion section.

MODEL SETUP

We consider a stylized two-stage model to examine firms' investment decisions with respect to a radical technological change. While radical in the sense of one generation of a product supplanting another, the investment may be made along different technological trajectories that either preserve or disrupt a firm's existing complementary assets. We term the former type as complement-preserving trajectory and the latter type as complement-disrupting trajectory. In the first stage, an incumbent firm, denoted by I, chooses to invest along either of the two trajectories. Let $r \in \{0,1\}$ represent firm I's chosen trajectory, where 1 represents the complement-disrupting trajectory and 0 represents the complement-preserving trajectory. We assume the market's preferred trajectory, denoted by $t \in \{0,1\}$, is uncertain. We further let the complement-disrupting trajectory be more promising, i.e., $p = Prob(t = 1) > 0.5$. As a result,

[5] This argument, however, cannot explain the totality of Kodak's investments, as Kodak did make substantial early investments in charge-coupled device (CCD) image sensors for digital cameras. Kodak was an early market leader in this area and introduced the first 1 Megapixel CCD in 1986. Such investments are not fully consistent with the proposed argument, since CCDs can replace film as image sensors, thus representing a complement-disrupting technology.

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the incumbent faces a trade-off between choosing a less promising technological trajectory along which it can leverage its complementary assets and choosing a more promising technological trajectory along which it cannot fully leverage its complementary assets. Given the entrant E is assumed to lack complementary assets and the value of p is postulated to be greater than 0.5, the entrant finds it in its interest to invest in the complement-disrupting trajectory. In this stage, we assume firm I plays as a Stackelberg leader who chooses its trajectory r and its R&D investment level u_I before firm E chooses its R&D investment level u_E.[6]

Firm i's technological trajectory, R&D investment, and the market's preferred trajectory together determine the 'base utility' of its product, denoted by V_i. In particular, we assume the base utility for firm E's product is $V_E = \delta^{1-t} u_E$, $0 < \delta < 1$. Namely, while the base utility increases in its R&D investment, it is discounted by δ if there is a mismatch between its trajectory (i.e., the complement-disrupting trajectory) and the realized market-preferred trajectory. Similarly, if firm I chooses the complement-disrupting trajectory, we assume that $V_I = \delta^{1-t} u_I$. However, if firm I chooses the complement-preserving trajectory, we assume that $V_I = \delta^t A^{1-t} u_I$, where $A > 1$ represents firm I's complementary assets (the entrant's complementary assets are normalized as one). Thus, the critical asymmetry between the incumbent and the entrant is the incumbent's possession of complementary assets along the complement-preserving trajectory.[7] Specifically, firm I is assumed to have some complementary assets that may increase its product's base utility, but such complementary assets are trajectory specific—they can be leveraged only when the incumbent chooses the complement-preserving trajectory and the market prefers the complement-preserving trajectory. We make this assumption regarding the limited fungibility of complementary assets to highlight the central trade-off faced by the incumbent. At the end of the analysis section, we show the robustness of the model by allowing complementary assets to have some degree of fungibility and retain some value in the complement-disrupting trajectory. Table 1 summarizes the two firms' base utility functions under different scenarios.

In the second stage, the two firms engage in quantity competition in the market. They simultaneously and independently choose their production quantities. Let q_i denote firm i's product quantity. We consider a linear demand system where firm i's product price equals $V_i - \beta q_i - \gamma q_j$ with $\beta > \gamma > 0$ for $i \in \{I, E\}$ and $j \in \{I, E\}, j \neq i$. This linear demand curve can be derived by considering a representative consumer with utility given by $V(q_1 + q_2) = V_1 q_1 + V_2 q_2 - \frac{1}{2}\left(\beta q_1^2 + 2\gamma q_1 q_2 + \beta q_2^2\right)$ (Vives, 2001: 145) and, as a result, the intercept V_i in the linear demand curve can be interpreted as capturing the base utility of firm i's product defined above. A similar demand relationship has also been used by Sutton (1997: 58–59) in modeling the impact of R&D investment on product quality. We normalize both firms' marginal production costs to zero.[8]

Market competition equilibrium in the second stage

Given the firms' technological trajectories and R&D investment levels, we can specify their second-stage profit functions stemming from product market competition. Let $\Pi_i(V_I, V_E)$ denote the equilibrium second-stage profit of firm i given V_I and V_E. Intuitively, as firm i's product base

[6] Furthermore, we also examine a case where the entrant is the Stackelberg leader; our main results hold. We also examine the model using a Nash equilibrium, in which the firms move simultaneously. However, multiple Nash equilibria can exist, including mixed strategy equilibria, under a simultaneous move setting. Therefore, for simplicity we focus on the Stackelberg setting. While there is no direct correspondence between the particular solutions that characterize the Nash equilibrium and the Stackelberg game, the basic tensions and trade-offs at play are present in both. Finally, the fact that the same qualitative results emerge whether the incumbent or entrant is the leader or the follower in the Stackelberg game indicates the robustness of these properties.

[7] One could also explore the effect of asymmetry in their technological capabilities with respect to the different trajectories. If so, a natural assumption would be that the incumbent is less capable, perhaps as reflected in a lower marginal return to R&D investment than the entrant. Clearly, such a property would decrease the incumbent's incentive to invest. We wish to explore a, in some sense, stronger case, where the incumbent has no intrinsic disadvantage with respect to the complement-disrupting technological trajectory, but faces, as a result of its complementary assets, a different decision calculus than that of the entrant.

[8] Complementary assets can either increase quality (willingness to pay) or reduce marginal production cost. What matters is the wedge between willingness to pay and marginal production cost (Adner and Zemsky, 2006). For the sake of simplicity, we normalize marginal production cost to zero and focus on willingness to pay.

Table 1. The utility functions for entrant's and incumbent's products

Incumbent's choice : $r \in \{0,1\}$	Realized market preference: $t \in \{0,1\}$	Comments	Entrant's product quality V_E	Incumbent's product quality V_I	Generalization with fungible complementary assets
$r = 0$	$t = 0$	The incumbent chooses the complement-preserving trajectory and the complement-preserving trajectory is preferred by market. The incumbent can fully leverage complementary assets *A*, and its R&D effort is fully effective. However, the entrant suffers a discount δ in its R&D effort due to the mismatch of trajectories.	$V_E = \delta u_E$	$V_I = Au_I$	$V_I = Au_I$
$r = 0$	$t = 1$	The incumbent chooses the complement-preserving trajectory, but the market prefers the complement-disrupting trajectory. Therefore, the incumbent cannot leverage its complementary assets *A* and suffers a discount δ in its R&D effort due to the mismatch of trajectories. The entrant's R&D effort is fully effective.	$V_E = u_E$	$V_I = \delta u_I$	$V_I = \delta A^{\kappa_1} u_I$
$r = 1$	$t = 0$	The incumbent chooses the complement-disrupting trajectory, but the market prefers the complement-preserving trajectory. The incumbent cannot leverage its complementary assets *A*. Both the incumbent and the entrant suffer a discount δ in their R&D effort due to the mismatch of trajectories.	$V_E = \delta u_E$	$V_I = \delta u_I$	$V_I = \delta A^{\kappa_2} u_I$
$r = 1$	$t = 1$	The incumbent chooses the complement-disrupting trajectory, and the market prefers the complement-disrupting trajectory. Therefore, the incumbent cannot leverage its complementary assets *A*. The R&D effort for both incumbent and entrant is fully effective.	$V_E = u_E$	$V_I = u_I$	$V_I = A^{\kappa_2} u_I$

utility V_i increases, its demand increases and the competitor firm j's demand decreases; furthermore, if V_i far exceeds V_j, firm i can produce so much that firm j sees the market price even lower than its marginal production cost, in which case firm j finds it optimal not to produce at all. In particular, both firms choose positive production quantity if and only if $2\beta V_i - \gamma V_j > 0$ for both $i = I, E$ and, in such a case, the equilibrium production quantities and profits are given by $q_i = \frac{1}{4\beta^2 - \gamma^2}\left(2\beta V_i - \gamma V_j\right)$ and $\Pi_i\left(V_I, V_E\right) = \beta q_i^2$. However, if $2\beta V_i - \gamma V_j > 0$ holds for only one firm, for example, $i = I$, then only firm I produces and we have $q_I = \frac{1}{2\beta} V_I, q_E = 0, \Pi_I\left(V_I, V_E\right) = \beta q_I^2$, and $\Pi_E(V_I, V_E) = 0$. This is similarly true for $i = E$.

R&D investment equilibrium and incumbent trajectory choice in the first stage

Following the literature (Rosen, 1991; Sutton, 1997), we assume that the cost of achieving u_i, $C(u_i)$, is sufficiently convex such that all profit functions have an interior optimum.[9] Let $\Sigma_i^r\left(u_I, u_E\right)$ be firm i's expected total profit given u_I and u_E, if firm I chooses trajectory r. Thus, we have

$$\Sigma_i^1\left(u_I, u_E\right) = p\Pi_i\left(u_I, u_E\right) + (1-p)\,\Pi_i\left(\delta u_I, \delta u_E\right) - C\left(u_i\right) \quad (1)$$

$$\Sigma_i^0\left(u_I, u_E\right) = p\Pi_i\left(\delta u_I, u_E\right) + (1-p)\,\Pi_i\left(A u_I, \delta u_E\right) - C\left(u_i\right) \quad (2)$$

Conditional on firm I's trajectory choice r, let u_i^{r*} denote firm i's R&D investment in equilibrium. In particular, we have $u_I^{r*} = \arg\max_{u_I} \sum_I^r \left(u_I, u_E^r\left(u_I\right)\right)$, where $u_E^r\left(u_I\right) = \arg\max_{u_E} \sum_E^r\left(u_I, u_E\right)$ and $u_E^{r*} = u_E^r\left(u_I^{r*}\right)$. Let $\Sigma_i^{r*} \triangleq \Sigma_i^r\left(u_I^{r*}, u_E^{r*}\right)$ be firm i's equilibrium total profit given firm I's trajectory choice r and let q_i^{rt} be firm i's equilibrium production quantity given firm I's trajectory choice r and the market preference t. Firm i's equilibrium total profit Σ_i^{r*} is the expected value with respect to the uncertain market preference, given firm i's trajectory choice r . However, firm i's equilibrium production quantity q_i^{rt} is the realized value given both firm i's trajectory choice r and the realization of market preference t. In equilibrium, firm I chooses trajectory $r = 0$ over $r = 1$ if and only if $\Sigma_I^{0*} > \Sigma_I^{1*}$.

ANALYSIS

In this section, we address the central question we posed in the Introduction: why incumbent firms often invest significant amounts in radical innovations, but develop inferior versions of the new technology. We investigate when the two firms' trajectories differ, which firm invests more, and which firm leads the market in terms of achieving larger market share; in particular, we focus on how the answers to these questions depend on the size of the incumbent's complementary asset A, the mismatch discount factor δ, and the market preference probability p. It is important to note that the comparison in terms of *ex post* market outcome may be different than the comparison in terms of *ex ante* investment. Specifically, although the investment amount and market outcome have a one-to-one relationship when the two firms choose the same technological trajectory, such a relationship does not hold when they are likely to take different technological trajectories. With heterogeneous technological trajectories, an equal investment in R&D may not lead to an equal market outcome.

Firm behavior: trajectory choices, investment level, and market share

Proposition 1 shows that these comparisons can be characterized by different regions defined by three threshold values of the incumbent's complementary assets. Proposition 2 provides existence conditions for these regions.

Proposition 1: For any $0 \le \delta \le 1$, *there exist three thresholds*[10] $A^r(\delta) \le A^u(\delta) \le A^l(\delta)$ *such that*

[9] Technically, when $C(u_i)$ is convex and its second-order derivative is sufficiently large everywhere, each firm i's expected total profit is quasi-concave in u_i, and, thus, there exists a unique and finite investment level u_i that maximizes its expected total profit.

[10] The superscript 'r' refers to the threshold regarding the incumbent's trajectory choice 'r,' above which the incumbent chooses the complement-preserving trajectory. The superscript

i) if $1 < A < A^r(\delta)$, *firm I chooses the complement-disrupting trajectory r = 1 (i.e.,* $\Sigma_I^{0*} < \Sigma_I^{1*}$*), ii) if* $A^r(\delta) < A < A^u(\delta)$, *firm I chooses the complement-preserving trajectory r = 0 (i.e.,* $\Sigma_I^{0*} > \Sigma_I^{1*}$*) and invests less than firm E, iii) if* $A^u(\delta) < A < A^l(\delta)$, *firm I chooses the complement-preserving trajectory r = 0 (i.e.,* $\Sigma_I^{0*} > \Sigma_I^{1*}$*),invests more than firm E, but does not lead the market (i.e.,* $q_I^{01} < q_E^{01}$*) if the market prefers the complement-disrupting trajectory t = 1, iv) if* $A^l(\delta) < A$, *firm I chooses the complement-preserving trajectory r = 0, invests more than firm E and leads the market (i.e.,* $q_I^{01} > q_E^{01}$ *), even if the market prefers the complement-disrupting trajectory t = 1.*

Proposition 2: For any $0 \le \delta < 1$, *there exists* $0 < \overline{p}(\delta) < 1$ *such that* $A^r(\delta) > 1$ *when* $p > \overline{p}(\delta)$. *Further, there exists* $\overline{\delta} > 0$ *such that for all* $\delta < \overline{\delta}$, $A^u(\delta) < A^l(\delta)$.

Proof: See Appendix.

Proposition 1 shows that firm I's trajectory choice and investments depend on both the level of complementary assets and the penalty from technical mismatch. A higher level of complementary assets encourages the incumbent to choose the complement-preserving trajectory and encourages larger investment given its choice of the complement-preserving trajectory. Further, when we look at the choice of technological trajectory and investment level simultaneously, various interesting possibilities emerge. Specifically, by varying the degree of heterogeneity with regard to the stock of complementary assets and the penalty from technical mismatch, Proposition 1 characterizes distinct regimes with respect to choices of technological trajectory and product market outcomes. Table 2 summarizes these results. Figure 1 illustrates these regimes for the case where $p = 0.7$, $\beta = 1$ and $\gamma = 0.5$, where the vertical axis A captures the incumbent's higher complementary assets (recall the entrant's complementary assets are normalized as one), while the horizontal axis δ captures the penalty from the mismatch between its chosen trajectory and the realized market-preferred trajectory. In all the numeric analyses, we use the cost function $C(u_i) = (\max(u_i - 1, 0))^2$.[11]

'u' refers to the threshold regarding the comparison of the two firms' investment level 'u,' above which the incumbent invests more. The superscript 'l' refers to the threshold regarding the incumbent's market leadership, above which the incumbent leads in market share.

The dotted region in Figure 1

The dotted region corresponds to a setting in which the incumbent chooses the complement-disrupting trajectory and competes on the same basis as the entrant. In some cases, the incumbent has a modest set of complementary assets and therefore these complementary assets do not bias the incumbent away from the complement-disrupting technological trajectory. As a result, the incumbent is willing to give up its historical endowment and take on the complement-disrupting technological trajectory.

The gray region in Figure 1

The gray region corresponds to a setting in which the incumbent chooses the complement-preserving technological trajectory, invests less than the entrant, and experiences a lower market share if the market prefers the complement-disrupting technological trajectory. The lower technological development on the part of the established firm may not be the difficulty of altering organizational routines to fit with the new environment (Leonard-Barton, 1992; Nelson and Winter, 1982); the lower research productivity may well be the endogenous outcome of how the firm chooses to respond to the technological opportunities they face. Of course, if the market ends up preferring the complement-preserving technology, we may observe, *ex post*, that the incumbent invests less than the entrant but obtains a higher market share. Figure 1, however, conditions on that the market prefers the complement-disrupting trajectory and, in such a scenario, the value of complementary assets A does not matter. As a result, the incumbent can never have higher market share since its complementary assets are not effective.

The white region in Figure 1

The white region depicts a setting in which the incumbent chooses the complement-preserving

[11] This cost function is chosen solely for the ease of numeric study. It guarantees that the profit function is well behaved. Further, we can understand the 1 in this functional form as a normalization of the minimum investment required to enter and provide a product that achieves some minimum base utility level. Numeric results are similar if we use a different normalization value such as 0.5.

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Table 2. Variables and results

Notation	Definition
Nature	
$t \in \{0,1\}$	The market's preferred trajectory, where 1 represents the complement-disrupting technological trajectory and 0 represents the complement-preserving technological trajectory.
Exogenous parameters to be manipulated	
p	The probability the complement-disrupting trajectory is preferred by the market.
$A > 1$	Incumbent I's complementary asset (the entrant's complementary assets are normalized as one).
δ	The discount in a firm's R&D effort due to the mismatch between the firm's chosen trajectory and the market's preferred trajectory.
Exogenous parameters not to be manipulated	
β, γ	Degrees of price sensitivity and product substitution in the demand function at the second stage.
Investment decisions at the first stage, determined by p, A, δ defined above.	
$r \in \{0,1\}$	Incumbent I's chosen trajectory, where 1 represents the complement-disrupting technological trajectory and 0 represents the complement-preserving technological trajectory.
u_i	R&D investment level by firm i (i = incumbent I and entrant E).
Market outcomes at the second stage, determined by investment decisions at the first stage	
V_i	Firm i's (i = incumbent I and entrant E) product base utility, determined by the two firms' trajectory choice and R&D investment.
$\Pi_i(V_I, V_E)$	The equilibrium second-stage profit of firm i (i = incumbent I and entrant E) given V_I and V_E.
Thresholds that define regimes characterizing both investment decisions (r and u_i) and market outcomes $\Pi_i(V_I, V_E)$	
$A^r(\delta)$	The equal trajectory threshold (the upper bound of the dotted region). The superscript 'r' refers to the threshold regarding the incumbent's trajectory choice 'r,' above which the incumbent chooses the complement-preserving trajectory. The dotted region is where the incumbent chooses the complement-disrupting trajectory.
$A^u(\delta)$	The equal investment curve $A^u(\delta)$ (the boundary between the gray and the black region). The superscript 'u' refers to the threshold regarding the comparison of the two firms' investment level 'u,' above which the incumbent invests more. The gray region is where the incumbent chooses the complement-preserving trajectory, invests less, and has less market share. The black region is where the incumbent chooses the complement-preserving trajectory, invests more than the entrant, but has less market share.
$A^l(\delta)$	The equal market share curve $A^l(\delta)$ (the lower boundary of the white region). The superscript 'l' refers to the threshold regarding the incumbent's market leadership, above which the incumbent leads in market share. The white region is where the incumbent chooses the complement-preserving trajectory but nonetheless invests more than the entrant and leads in market share.
Robustness checks	
κ_1, κ_2	The degree to which complementary assets are trajectory specific. If the incumbent chooses the complement-preserving trajectory $r = 0$ but the market prefers the complement-disrupting trajectory $t = 1$, the incumbent's effective complementary assets becomes A^{κ_1}, where $0 \le \kappa_1 \le 1$. Similarly, if the incumbent chooses the complement-disrupting trajectory $r = 1$, the incumbent's effective complementary assets become A^{κ_2}, $0 \le \kappa_2 \le 1$, whether the market prefers the complement-preserving or the complement-disrupting trajectory.

trajectory but still 'wins' despite the fact that the market prefers the complement-disrupting trajectory. This setting represents a kind of 'lock-in' to an inferior technology, in that there is an inherent preference for the complement-disrupting technology (δ), but not with sufficient intensity relative to the incumbent's stock of complementary assets (A) to result in displacing the incumbent firm's market position.[12] This finding is akin to work on standards or platforms (Arthur, 1989; Shapiro and Varian, 1999; Zhu and Iansiti, 2012) which shows

[12] In Figures 1 and 4, due to the choice of parameter values, the white region hits the ceiling of the figures when the penalty from technical mismatch is very high (δ is close to zero). In fact, the white region exists even when δ is close to zero.

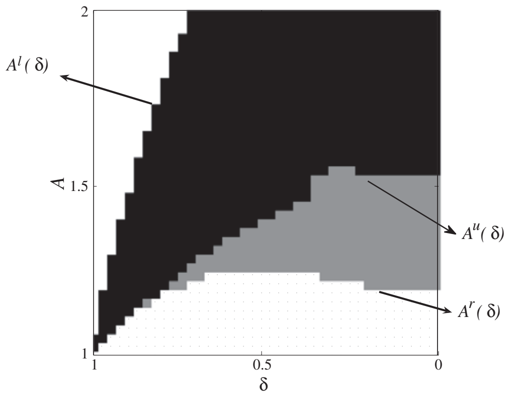

Figure 1. Illustration of Proposition 1 $p = 0.7, \beta = 1, \gamma = 0.5$. This figure is conditional on the case where the complement-disrupting trajectory is preferred by the market: (1) The white region is where the incumbent chooses the complement-preserving trajectory but nonetheless invests more than the entrant and leads in market share. (2) The black region is where the incumbent chooses the complement-preserving trajectory, invests more than the entrant, but has less market share. It is also the region highlighted by Proposition 2. (3) The gray region is where the incumbent chooses the complement-preserving trajectory, invests less, and has lower market share. (4) The dotted region is where the incumbent chooses the complement-disrupting trajectory and competes on the same basis as the entrant

that inherently inferior technologies may come to dominate as a result of early market presence and the presence of strong network externalities. In the work on standards, the lock-in stems from the direct effect of network externalities or the presence of complementary goods or service that enhance the value of the use of the dominant technology. Here, the complement is not a distinct good or service possibly provided by a third party, but an element of the focal firm's business system, possibly in manufacturing, distribution, or marketing.

If the incumbent has indeed amassed a sufficiently large stock of complementary assets, these complementary assets may create a sufficient incentive for the incumbent to invest significantly more than the entrant. In this case, even if the incumbent takes an inferior technological trajectory, the incumbent may still maintain a larger market share due to its large investment. Consider the engagement of newspaper firms in digital media as characterized by Gilbert (2005) and Kim (2011). Gilbert (2005) shows that while most newspapers invest significant financial resources in digital media, they continue to follow the traditional business models and try to leverage resources from the print media. Their newspaper sites often do not incorporate features such as online forums and search tools commonly available in new entrants. Kim (2011) shows that firms such as *The New York Times*, which have a large set of complementary assets (e.g., content, journalist team, social status), are more inclined to develop Web sites that create digital media in a manner similar to that of print media, while firms such as the *Denver Post*, which lack such complementary assets, are more likely to develop Web sites that are more characteristic of the technology of digital media. The look and feel of the two Web sites and the degree of interactive components seem consistent with this argument. In contrast, a new entrant, such as Slate or Yahoo, adopts a pure digital form with little reference to traditional print news.

Gilbert (2005) uses a cognition lens to explain this behavior. The perception of the new technology as a threat works as the catalyst of change and, thus, reduces resource rigidity. As such, firms may be willing to invest a large amount in financial resources and human resources. However, the perception of threat also increases threat rigidity, due to the reduction of information processing and the constriction of control. Threat rigidity, in turn, leads to routine rigidity where firms may integrate the new business with the parent company, reduce experimentation, and utilize their existing resources.

The black region in Figure 1

The black region corresponds to the puzzle we introduced in the beginning of the article; the incumbent chooses the complement-preserving trajectory, invests more, but achieves a lower market share than the entrant if the market prefers the complement-disrupting trajectory. It helps explain why an incumbent can fare poorly in the face of radical technological change despite its heavy investment. In our model, radical technological change is captured by the fact that, due to the emergence of a complement-disrupting technological trajectory, the entrant is not in a disadvantageous position vis-à-vis the incumbent in terms of technical capabilities; in that regard, the entrant can compete on the same basis as the incumbent. Furthermore, the incumbent has to choose between

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the complement-preserving and the complement-disrupting trajectory to pursue the radical technological change. Should the incumbent choose the complement-preserving trajectory, it would have an incentive to invest more than the entrant due to the existence of complementary assets, which can amplify the return from a given level of investment. However, the existence of complementary assets also makes it more attractive for the incumbent to choose the complement-preserving trajectory, as it can fully leverage complementary assets when the market prefers this trajectory. When the parameters are in the black region of Figure 1, these two forces generate this distinct regime. The prior examples of Kodak, Polaroid, and NCR all correspond to this regime. Thus, we suggest that these firms, despite their unfavorable outcomes, may have made rational investments that attempted to engage emerging technologies in ways that allowed them to leverage their existing complementary assets. Indeed, as Benner (2010) shows, stock analysts reacted quite favorably when Kodak invested in 'hybrid' products.

Proposition 1 lays out the overall distribution of various possible regions; however, it does not specify the conditions under which each region will occur. In particular, Proposition 1 consists of a set of weak inequalities. Proposition 2 characterizes when the distinct regions will, in fact, exist. Proposition 2 states that for the dotted region (where the incumbent chooses the complement-disrupting trajectory) to exist, the likelihood of the complement-disrupting trajectory being preferred by the market needs to be sufficiently large. In other words, it may be possible that the incumbent always chooses the complement-preserving trajectory even when the level of its complementary assets is very low (i.e., $A^r(\delta)$ approaches one from above). Similarly, Proposition 2 states that for the black region to exist, the penalty of technical mismatch needs to be sufficiently high (i.e., δ is sufficiently small).

Propositions 1 and 2 characterize a kind of path dependency, but it differs from the standard notion of path dependency, which generally suggests some behavioral mechanism that reinforces the firm's current pattern of action and investment. In our model, the incumbent is acting rationally and is forward looking. It is induced by its complementary assets to make its particular technical choice. The incumbent has the option to give up its complementary assets and take the complement-disrupting trajectory, but it may be a rational decision for it to refrain from doing so. It is true that the complement-disrupting technological trajectory is more likely to be preferred by the market, but it is uncertain. Therefore, a little bit of uncertainty and the inducement of complementary assets can generate the pattern that, *ex post*, the incumbent seems to make a mistake. The incumbent invests heavily in its complement-preserving trajectory despite evidence to suggest that the complement-disrupting trajectory is more likely to be preferred by the market. Such behavior may appear irrational and perhaps reflect some pathology of organizational inertia. But, *ex ante*, despite the likelihood that the complement-disrupting trajectory may be preferred, it still may be rational for the incumbent not to, effectively, throw away their complementary assets and become equivalent to the entrant. A firm may irrationally ignore the possible benefits of leveraging new technologies, but it is important to recognize that incumbents, in the face of radical technological change, may be sensibly maximizing their *ex ante* expected returns rather than failing to realize the full strategic implications of their decisions.

Impact of complementary assets on market outcomes

We next examine the impact of complementary assets on relative market shares when the market prefers the complement-disrupting trajectory. This analysis offers testable implications of the model and highlights the mechanisms that lead to such implications.

Proposition 3: There exists $0 < \underline{\delta} < 1$ *such that when* $0 < \delta < \underline{\delta}$, $p > \overline{p}(\delta)$, *and the complement-disrupting trajectory is preferred by the market, firm I's market share is nonmonotonic as A increases from 1 to arbitrarily high levels. In particular, firm I's market share is constant with respect to its level of complementary assets when* $A < A^r(\delta)$, *at* $A^r(\delta)$ *firm I's market share drops and subsequently increases as A expands beyond* $A^r(\delta)$, *and exceeds firm E's market share when* $A > A^l(\delta)$.

Proof: See Appendix.

Proposition 3 states that we can observe a non-monotonic relationship between the level of complementary assets and firm I's market share for a given level of δ when the complement-disrupting

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trajectory is preferred by the market. By recognizing the endogeneity of the firm's choice of technological trajectory and, in particular, how this choice is influenced by the level of complementary assets, we show that complementary assets may not only allow incumbents to appropriate more value given their innovation success (Teece, 1986) and buffer incumbents from exit given their innovation failure (Tripsas,1997), but by distorting the incumbent's choice of technological trajectory, complementary assets can be linked to inferior market outcomes in some settings.

This result has two conceptual drivers. One driver is a switch in 'regime' (choice of complement-preserving or complement-disrupting trajectory) and the other is the marginal impact of changes in complementary assets on performance within the same regime. As a result, an increase in A may lead to a jump shift downward in performance with the change in regime. Further increases lead to incremental increases in market outcomes within a given regime. Specifically, when the level of complementary assets is low, it is not worthwhile for the incumbent to choose the complement-preserving trajectory. Therefore, the incumbent chooses the complement-disrupting trajectory, becoming, in some sense, equivalent to the entrant. As the level of complementary assets increases to an intermediate level, however, the incumbent switches to the complement-preserving trajectory. Now, when the complement-disrupting trajectory is preferred, clearly the incumbent will be penalized, *ex post*. Note that such penalty is compensated for by the possibility, albeit perhaps small, that the complement-preserving trajectory may be preferred. When the level of complementary assets is sufficiently high, the incumbent will do well even if the complement-disrupting trajectory is realized. The firm's strong performance is not the result of buffering by complementary assets. Rather, the firm's complementary assets induce the firm to invest in high levels of R&D, resulting in the superior performance. We illustrate this case with a numerical example in Figure 2 ($\delta = 0.8$, $p = 0.7$, $\beta = 1$, $\gamma = 0.5$). We can see the incumbent's market share is U-shaped with respect to the level of complementary assets when the complement-disrupting trajectory is preferred by the market. In particular, we observe a sharp drop in sales around $A = 1.2$ (the point at which the incumbent shifts from the complement-disrupting to the complement-preserving trajectory).

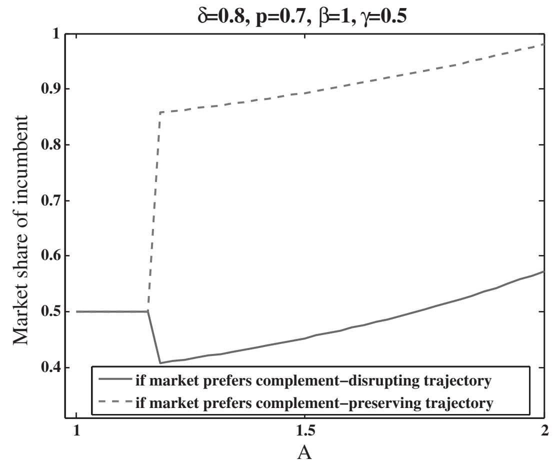

Figure 2. Illustration for Proposition 3

Strategic differentiation

Up to this point, the analysis of the incumbent's trajectory choice has focused on the incumbent's incentive to leverage its complementary assets as a source of potential competitive advantage if the firm chooses the complement-preserving trajectory. However, it is important to note that the incumbent may also find it optimal to choose the complementary-preserving trajectory even when its complementary assets are very small (i.e., A is close to one). In this case, the incumbent's trajectory choice decision is instead driven by what we call 'strategic differentiation'—a strategic choice of a different trajectory from the entrant merely to mitigate competition.

Consider the case in which the incumbent's complementary assets are low. If the incumbent chooses the complement-disrupting trajectory, it competes with the entrant in a duopoly regardless of the market preference. In contrast, if the incumbent chooses the complement-preserving trajectory, it makes a bet on the ultimate nature of market preferences. Should the market prove to prefer the technological trajectory adopted by the incumbent, the incumbent would gain an advantage over the entrant (i.e., obtain higher profit than the duopoly profit) not only because of its complementary assets, which in any case are low, but because the market discounts the entrant's 'wrong' trajectory choice. Obviously, under such a circumstance, the incumbent's advantage and, hence, profit, increases as the mismatch discount is heavier (i.e., δ approaches zero). Of course, this circumstance arises only if the market prefers

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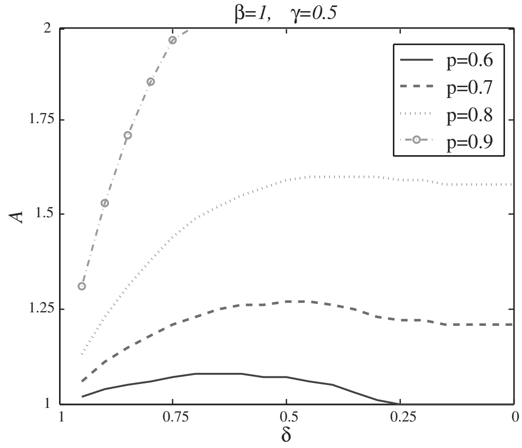

Figure 3. Effect of market preference probability p on the equal trajectory threshold $A^r(\delta)$

the complement-preserving trajectory, which happens with probability *1-p*. In other words, should the market preference prove to be for the complement-disrupting trajectory, the incumbent would fare poorly relative to the entrant and earn a lower profit than the duopoly level achieved when both the entrant and the incumbent choose the same, complement-disrupting trajectory.

As a result, it is clear that the incumbent would prefer strategic differentiation only when there is a reasonable chance that the market will prefer the complement-preserving trajectory (i.e., the probability the market prefers the complement-disrupting trajectory p is close to 0.5) and the mismatch discount is sufficiently severe (i.e., a low value of δ). We find that the incumbent indeed prefers strategic differentiation under these cases. For example, in Figure 3, when the market preference probability p equals 0.6, the trajectory choice threshold $A^r(\delta)$ equals one for all $\delta < 0.25$. This implies that when the incumbent finds the two trajectories almost equally promising or when the market preference is most uncertain, the incumbent will always choose the complement-preserving trajectory even when its complementary assets are very low. Although the market preference for the two trajectories is nearly equal, the incumbent finds it preferable to choose the complement-preserving trajectory to avoid competition with the entrant given that the entrant will choose the complement-disruption trajectory.

The intensity of product market competition, as determined by the ratio of the parameters β and γ in the demand function, also affects the value of the threshold A^r. As the ratio γ/β approaches one, the products become closer substitutes and, as a result, the incumbent finds strategic differentiation increasingly favorable. This incentive for strategic differentiation, in turn, leads to a decrease in the threshold A^r.

The incumbent's incentive for strategic differentiation has an interesting implication: the equal trajectory threshold $A^r(\delta)$ (the upper bound of the dotted region) exhibits an inverse-U shape as δ changes from 1 to 0 (Figure 1). This nonlinear relationship implies that for an incumbent with low complementary assets, it is less profitable to choose the complement-disrupting trajectory when δ is either too large (close to 1) or too low (i.e., close to 0), but more profitable to do so when δ is moderate. While the complement-preserving trajectory is obviously attractive to the incumbent when it can leverage its complementary asset with a low mismatch penalty (δ relatively high), the complement-preserving trajectory is also attractive to the incumbent when the mismatch penalty is high (δ relatively low) because the benefit from the strategic differentiation increases as the mismatch penalty increases (i.e., δ decreases). As discussed in the prior paragraph, a higher mismatch penalty means that the entrant's product would be more severely discounted in consumers' valuations. In the extreme case when $\delta = 0$, the incumbent would gain a monopoly profit should the incumbent choose the complementary-preserving trajectory and the markets prefer this trajectory. As the market preference probability p approaches 0.5, the incumbent's incentive for strategic differentiation increases, leading to a more pronounced downward slope for the inverse-U shape of the equal trajectory threshold. For example, when $p = 0.6$, the threshold $A^r(\delta)$ first increases and then decreases to and remains at zero as δ decreases from 1 to 0 (Figure 3).

To summarize, we find that the incumbent's choice of strategic differentiation could be an *ex ante* rational choice given high technical uncertainty and competitive interactions in product markets. Thus, technological strategies that may appear to be associated with inertia (Leonard-Barton, 1992) may be driven by an incentive to minimize competitive interaction. The influence of competitive interaction on firms' innovation activities has received growing interest in the field of technological strategy, complementing the consideration of internal resource allocation

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(Adner and Zemsky, 2005; Turner, Mitchell, and Bettis, 2010). Supplementing this stream of prior work, we show that in the presence of uncertainty, strategic differentiation need not require engaging distinct segments of the product market. Rather, the differentiation can occur by placing different bets on more or less promising technological trajectories.

We have discussed the shape of the equal trajectory threshold as the mismatch discount factor δ and the market preference probability p change. Finally, we briefly discuss the impact of these two parameters on the other two thresholds. Both the equal market share curve $A^l(\delta)$ (the lower boundary of the white region) and the equal investment curve $A^u(\delta)$ (the lower boundary of the black region) increase nearly monotonically in δ as Figure 1 shows, because a larger penalty associated with the choice of the less preferred technological trajectory requires a higher level of complementary assets to compensate and generate equal investment incentives and market outcome.[13] We also vary the market preference probability p. The two thresholds increase in p since a higher p value provides the entrant with a higher expected payoff over the incumbent, who chooses the less promising trajectory. As a result, the entrant increases its investment level with p. Consequently, the incumbent requires a higher level of complementary assets to justify a higher investment level that matches the entrant's (i.e., A^u increases in p) or to achieve a guaranteed leading position in terms of market share (i.e., A^l increases in p).

Robustness to fungible complementary assets

In our analysis, we assumed that the incumbent is able to leverage its complementary assets only when it chooses the complement-preserving trajectory and the complement-preserving trajectory is preferred by the market (second to last column of Table 1). We made this assumption to focus on the central mechanism at work in determining firms' choices and their market outcomes. In this section, we relax this assumption by allowing for a certain degree of fungibility of complementary assets in the case that the complement-disrupting trajectory is preferred.[14] The last column of Table 1 presents a fairly general form of the fungibility of complementary assets. If the incumbent chooses the complement-preserving trajectory $r=0$ but the market prefers the complement-disrupting trajectory $t=1$, then the incumbent can still leverage its complementary assets but suffers from a discount in the value of these assets. In particular, the incumbent's effective complementary assets become A^{κ_1}, where $0 \leq \kappa_1 \leq 1$. Similarly, if the incumbent chooses the complement-disrupting trajectory $r=1$, the incumbent can leverage its complementary assets to only a certain degree, with the incumbent's effective complementary assets becoming A^{κ_2}, $0 \leq \kappa_2 \leq 1$.[15] We can interpret κ_1 and κ_2 as the degree to which complementary assets are trajectory specific. When complementary assets are fully trajectory specific to the complement-preserving trajectory, then $\kappa_1 = \kappa_2 = 0$; that is, the incumbent's advantage from complementary assets will disappear if the firm chooses the complement-disrupting trajectory or if the firm chooses the complement-preserving trajectory but the market prefers the complement-disrupting trajectory. In contrast, when complementary assets are fully trajectory independent, then $\kappa_1 = \kappa_2 = 1$ and the incumbent's advantage from complementary assets will be fully retained regardless of its trajectory choice or which trajectory is ultimately preferred by the market.

Our results are robust to this more general setup. In particular, the black regime we identified in Propositions 1 and 2 always exists. The black regime characterizes the case when the complementary asset is sufficiently large that the incumbent prefers the complement-preserving trajectory and invests more than the entrant, but the penalty from technical mismatch is sufficiently high (i.e., the value of δ is sufficiently

[13] The equal market share curve $A^l(\delta)$ increases monotonically. However, there is a slight drop between the upward increasing part and the flat part of the equal investment curve $A^u(\delta)$. This drop is caused by the exit of the incumbent's product when the market favors the complement-disrupting trajectory at a critical threshold of δ such that $2\beta V_I - \gamma V_E = 2\beta\delta u_I - \gamma u_E = 0$. Given the exit of the incumbent from product market competition, the entrant reduces its investment *ex ante* and, as a result, the equal investment curve $A^u(\delta)$ drops at this point.

[14] While we are treating the degree of fungibility as a function of inherent breadth of applicability of complementary assets, Taylor and Helfat (2009) point out that effective fungibility may, to an important degree, be a function of organizational structures and integrative mechanisms that facilitate resource sharing across units.

[15] We could further introduce a κ_3 to separately represent the case where the firm chooses the complementary-destroying trajectory and the market prefers the complement-preserving trajectory, but the mechanisms we show do not change.

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small) that the product market payoff from the incumbent's investment greatly diminishes and the entrant would garner more product market success should the complement-disrupting trajectory be preferred. The existence of the black regime persists when $\kappa_1, \kappa_2 > 0$ because κ_1 and κ_2 influence only the incumbent's preference between the two trajectories and determine how large a value of complementary asset A is required to turn the incumbent's preference toward the complement-preserving trajectory.

However, since the factors that affect the degree to which complementary assets are specific to a given technological trajectory, κ_1 and κ_2, can influence the incumbent's trajectory choice, the shape of the regimes in Figure 1 is affected when we allow for a certain degree of fungibility of complementary assets. A larger value of κ_1 makes the complement-preserving trajectory more preferable and, hence, leads to higher investment and profit for the incumbent but lower investment and profit for the entrant if the incumbent chooses the complement-preserving trajectory. Therefore, as κ_1 increases, the region (in the A- δ plane) where the incumbent prefers the complement-disrupting trajectory (the dotted region) shrinks and the thresholds of equal investment (the lower boundary of the black region) and equal market share (the lower boundary of the white region) decrease. The four figures in Figure 4a show this pattern.

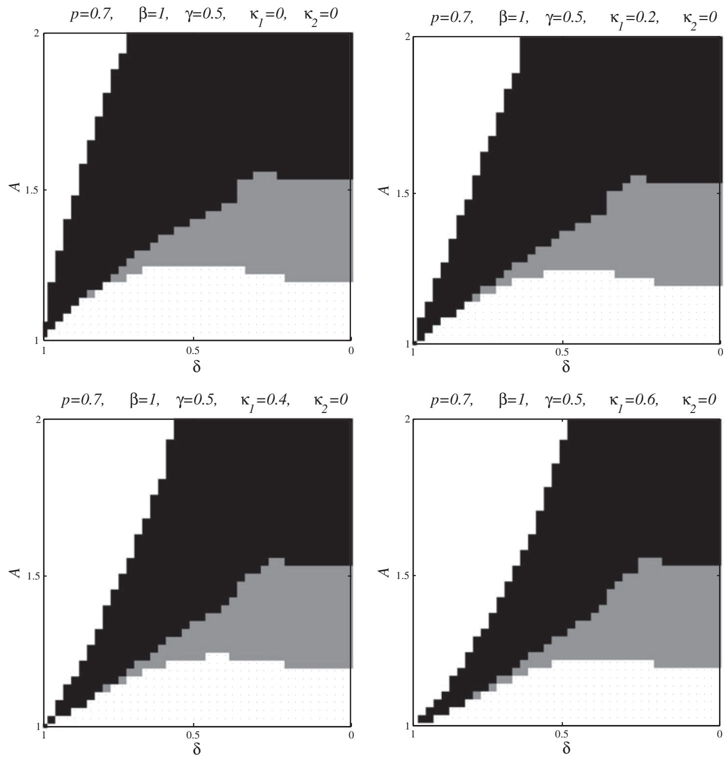
A larger κ_2 makes the complement-disrupting trajectory more preferable and, hence, it leads to higher investment and profit for the incumbent but lower investment and profit for the entrant if the incumbent chooses the complement-disrupting trajectory. In contrast to its impact on trajectory choice, κ_2 does not affect the equal investment and equal market share thresholds because these thresholds only apply when the complement-preserving trajectory is chosen. If the complement-preserving trajectory is chosen, the value of κ_2 does not affect the outcome (i.e., the two firms' investment decisions). Therefore, as κ_2 increases, the dotted region will expand and may ultimately encompass part or all of the gray region. The four figures of Figure 4b show this pattern.

CONCLUSION AND DISCUSSION

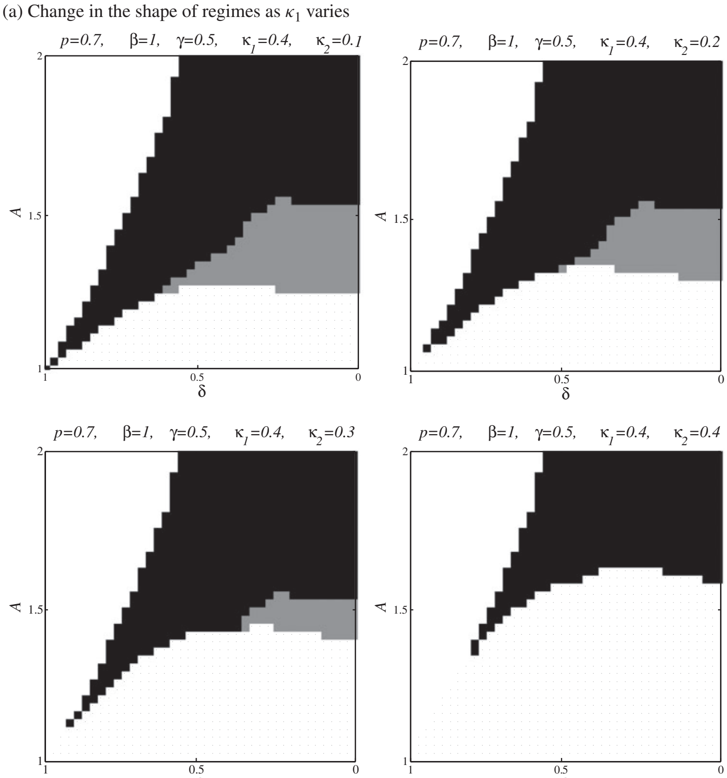
Complementary assets not only shield firms from radical technical changes, but also affect investment incentives. While the existing literature has made the important point that complementary assets can, *ex post*, influence product market and financial outcomes, the potential effect of complementary assets on economic incentives for *ex ante* investment behavior has been underexplored. In this work, we examine how the incumbent's complementary assets impact its choice of technological trajectory, as well as its investments along the chosen trajectory.

Technological change generally presents multiple technological trajectories among which a firm must choose. In making such choices, a firm must not only evaluate the inherent promise of the alternative technologies, but also the degree to which alternative approaches leverage its existing complementary assets or renders these assets valueless. Bringing attention to the issue of the existence of alternative technological trajectories highlights an important distinction between investment intensity, the qualitative nature of the firm's investment (i.e., choice of trajectory), and final product market outcomes. We formally examine firms' technology investment behaviors and outcomes by analyzing the influence of their complementary assets on their technological trajectory choices. Our analysis identifies several distinct regimes with corresponding empirical implications regarding investment levels, trajectory choices, and product market outcomes. In particular, we are able to identify settings in which established firms make substantial technological investments in the face of radical technical change, but may pursue inferior technological trajectories in order to leverage their existing complementary assets. As a result, the incumbent's inferior market outcome may be a consequence of its endogenous choice of technological trajectories, rather than a consequence of inferior technical capabilities. As a result, an incumbent firm's trajectory choice may empirically exhibit a form of path dependency not as a consequence of cumulative technical knowledge (Dosi, 1982), but as a consequence of its existing complementary assets. Further, an incentive for strategic differentiation may amplify this complementary asset-based path dependence, as the presence of complementary assets creates a basis for asymmetry in the firms' approach to the market that leads to some mitigation of product market competition.

The distinct regimes identified in this study can generate nonlinear relationships between market success and the level of complementary



(a) Change in the shape of regimes as κ_1 varies



(b) Change in the shape of regimes as κ_2 varies

Figure 4. Robustness to more fungible complementary assets

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assets. Firms with low levels of complementary assets may give up such assets and pursue complement-disrupting technological trajectories and, in that respect, become equivalent to the new entrant. It is also possible that firms with sufficiently high levels of complementary assets can still dominate the market, even with the choice of seemingly less promising technological trajectories. However, in a broad range of settings, established firms, with investment decisions influenced by their existing stock of complementary assets, may choose less promising technological trajectories and suffer adverse product market outcomes as a consequence.

Of course, there are a number of limitations to our analysis that open opportunities for future research. First, the dynamic nature of the setting could be enriched. The current study assumes that complementary assets are fixed and, therefore, treats them as exogenous parameters. It is certainly the case that this factor evolves over time (Pacheco-de-Almeida, 2010). The research could be extended by examining firms' investments not only with respect to R&D investment, but also with respect to investments in complementary assets. The investments along these two dimensions may be made simultaneously or sequentially. Further, we treat the technical capabilities of the firms as being homogenous. In some sense, this assumption strengthens our findings, as we show that inertia (keeping to a prior technology) may emerge even in the absence of the incumbent having an inherent disadvantage in the new complement-disrupting technology. However, a more general model would allow for the possibility of heterogeneity of technical capabilities along different technological trajectories, whether as an inherent property of the firm's 'type' or an outcome of prior R&D investment activity, as well as heterogeneous complementary assets.

Second, as discussed in the model setup, a critical assumption is that the market for complementary assets and technical capabilities are imperfect and, as such, an entrant cannot gain access to complementary assets (e.g., through contracting), while the incumbent may not gain access to external technology (e.g., through licensing). Relaxing this working assumption can lead to a fruitful research avenue that examines the role of licensing or mergers and acquisitions (M&A) activities between the incumbent and the entrant (Gans, Hsu, and Stern, 2002; Gans and Stern, 2000). Building on the logic of Gans and Stern (2000), in the presence of licensing, alliances, and M&As, complementary assets can increase the incumbent's bargaining power in the licensing process, thereby lowering the licensing fee paid to the entrant. The effects of complementary assets on the licensing fees that might be earned by an entrant, in turn, amplify the incumbent's preinnovation incentives, as well as its postinnovation returns. A large stock of complementary assets would favor the incumbent by enhancing its returns on R&D relative to the entrant. This is, ultimately, the critical factor underlying our results regarding the rationality of the incumbent's R&D investments in the face of radical technical change. Furthermore, the choice of technological trajectory in a given domain may impact the cost and effectiveness with which a firm can access and acquire these capabilities in the form of licensing, alliances, and acquisitions (Cohen and Levinthal, 1990). Future research can extend this line of investigation to settings of broader innovation ecosystems (Kapoor and Lee, 2012).

While these are important possible extensions, the current effort provides an important enrichment of our current treatment of the effect of complementary assets. Complementary assets are not merely asset stocks that buffer firms from competitive dynamics; they are also an important element of the investment context for firms' R&D decisions. Complementary assets can be leveraged to amplify the returns to an existing competitive position, but that act of leverage is not neutral with respect to the direction of the firm's technical efforts. In this regard, complementary assets have a dual role, somewhat akin to the duality of network ties as 'pipes,' conveying resources, and 'prisms,' providing general signals of quality and legitimacy, put forth by Podolny (2001). Complementary assets are a resource. As noted by a number of prior scholars, such resources may buffer firms from subsequent competitors (Mitchell, 1989; Tripsas, 1997). However, these resources also influence a firm's perception of what might constitute more or less promising technological directions. We examine the 'prism' of complementary assets from a rational choice, profit-maximizing perspective, as we highlight some of the tensions between the incentive to leverage existing resources and the need to make technologically appropriate choices, and we suggest how the balance of such tensions may help explain some of the empirical patterns and puzzles we observe.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article:

Appendix S1. Online Appendix: Proof For The Propositions