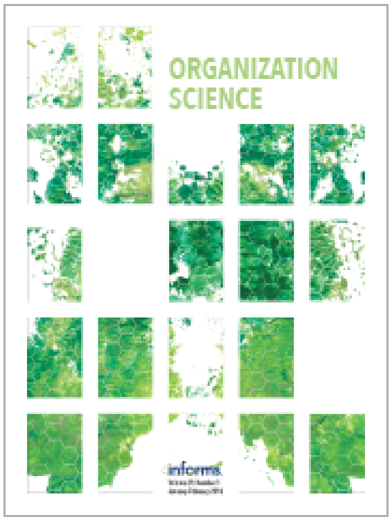

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Creating Radical Technologies and Competencies: Revisiting Interorganizational Dynamics in the Nascent Bionic Prosthetic Industry

Seojin Kim,[a] Rajshree Agarwal,[b,]* Brent Goldfarb[b]

[a] Management, LeBow College of Business, Drexel University, Philadelphia, Pennsylvania 19104; [b] Management and Organization, Robert H. Smith School of Business, University of Maryland, College Park, Maryland 20742

*Corresponding author

Contact: seojin.kim@drexel.edu, https://orcid.org/0000-0003-4390-6999 (SK); rajshree@umd.edu, https://orcid.org/0000-0002-7272-314X (RA); brentg@umd.edu, https://orcid.org/0000-0002-8828-9018 (BG)

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Abstract. Why were incumbents able to pioneer and dominate the nascent bionic prosthetic industry, even though entrants represented the majority of the firms investing in this radical technology? To answer this question, our abductive study builds on the novel base principles definition and uses a historical approach to investigate the incubation and early commercialization periods (1974–2018) of bionic prosthetics. We use comprehensive quantitative data on all technological entrants and historical analysis of significant firms to reveal that organizational prehistory affects both the knowledge and intent of technological entrants. Start-ups, incumbents in conventional prosthetics, and established firms in other industries created and integrated subtechnologies into a radical system. Although all firms invested in component technologies, incumbents played a key role as system integrators. Incumbents dominated product commercialization; start-ups captured value through alliances or by being acquired, and established firms in other industries leveraged their knowledge in adjacent value chains as a function of their prior histories and intents. In comparing the virtues of our explanation—the creating radical systems effects—with widely accepted alternative explanations, we develop a more generalized framework of interorganizational dynamics in nascent industries as an endogenous, coevolutionary process that goes beyond explanations that privilege competitive dynamics to also include collaborative dynamics in value creation (and capture).

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Keywords: radical technological systems • organizational competencies • nascent industries • incumbents • entrants • value creation • value capture

In 1997, Ottobock introduced the C-Leg, a pathbreaking bionic prosthetic limb. First imagined in the late 1940s, bionic prosthetics infused novel base principles (electronics, robotics, neuroscience, and artificial intelligence (AI)) to create electrically powered control systems, interfaces providing sensory feedback, and self-learning of the prosthetics for greater functionality. It is hard to view bionic prosthetics as anything but a radical departure from prior state-of-the-art mechanical prosthetics. Existing theories of interorganizational dynamics, based on studies that begin with first commercialization, hold the premise that such radical technologies are shocks ushered by entrants (start-ups or diversifying entrants), rendering existing technological competencies of incumbent firms obsolete (Gort and Klepper 1982, Tushman and Anderson 1986, Henderson 1993). However, bionic prosthetics did not herald disruption of mechanical prosthetics incumbents. Instead of a mere post-shock response to the radical technology by leveraging complementary assets (Mitchell 1991, Tripsas 1997) and reconfiguring capabilities (Eggers and Park 2018), incumbents pioneered bionic products and dominated the technology's subsequent takeoff. The puzzle deepens when one considers that about 80% of firms investing over several decades to create bionic prosthetic technology were *not* incumbents but firms in other industries and start-ups. These patterns are consistent with studies where entrants take center stage in developing a radical technology (Aversa et al. 2022, Gao and McDonald 2022) to displace incumbents (Moeen and Agarwal 2017). The bionic prosthetics industry is thus anomalous to predictions of prevailing theories of incumbent-entrant dynamics. Even though they were a minority fraction of firms investing in creating bionic prosthetics technology, mechanical prosthetics incumbents were not disrupted by entrants; instead, they captured value by pioneering several bionic products for continued dominance.

We address this anomaly by using abductive, historical methods (Pillai et al. 2024) to adjudicate among prevailing theories to explain observed patterns of value creation and capture in bionic prosthetics and to provide an alternative explanation most consilient with observed patterns and precise in its underlying mechanisms. Our inference to the best explanation starts with the incubation period of the radical technology rather than the time of first commercialization based on the premise that it is important to understand how radical technologies emerge in the first place, aided by organizational efforts to create requisite technological capabilities. We show that organizations that invested in creating radical technological systems—incumbents, firms in related industries, and start-ups—differed in their capabilities and intent. Mapping these underlying attributes to components of the bionic prosthetic technological system, we find that all three firm types developed component- and system-level capabilities. They interacted in "small-world" collaborative networks to simultaneously create internal competencies and build requisite components of the bionic prosthetic system. Such value creation efforts drove subsequent value capture, not only in product markets but also, in alternative markets (for technology and corporate control) and value chains. Incumbents focused on technological system integration to pioneer bionic prosthetics products. Start-ups—largely founded by academic or user inventors—captured value by entering bionics component markets, engaging in alliances, or becoming acquisition targets. Established firms from other industries sought applications in adjacent value chains, such as mobility assistance, exoskeletons, or robotics, and very rarely diversified into bionic prosthetics or licensed their technology.

The abductive explanatory exercise enables us to develop a general theory that is both parsimonious and coherent with prior work. This theory—*creating radical systems process* (CRSP)—highlights the process wherein different types of firms cocreate radical technologies and organizational capabilities and subsequently, capture value. The parsimony stems from eschewing the assumption that radical technologies are introduced by entrants. Instead, it relies on the novel-base-principles definition (Arthur 2009); radical technological systems provide novel solutions for a specific purpose by embodying new base principles at either the component level or the system level. Divorcing what radical technologies *are* from *who* possesses relevant prior knowledge and intent implies that the latter may be distributed across *all* three types of firms rather than only with entrants. The process model showcases that prior experiences shape *who* engages in value creation, *why*, and *how* they do so, including through collaborations between the various firm types. Together, these endogenously determine modes of value capture: entry into product markets, markets for technology, or alternative value chains.

The coherence of this general theory with prior work stems from underlying mechanisms at play. These include the relevance of prior technological capabilities for incubation of radical technological systems (Moeen and Agarwal 2017), the importance of recombination and reconfiguration in creating the requisite technological capabilities (Capron and Mitchell 2009, Xiao et al. 2022), and possession of downstream or complementary assets across different value chains in shaping both intent and subsequent modes of value capture (Gans and Stern 2000, Gambardella and McGahan 2010). Contextual differences then impact how these mechanisms manifest in practice. If the radical technology leverages altogether novel base principles and incumbents completely lack relevant technical capabilities, it is more likely to be introduced by entrants. In such contexts, prior explanations of interorganizational dynamics are special cases of the general theory, be they incumbent obsolescence (Tushman and Anderson 1986), incumbent inertia (Henderson and Clark 1990, Tripsas and Gavetti 2000), survival through reliance on complementary assets (Tripsas 1997), or organizational adaptation (Eggers and Park 2018). Beyond these special cases, our generalized theory highlights that the underlying mechanisms are at play to allow for diverse firms to both create and capture value; when relevant technical capabilities are distributed across both entrants and incumbents, these firms engage in *collaborative dynamics* to create the radical technology rather than only leverage markets for technology after it has been created (Gans and Stern 2000). Such endogenous creation of radical technologies and underlying competencies is also aided by markets for corporate control for capability reconfiguration (Karim 2009) and subsequently, shapes modes of value capture, including in adjacent value chains (Gambardella and McGahan 2010).

Conceptual Backdrop and Research Questions

Prior Explanations of Interorganizational Dynamics Ushered by Radical Technologies

In a seminal work, Arrow (1962) defines radical technologies as an advance that renders the old technology no longer a viable substitute; moreover, he notes that incumbents (particularly with market power) lack incentives to optimally invest in radical change (see also Reinganum 1983 and Dew et al. 2006). Similarly, Tushman and Anderson (1986, p. 441) define radical technologies as discontinuities that offer "sharp price-performance improvements over existing technologies." These *organizational effects* explanations cast entrants (start-ups or diversifying entrants) as pioneering radical technologies, dominating new industries, and disrupting incumbents because of technological obsolescence of their competencies (Tushman and Anderson 1986, Henderson 1993, Benner and Tripsas 2012).[1]

An extensive literature has subsequently framed subsequent interorganizational dynamics as "antecedents allowing (or inhibiting) incumbent firms to adapt to (exogenous) technological change" (Eggers and Park 2018, pp. 359–360). *Organizational inertia effects* implicate structural and cognitive rigidities. Structurally, radical technologies may transform incumbent core competencies into core rigidities to prevent incumbents from transitioning successfully (Henderson and Clark 1990, Leonard-Barton 1992). Cognitively, incumbent inertia may stem from managers holding on to prior beliefs even when their own R&D efforts are aligned with the radical technology (Tripsas and Gavetti 2000, Eggers and Kaplan 2009). *Complementary assets effects* offer that (downstream) complementary assets (Teece 1986) may buffer incumbents (Mitchell 1989, Tripsas 1997). Additionally, *organizational adaptation effects* identify processes through which incumbents may develop requisite technological capabilities through acquisition, assimilation, and reconfiguration (Cattani 2005, Eggers 2012), such as engaging in markets for technology (Gans and Stern 2000, Arora et al. 2001) to trade or ally with entrants that are ushering in the radical technology (Rothaermel and Boeker 2008).

Anomaly Arising from Assumptions Within Prior Explanations of Interorganizational Dynamics

Bionic prosthetics are anomalous to these explanations in that incumbents pioneered bionic prosthetics products, even though entrants outnumbered them as technology investors during its incubation. Our reconciliation of the anomaly begins with identifying three assumptions baked into the above work.

Tautology Resulting from a Definition of Radical Technology. The *organizational effects* definition of radical technology conflates "what a radical technology is" with "who introduces the radical technology." Economic models (Arrow 1962, Reinganum 1983) explicitly assume that incumbents lack incentives (intent) to invest in creating radical technologies. Similarly, definitions and categorizations of radical technologies explicitly invoke the assumption that incumbents lack relevant technical capabilities (Tushman and Anderson 1986, Henderson 1993). Such assumptions imply that radical technologies *must be* exogenous shocks to incumbents, and resultant interorganizational dynamics give entrants a technological advantage *by definition*. Incumbents confronting radical technologies are either doomed (*organizational inertia effects*) or face the imperative to respond; to do so, they need to rely on *complementary assets effects* or on *organizational adaptation effects*. Within bionic prosthetics, such a tautology creates a contradiction and hence, the anomaly; either incumbents could not have pioneered it in the first place for subsequent domination in the new industry, or bionic prosthetics cannot be considered a radical technology.

Sampling on Industries Introduced by Entrants and Focus on the Period Post-first Commercialization. Empirical support for the above explanations has been derived by sampling industry contexts where entrants pioneer the radical technological change (Mitchell 1989, Rothaermel 2001) to examine interorganizational dynamics starting with the first instance of commercialization (by entrants) of a product embodying the radical technology (Gort and Klepper 1982, Tushman and Anderson 1986, Agarwal et al. 2002). More recently, studies have relaxed the latter assumption to study the incubation period of radical technologies (see below for greater detail). Here too, however, entrants take center stage, whether they are diversifying entrants (Moeen and Agarwal 2017) or start-ups (Aversa et al. 2022). Bionic prosthetics are an anomalous context where incumbents pioneered and subsequently dominated markets for bionic prosthetic products, despite significant investments by start-ups and firms in related industries during incubation.

Focus on Value Capture in Product Markets Without Attention to the Antecedent Value Creation. The above two issues feed into a third; defining radical technologies as an exogenous technological shock results in explanations of *competitive dynamics in product markets* that focus on how value is being captured by entrants and incumbents. Moreover, markets for technology are seen merely as tools for value capture between innovators and holders of complementary assets (Teece 1986). Existing explanations are silent on how radical technologies are created in the first place, by whom, and why. Given their focus on postcommercialization dynamics, most research assumes away the antecedent endogenous processes for creation of radical technologies and the requisite organizational capabilities. For bionic prosthetics, the puzzle arises because start-ups and firms in related industries constituted most of technological entrants (creating value), yet they seemed not to capture value (by pioneering resulting product markets).

Building Blocks to an Alternative Explanation

Radical Technologies as Systems Embodying Novel Base Principles Designed to Serve a Purpose. To sever the tautological link between radical technologies and entrants, we build on an alternative conceptualization: technology as a system embodying base principles and designed to serve a purpose (Arthur 2009). The Arthur (2009, p. 277) definition of technology that "possesses a purpose, a combination of components, an architecture, and embodies a base principle that exploits some base phenomenon" is consistent with prior work defining technology as a complex system consisting of interdependent and hierarchical components with attention to managing trade-offs and optimizing functions within and across design parameters of components (Henderson and Clark 1990, Baldwin and Clark 2000). Accordingly, what components constitute a technological system and how these components are assembled are dictated by why and how the specific architecture delivers a workable solution to a problem (Goldfarb and Kirsch 2025). Such a "purpose-driven system" view has three important implications. First, at both component and system levels, technologies utilize base (scientific) principles. Second, these base principles are exploited for a desired effect (i.e., to fulfill a purpose through the creation of a seamless working architecture that brings the requisite components together). Third and as a corollary, different technological systems may be constructed using subsets of components to achieve different purposes.

A radical technology is then defined as a technological system that uses new design concepts and architecture (Henderson and Clark 1990) or more precisely, as one that "achieves a purpose by using a new or different base principle than used before" (Arthur 2009, p. 278).[2] The interplay between a technology's purpose (problems that it solves) and the use of new principles for developing radical technologies harks back to Rosenberg (1969). Given that novel base principles may be utilized for several alternative purposes, the third implication above represents the reality that such breakthroughs often serve as a basis for several new technologies, where each new technology applies a novel principle to achieve a specific intended purpose.[3]

Moreover, in this system view, components represent "subtechnologies" (Arthur 2009). For example, the introduction of the jet engine was a radical subtechnology in broader airplane technology because it used different base principles to propel an airplane than the internal combustion engine. Creating a complete solution requires a deliberate process wherein the radical subtechnology is integrated with other subtechnologies, which themselves may need to be refined or reconfigured. The creation of radical technologies requires attention to what Rosenberg (1969) stated is a "sequence—changes in one component of an interdependent system creates a stimulus for changes elsewhere in this system" (Rosenberg 1969, p. 9). Regardless of where a novel base principle is used (i.e., which component level), a core aspect of the process is that new base principles require reconfiguration of (existing and new) components into a new architecture. As noted by Arthur (2007, p. 278), "translating [a] base principle into physical reality requires the creation of suitable working parts and supporting technologies," some of which "may require inventions of their own." Thus, a radical innovation entails matching a need to a principle (or effect envisaged in use) and "solving the ensuing hierarchy of problems and subproblems" (Arthur 2007, p. 278). This implies that making radical technologies useful requires waves of technical and economic experimentation wherein both failed and successful efforts generate valuable information regarding trade-offs encountered in the recombination of scientific principles and their economic implementation (Rosenberg 1992, Goldfarb and Kirsch 2025).

Purposeful Efforts at Incubating Technologies and Industries by Heterogeneous Actors. Although the above "nature of technological systems" literature highlights *what* technology *is*, it is silent on *who* engages in the technological and economic experimentation necessary to fulfill its purpose. The latter is the focus of work on industry incubation (Moeen et al. 2020). Even prior to first commercialization of a product that embodies a radical technology, there exists a vibrant period wherein diverse economic actors envision and aspire to transform triggers, such as scientific discoveries or unmet needs (Agarwal et al. 2017), into usable technologies by expending innovative effort to address a series of bottlenecks (Goldfarb and Kirsch 2025). The use of the term "economic actors" at this stage is intentional; beyond established firms in focal or other industries, the term encompasses academic, public, and nonprofit organizations (Roy et al. 2019, Agarwal et al. 2021) and individuals aspiring to build novel solutions based on insights gained through invention or user unmet needs (Mowery and Rosenberg 1991, Franke and Shah 2003, Agarwal and Shah 2014, Sanderson and Simons 2014). Moreover, there is rich diversity in prior histories and knowledge contexts. For example, Moeen and Agarwal (2017, p. 572) document that among the 69 firms investing in agricultural biotechnology's incubation, "18 firms (26%) are entrepreneurial start-ups, 33 firms (48%) are conventional agriculture incumbents, and 18 firms (26%) are diversifying entrants from related industries." The incubation period itself is characterized by a recursive process of knowledge generation through investments and experimentation and knowledge sharing through appending and aggregating mechanisms (Moeen et al. 2020).

Given vibrant technological investments, formal and informal collaborations, and (re-)configuration of firm boundaries during industry incubation, the first instance of product commercialization is an important milestone but perhaps not as much as a watershed event as accorded in prior studies (e.g., Gort and Klepper 1982, Tushman and Anderson 1986). Moreover, commercialization—or becoming *product market* entrants—is only one plausible value capture strategy (Moeen and Agarwal 2017). Alternative strategies include selling technological capabilities in markets for technology to become *alliance partners* in upstream markets, selling the entire firm to become *acquisition targets* in markets for corporate control (Moeen and Mitchell 2020), or application of the technology to a different purpose and associated market (Goldfarb and Kirsch 2025).

Research Question

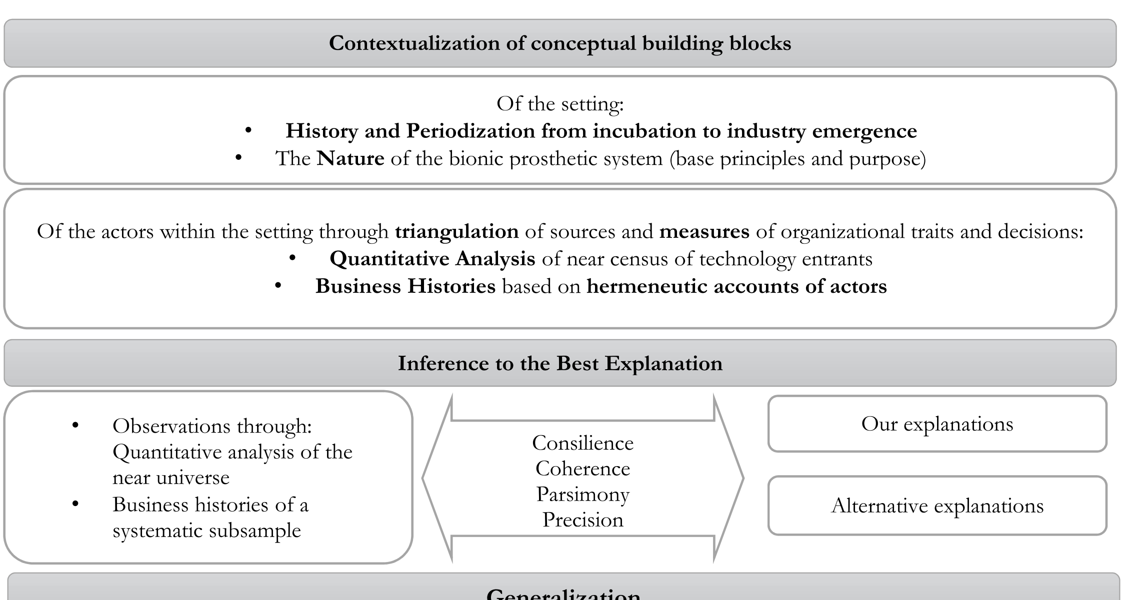
The above building blocks enable us to frame the quest for a better explanation. The first divorces the tautology inherent in defining a radical technology based on who has the requisite intent or capabilities. The second severs the exogenous shock assumption; radical technologies require efforts by heterogeneous economic actors to create the radical technology (value creation), which then shape how they subsequently capture value (including through pioneering and dominating in bionic prosthetics product markets). Recasting the anomaly within this frame, our study seeks to answer the following research questions. *How did prior histories of organizations affect their investments in incubating radical technological systems for value creation in bionic prosthetics? Additionally, how did organizations' prior histories and technological investments impact their subsequent value capture strategies?*

Research Methods and Analytical Road Map

We use abductive, historical methods to infer the best explanation through analysis of longitudinal quantitative data and business cases (Agarwal et al. 2020, Pillai et al. 2024). The approach uses an iterative reconciliation of patterns of observed events with existing and new candidate explanations to adjudicate which candidate is "best" in the sense that it provides the most meaning and is likely to be close to the truth (Lipton 2004, Douven 2022). Figure 1 provides the analytical road map for subsequent sections, and Online Appendix A provides a detailed description of the method and explanatory virtues.

The critical first step is contextualizing conceptual building blocks with historical accounts of bionic prosthetics. Understanding the setting—the nature of the bionic prosthetics system and its technological development—guides not only subsequent analyses but even what data to collect over what period for the evaluation of each explanation's virtues (Braguinsky and Hounshell 2016, Pillai et al. 2024). We also construct hermeneutic accounts to understand actors' perspectives and beliefs at the time of decisions. Throughout, we triangulate across sources to ensure that we do not overweight idiosyncratic perspectives (Bucheli and Wadhwani 2014, Pillai et al. 2024). Such accounts enable us to determine the most important causal linkages and find an explanation with the most consilience with the data through both quantitative and historical analyses. For the quantitative analysis, we compile and analyze a comprehensive census of all technological entrants in bionic prosthetics (to understand the technological trends and *which* actors contributed *how* and *when*). For the historical analysis, we conduct detailed case studies of 15 historically significant firms in bionic prosthetics stratified by prior histories (i.e., incumbents in mechanical prosthetics, established firms in other industries, and start-ups). Their historical significance stems from these firms being the

Figure 1. Abductive Process and Analytics Road Map



top five contributors (within each firm type) to the technological development of bionic prosthetics. The business histories and hermeneutic accounts enable us to identify *why* the actors entered and the subsequent cause-effect relationships for the evolution of firm capabilities, creation of the radical technological system, and value capture strategies. The analyses position us to evaluate the virtues of alternative explanations. We judge not only (a) which explanation is closest to the truth in terms of consilience but also, (b) coherence with prior theory or observation, (c) parsimony in terms of underlying assumptions, and (d) precision regarding cause-effect mechanisms. We then discuss whether and how our explanation generalizes into a more universal theory applicable in other settings. Here, we use "*explanation*" to refer to our best understanding of bionic prosthetics and "*theory*" to describe the logic that extends the explanation's generalizability to other cases.

Bionic Prosthetics Context: Historical Periodization and the Nature of Technology

Prosthetic limbs serve the purpose of providing amputees with artificial limbs to restore functionality lost because of missing natural limbs. During the twentieth century, this purpose was served through a technological system that used mechanical base principles to enable limb functionality. The first fully microprocessor-controlled bionic limb—Otto Bock's C-Leg—was introduced in 1997 in Germany and received The United States Food and Drug Administration (FDA) approval in the United States in 1999. Bionic prosthetics were heralded as a significant technological advancement, leading to a surge of new products in the orthopedics and prosthetics (O&P) industry (Fairley 2014).

In determining the relevant period of the historical narrative for bionic prosthetics, we note that although the first commercialization occurred in 1997, investments in technological development (as measured by patents that utilize bionic principles) preceded this date by several decades (Childress 1985). We traced the first bionic prosthetic patent as filed in 1974 and tracked the emergence of bionic prostheses through industry incubation (1974–1996) and postcommercialization industry growth (1997–2018). Focusing on the entire period enables us to contextualize the technological environment and identify firms investing in the radical technology. It also ensures that we are not sampling on merely those firms that eventually commercialized bionic prosthetics.

Consistent with the nature of the technological system definition (Arthur 2009), bionic prosthetics represent a radical technology that leverages novel base principles to serve the same purpose as mechanical prosthetics—the end user's mobility needs, which include (1) function (e.g., durability and improved mobility with controls over the device), (2) fitting (e.g., wearability and being less cumbersome and stiff), and (3) appearance (e.g., looks part of the natural human body and pleasing aesthetics). Table 1 displays how this purpose is served by both mechanical and bionic prosthetics technological systems by utilization of three critical subtechnologies: materials, controls, and design. (See Online Appendix B for further descriptions of the evolution of prosthetics along critical subtechnologies and the figures in Online Appendix B for the differences in the two types of prosthetics.) The critical differentiator across the two systems, not surprisingly, is within the *controls* subtechnology. Bionic prosthetics shift from a sole reliance on mechanical base principles (e.g., hydraulic or pneumatic mechanisms) to include bionic base principles that combine electrical engineering, robotics, and neuroscience (Burck et al. 2011). The bionic-based technological system enables new technical features, including an interactive interface between the prosthesis and the residual limb for intuitive controls and sensory feedback and AI-based technology that allows a device to adapt to the user. Bionic prosthetics, thus, offer users much greater degrees of freedom in their limb movements, enabling diverse activities ranging from climbing hills and running on uneven surfaces to natural and delicate motions, such as gripping and pinching.

Incorporating bionic controls also required significant innovation and reconfiguration of other subtechnologies for the development of a new architecture. Rather than a mere modular change, the new control subtechnology necessitated systemic changes in materials, redesign of the device structure, and new fitting mechanisms. Bionic prosthetics require lighter and more weight-bearing composites (e.g., carbon fiber and advanced plastics) to accommodate the weight of artificially powered mechanisms. Moreover, the need for creating sensation and neural interfaces requires the use of novel materials (e.g., tactile skins, biocompatible and implantable materials, and electromagnetic composites). In design, differences stem from design optimization to match features and benefits enabled by the shift from mechanical to bionic controls. Mechanical prosthetics customize limb shapes for specific activities (e.g., C-shaped blades for running, fin-shaped feet for swimming, hook-shaped hands for daily activities, and wrench-shaped hands for heavy-duty work). Bionic prostheses use complex designs replicating human anatomy for diverse motions (e.g., hands with individually actuated five digits). Bionic controls also utilize new fitting principles. Osseointegration (implanting synthetic connectors) provides more secure connection and sensory feedback, so bionic prosthetics sockets are not mere connectors but also, record electric signals from the body (Moran 2011).

Table 1. Comparison Between Conventional Prosthetics and Bionic Prosthetics

		Bionic prosthetics	
Component	Mechanical prosthetics	Differences	Similarities
Control	Mechanical controls only: Body powered and pneumatic (air) or hydraulic (liquid) controls Cables and harness-based control using body movement Springs for energy regain Rubber as shock absorbers Hinges with a brake and locks to stop and stabilize movement	Bioelectric controls: Electric powered (lithium batteries and motors) Microprocessor controlled, myoelectric controlled (muscle signals), mind controlled (the central nervous system) Sensors and artificial intelligence for real-time motion analysis Sensory feedback systems: the sense of touch and warmth	Integrating mechanical controls into bioelectric controls Pneumatics, hydraulics, hinges
Design	Modularization of customization and interchangeability Specially shaped limbs for specific activities: C-shaped leg for running, swimming legs, wrench hands for work Simpler designs: Hook-shaped hand with voluntary opening Lifelike passive prosthetics/covering	Human-computer interface: Osseointegration that enables neural connection and sensory feedback Sockets with electromyography sensors Complex design: A hand with individual fingers and more joints	Modularization of parts Sockets and liners Mimicking human anatomy Aesthetic covering
Materials	Lightweight, weight-bearing, energy-restoring materials Metallics (steel, aluminum, titanium) and composites (plastics, resins, laminates, carbon fiber, silicone)	Electromagnetic composites Biocompatible materials Flexible, thin, tactile skins	Lightweight, weight-bearing, energy-restoring materials Composites (plastics, resins, laminates, carbon fiber, silicone)

Note. The two columns under Bionic prosthetics compare key differences and similarities between mechanic and bionic prosthetics.

Quantitative Analysis

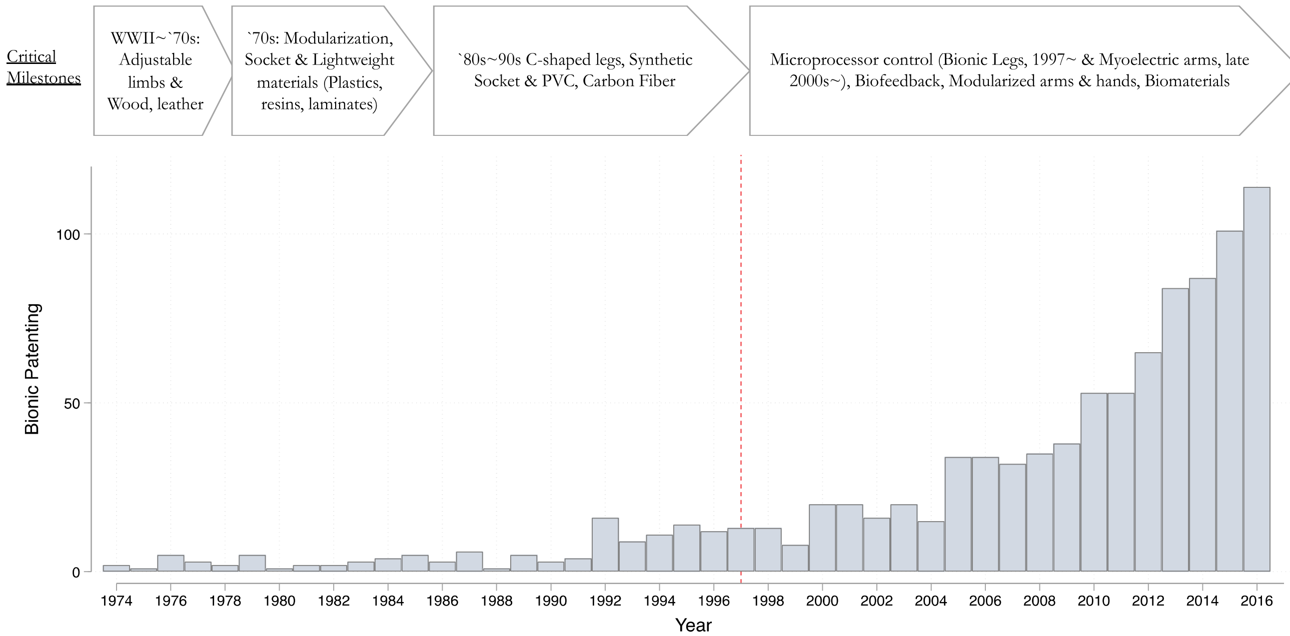
Building on the nature of the two distinct technological systems described above, we turn to the questions of *who* invested in creating the novel technological system and *how* bionic prosthetics were incubated at component and system levels. These questions are prerequisites to explaining the strategic choices and the resultant outcomes in terms of value capture by organizations in the emergent bionic prosthetics industry.

Online Appendix C describes our approach to sample construction of investing firms and efforts to ensure accuracy and comprehensiveness of the data through triangulation across multiple sources. (See Tables C1–C3 in Online Appendix C for descriptions and data sources.) Briefly, given high patenting rates in the prosthetic industry and regulatory requirements for clinical trials and product announcements, we track firms and their internal research and development (R&D) efforts through these measures, and also, we compile data on firms' external R&D efforts as measured by technology alliances or buy side in acquisitions. The comprehensive and careful nature of the search enabled us to identify 111 firms, which we judged to be the population of firms investing in the bionic prosthetics industry during the 1974–2018 period. Most entrants (87%) engaged in internal investment. Additionally, 25% sourced technology through alliances, and 16% acquired other technology-investing firms. Moreover, 23% of technological entrants used more than one mode, and 5% used all three R&D modes. Tables C4–C6 in Online Appendix C provide summary statistics for key variables used in the various analyses below.

Figure 2 depicts trends in bionic prosthetic patents and important technological milestones starting from 1974, the first year in our bionic patent data. The patenting trend reveals minimal activity through the mid-1980s and a sharp acceleration beginning in the late 1990s, spurred by advances in information and computer technology. Figure 3 depicts trends in (a) a cumulative number of firms that entered the prosthetic technology space, (b) a cumulative number of firms that commercialized a bionic prosthetic product or component, and (c) market sales based on Medicare spending on bionic limb prostheses. Both technological and product market spaces depict increasing trends. Cumulative technological entry accelerated earlier (mid-80s) than market entry (late 90s) and is at a larger scale through all years. Figure 3 also depicts a sharp increase in sales starting in 2004. Taken together, Figures 2 and 3 showcase a deepening of technological activity within an increasing number of firms. These trends and associated incubation and takeoff stages of firm and sales in bionic prosthetics are consistent in terms of duration and patterns with those reported for other industries (Agarwal and Bayus 2002, Golder et al. 2009, Moeen and Agarwal 2017).

We created three mutually exclusive dummy variables for firm types—*start-ups, mechanical prosthetic firms (incumbents), and established firms from other industries (other established firms).* A firm is classified as an

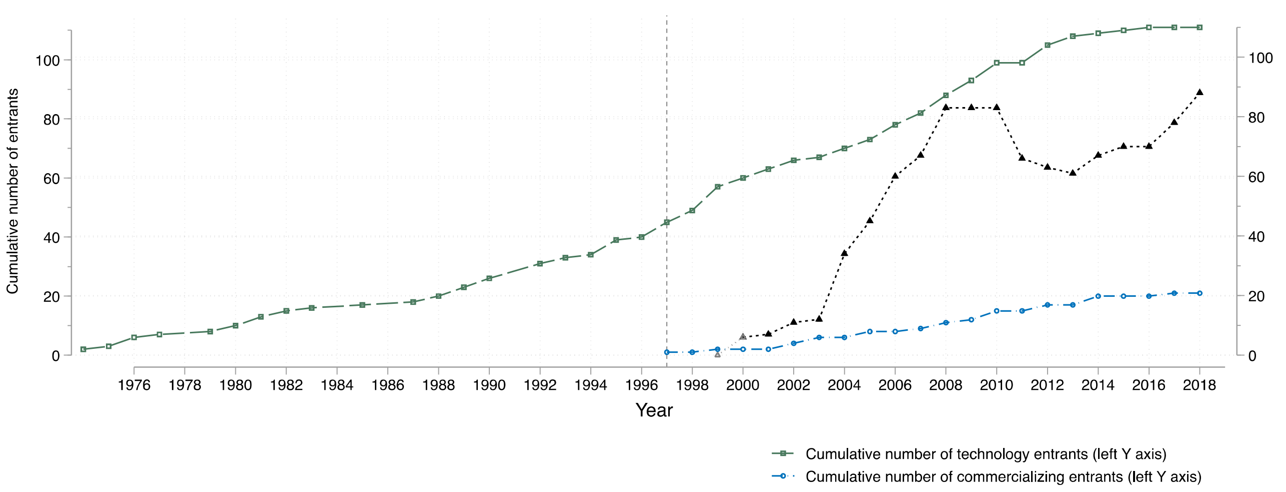
Figure 2. (Color online) Technological Evolution of the Prosthetic Limbs



Notes. The figure represents the counts of granted and pending patent applications made to the United States Patent and Trademark Office (USPTO) by their filing year that are relevant to key bionic prosthetic technology based on rows (a) and (b) in Table C2 in Online Appendix C. The applicants of the patents include various actors, including firms, nonprofit organizations, government agencies, and individual inventors. WWII, World War II.

incumbent if it had previously produced any prosthetic limbs, as an established firm from other industries if its products were in other industries prior to technological entry, and as a start-up if no business history could be identified. Our data include 33 start-ups, 24 incumbent prosthetic manufacturers,[4] and 54 established firms

Figure 3. (Color online) Firm and Sales Trends in Bionic Prosthetic Limbs



Notes. The left y axis represents the cumulative count of entrants. The right y axis represents sales (unit: U.S. dollars in millions). We use cumulative entry (not the number of actors) in a particular year because we lack information on exits from the technological space and because it captures the numerosity and intensity of technological and commercialization efforts. Data on sales are systematically available from allowed charges for Medicare Healthcare Common Procedure Coding System codes frequently associated with bionic prosthetic limb reimbursement using the U.S. Medicare National Part B spending data during 2000–2018 (https://www.cms.gov/). The Medicare reimbursement data cover approximately 30% of medical payments for prostheses and set standards for private insurers. The sales trend correlates but underestimates revenues associated with bionic prosthetics. Of note, Medicare beneficiaries are people over 65 years of age, so the underestimation is also because of the omission of younger prosthetic users (more active and interested in high-functioning devices). Nonetheless, Medicare spending is an important index for growth trends and widely accepted in the O&P field. The sharp decrease between 2011 and 2013 in Medicare spending is because of stringent Medicare audits rather the contraction of the market demand.

operating in other industries. These patterns of numerosity and organizational diversity in technological entrants are consistent with studies of fiber optics (Cattani 2005) and agricultural biotechnology (Moeen and Agarwal 2017). Not reported, 60% of the start-ups had at least one cofounder whose ideas originated from their academic research in bionics (Kim 2020). Eighty-seven percent of incumbents were exclusively focused on the prosthetics and orthopedics industry. The other established firms were from other medical sectors (38%), medical science and technology engineering (15%), and nonmedical industries ranging from electronics and electrical equipment (18%) to automotive (7%); science, technology, and engineering (5%); aircraft and aerospace craft (4%); and others, including military technology applications, insurance, and personal care (13%).

Value Creation Through Internal and External Technological Investments

Per Table 1, prosthetic technology systems include three main subtechnological systems: control, design, and materials. Using patent measures, we distinguish between mechanical technology in control, design, and materials and bionic technologies in all three subsystems (see Table C2 in Online Appendix C). The variable *Bionic Prosthetic Patents* is the stock of a firm's patents in bionic technologies. Similarly, *Nonbionic prosthetic patents* are the stock of a firm's patents in mechanical control, design, or material subsystems. Patent count variables are right censored at the time of a firm's first value capture event (defined below) or if there was none, 2018. Among external modes, *Alliance* and *Acquisition (Buyer)* are dummy variables that take the value of one if a firm engaged in either of these interorganizational efforts. We measure *Knowledge Spillover to Other Technology-Investing Firms* by averaging the sum of nonself forward citations for each firm. Also, we compute *Knowledge Spill in from Other Technology-Investing Firms* as the ratio of backward citations to other technology-investing firms (excluding self-citations) to total citations within the bionic patents through 2018.

The linear probability regressions (robust to logit specifications) in Table 2 and the crosstabs in panel B of Table C6 in Online Appendix C report the various R&D modes utilized by each organizational type.[5] For internal development, the mean, median, and maximum patents (panel B of Table C6 in Online Appendix C) reveal that incumbents had more bionic prosthetics patents than start-ups and other established firms and that patenting activity is right skewed (i.e., a few firms in each type are highly innovative; this fact motivates choices in historical samples below). From panel B of Table C6 in Online Appendix C, incumbents patented, on average, 3.6 bionic prosthetic patents compared with 2.4 for other established firms and 1.3 for start-ups. In Table 2, the simple linear probability models reflect these numbers (the constant term reflects the likelihood for *Other Established Firms*—the omitted category—and we arrive at the likelihoods for the other two types by adding the respective coefficient to the constant term). The precision of these coefficients is low, indicative of a higher within-type (relative to between-type) variation in patenting. Nevertheless, incumbents had more prosthetics patents than start-ups (F-test (null) = 8.92).

Among external R&D modes, Models (2) and (3) in Table 2 depict the use of formal channels of alliances and acquisitions. Relative to other established firms (11%), both start-ups (36%) and incumbents (44%) were more likely to enter technological alliances, and the F-

Table 2. Dependent Variable: *Modes of R&D and Interorganizational Interactions*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Estimation model	OLS	LPM	LPM	OLS	OLS	OLS	OLS
Variables	*Internal R&D*	*Tech Alliance*	*Acquisition (Buyer)*	*Knowledge Spillover to Other Technology-Investing Firms*		*Knowledge Spill in from Other Technology-Investing Firms*	
Incumbents	1.38 (0.96)	0.33 (0.11)	0.30 (0.11)	−3.26 (5.17)	−1.26 (5.52)	0.08 (0.04)	0.07 (0.04)
Start-up	−1.03 (0.65)	0.25 (0.09)	0.03 (0.07)	−7.53 (4.09)	−8.01 (4.13)	0.08 (0.04)	0.08 (0.04)
# of prosthetic Patents (internal)					−0.08 (0.03)		0.01 (0.01)
Constant	2.36 (0.59)	0.11 (0.04)	0.09 (0.04)	12.63 (3.05)	13.22 (3.11)	0.10 (0.02)	0.08 (0.02)
Observations	111	111	111	111	111	111	111
R^2	0.05	0.11	0.10	0.03	0.04	0.05	0.07
F-statistic	5.11	6.62	3.71	1.72	4.05	2.686	2.608
$\beta_{incumbent} = \beta_{startup}$	8.92	0.28	5.23	0.73	1.46	0.00003	0.09

Notes. Firm-level analyses are shown with robust standard errors in parentheses. Baseline is other established firm. $\beta_{incumbent} = \beta_{startup}$ reports F-statistics for differences across these firm types. We note that some readers may consider the patent count a bad control as it may be representative of a broader strategic choice. Ordinary Least Squares (OLS) and Linear Probability Model (LPM) are used for estimation.

test reveals no difference between the latter two (*F*-test (null) = 0.28). Incumbents were more likely to acquire other firms (39%) relative to other established firms (9%) and start-ups (12%) (*F*-test (null) = 5.23). Finally, the knowledge spillover and spill-in variables (Models (4)–(7) in Table 2) show that all firm types built on each other's patents as indicated by forward and backward citations.[6] Notably, technology-investing firms cited patents of other established firms more than of incumbents and start-ups (Models (4) and (5) in Table 2); however, the lack of precision in these estimates is because of high within variation as reflected by the standard deviations and maximums of *Knowledge Spillover and Spill in* in panel B of Table C6 in Online Appendix C.

Integration Efforts for the Development of the Bionic Prosthetics Technological System. We turn to differences across organizational types in terms of focus on component- versus system-level integration activity. *Number of Subtechnologies Integrated* is the number of subtechnological systems combined with bionic controls either at the time of the firm's first commercialization event or if none, in 2018. A value of zero indicates no firm-level integration between bionic controls and the other three components of the system represented in a firm's patent portfolio. A maximum value of three indicates that a firm possesses patents assigned a patent class into bionic controls and all three subsystems. When inferring integration, we assume that if a firm patents across multiple subtechnological systems, it is integrating between them. We also create a dummy variable for *System Integration,* which equals one if *Number of Subtechnologies Integrated* is positive (and zero otherwise).

Table 3 reports regressions examining whether firms are more likely to invest in components or system integration (internally or by acquiring patents through markets) prior to their first value capture event. Model (1) in Table 3 shows no evidence that incumbents were different from other established firms in integrating bionics with at least one other component, but start-ups had a 19% lower probability of doing so. The differences are more stark for *Number of Components Integrated* (Model (3) in Table 3), revealing that incumbents occupied the critical role of system integrators; they integrated 0.52 more components and start-ups integrated 0.38 fewer component than other established firms to do so. This corroborates the descriptive statistics in panel B of Table C6 in Online Appendix C; incumbents integrated on average 1.88 nonbionic component systems with bionic systems, other established firms integrated on average 1.47, and start-ups integrated on average just 1 additional component. Models (2) and (4) in Table 3 suggest that these differences are not an artifact of higher patenting rates.

Together, the results from Tables 2 and 3 reveal that all firms engaged in all modes of R&D investment and contributed important innovations to the technological ecosystem, with varying degrees of precision observed across firm types. Moreover, incumbents assembled more complete bionic prosthetics technological systems (versus subsystems or only bionic components).

Value Capture Through Alternative Modes and Markets

Per Moeen and Agarwal (2017), we use the following dummy variables (taking the value of one and zero

Table 3. Dependent Variable: *Technological System Integration by Firm Type*

	(1)	(2)	(3)	(4)
Estimation model	LPM		OLS	
Variables	*System Integration, dummy*		*Number of Components Integrated*	
Incumbent	0.07	0.03	0.52	0.43
	(0.09)	(0.10)	(0.24)	(0.24)
Start-up	−0.19	−0.19	−0.38	−0.36
	(0.10)	(0.10)	(0.22)	(0.22)
# of prosthetic patents		0.001		0.003
		(0.001)		(0.002)
Constant	0.80	0.79	1.44	1.41
	(0.05)	(0.06)	(0.13)	(0.13)
Observations	111	111	111	111
R^2	0.06	0.07	0.10	0.11
F-statistic	2.89	7.27	5.67	4.29
$\beta_{incumbent} = \beta_{startup}$	5.55	3.14	11.34	8.27

Notes. Firm-level analyses are shown with robust standard errors in parentheses. Baseline is other established firm. $\beta_{incumbent} = \beta_{startup}$ reports *F*-statistics for differences across these firm types. We limit patents before the first value capture to isolate value creation strategies prior to the value capture event. Results are robust when (a) including patents filed after the first value capture and (b) excluding externally acquired patents. Ordinary Least Squares (OLS) and Linear Probability Model (LPM) are used for estimation.

otherwise) if a firm (a) commercialized a product through *Market Entry*, additionally distinguishing *Entry into Bionic Prosthetics System* or *Entry into Component*; (b) *Provided Technology in Alliance*; or (c) is *Being Acquired* by other firms in the bionic prosthesis space. Sources used to compile these variables are listed in Table C1 in Online Appendix C. The descriptive statistics in panel A of Table 4 and the linear probability regressions (robust to logit specifications) in panel B of Table 4 provide the various modes of value capture by firm type, with other established firms once again as the omitted category. Even numbered columns in panel B of Table 4 control for the number of a firm's bionic patents. See Tables C8 and C9 in Online Appendix C for robustness checks.

Turning first to product markets, most technology entrants never entered the product market. Among the 21 (of 111) technology investors that entered product markets, 12 (of 24) were incumbents, 7 (of 33) were start-ups, and 2 (of 54) were other established firms. Notably, the coefficients in panel B of Table 4 are more precise given higher intermarginal variation in the dependent variable. Other established firms rarely entered; the constant terms show that their likelihood of market entry in Model (1) in panel B of Table 4 (market entry) and Model (3) in panel B of Table 4 (system-wide solutions) was 4%, and they did not enter component markets. Adding the constant for other established firms and the point estimate for start-ups, Model (1) in panel B of Table 4 reveals a 22% probability of start-ups entering product markets; moreover, start-ups were less likely to provide system-wide solutions (10%) than enter component markets (15%). In stark contrast, incumbents were more likely to enter product markets (50% did so); of these, 38% provided system-wide solutions. The *F*-statistics for coefficient differences between incumbents and start-ups for market entry and system-wide solutions in Models (1) and (2) in panel B of Table 4, respectively, are inconsistent with the likelihood that they are the same.

In terms of value capture by seeking acquisitions, the descriptive statistics and model estimates reveal that start-ups had a larger likelihood of *Being Acquired* relative to both incumbents and other established firms. *Being Acquired* was a rare event for other established firms (constant term is 2%), reflecting that only 1 of 54 other established firms was acquired. Adding constant and point estimates, Models (7) and (8) in panel B of Table 4 reveal a 33% likelihood of start-ups being acquired, reflecting that 11 of 33 start-ups were

Table 4. Value Capture Strategy and Firm Type

Panel A: Descriptive statistics on value capture strategy by firm type

	N	*Market Entry*: (a) or (b)	(a) Entry: System level	(b) Initial entry: Component	Ever being acquired	Acquired after market entry	Provided technology in alliance
Incumbents	24	12	10	3	3	1	3
Start-ups	33	7	3	5	11	3	11
Other established firms	54	2	2	0	1	0	5
Total	111	21	15	8	15	4	19

Panel B: Dependent variable—*Value Capture Strategy* (linear probability models)

Variables	(1) *Market Entry*	(2) *Market Entry*	(3) *Entry into System*	(4) *Entry into System*	(5) *Entry into Component*	(6) *Entry into Component*	(7) *Being Acquired*	(8) *Being Acquired*	(9) *Providing Tech. in Alliance*	(10) *Providing Tech. in Alliance*
Incumbent	0.46	0.50	0.38	0.42	0.12	0.12	0.11	0.11	0.03	0.04
	(0.11)	(0.11)	(0.11)	(0.11)	(0.00)	(0.07)	(0.07)	(0.07)	(0.08)	(0.08)
Start-up	0.18	0.17	0.05	0.05	0.15	0.15	0.31	0.31	0.24	0.24
	(0.08)	(0.08)	(0.06)	(0.06)	(0.00)	(0.06)	(0.09)	(0.09)	(0.09)	(0.09)
# of prosthetic Patents		−0.00		−0.00		0.0001		0.00001		−0.0002
		(0.00)		(0.00)		(0.0004)		(0.0006)		(0.0003)
Constant	0.04	0.05	0.04	0.05	−0.00	−0.00	0.02	0.02	0.09	0.09
	(0.03)	(0.03)	(0.03)	(0.03)	(0.00)	(0.00)	(0.02)	(0.02)	(0.04)	(0.04)
Observations	111	111	111	111	111	111	111	111	111	111
R^2	0.21	0.23	0.19	0.21	0.07	0.08	0.16	0.16	0.08	0.08
F-statistic	11.27	7.878	6.645	4.674	4.535	2.996	7.654	5.056	3.415	2.661
$\beta_{Incumbent} = \beta_{startup}$	5.21	6.5	8.17	9.21	N/A[a]	0.11	3.74	3.62	3.74	3.3

Notes. Columns (a) and (b) in panel A are not mutually exclusive in that two firms entered at both system and component levels. In panel B, firm-level analyses are shown with robust standard errors in parentheses. Baseline is the other established firm. $\beta_{incumbent} = \beta_{startup}$ reports *F*-statistics for differences across these firm types. Note that we do not report the result for coefficient equality in Model (5) as no other established firm made a component-level product entry. N/A, not applicable.

[a]Alternatively, we ran a *t*-test to compare the sample means between incumbent and start-up, which indicated no meaningful difference between the two ($t = -0.28$).

ultimately acquired, 3 of which had engaged in market entry prior to the acquisition. Incumbents had a 13% probability of being acquired, which is significantly different than that in start-ups. Finally, *Providing Technology in Alliance* was one strategy that other established firms were most likely to employ. Five of 54 other established firms provided technology in an alliance, reflecting the 9% likelihood of doing so in Models (9) and (10) in panel B of Table 4. From panel A of Table 4, 11 of 33 start-ups provided their technology to other firms, which translates to the likelihood of 33% (=0.24 + 0.9) in Models (9) and (10) in panel B of Table 4. Incumbents were in between; they had a 13% likelihood of providing technology in an alliance.

Taken together, the results indicate that almost all complete bionic prosthetic systems were introduced to the market by incumbents, although a few start-ups were able to do this, and other established firms invested in the technology were unlikely to monetize in this way.

Analysis of Business Histories

Although the above analyses provide insight into value creation and capture by firm types, they do not provide insight on *why*. Business histories help uncover the cause-effect reasonings that explain these patterns. Guided by scholars utilizing historical methods in strategy and entrepreneurship (Bucheli and Wadhwani 2014, Agarwal et al. 2020, Pillai et al. 2024), we identify 15 historically significant cases by identifying the top five patenting firms from each firm type (see Online Appendix D for our sampling strategy, data source, descriptive statistics, and use of various historical research practices (e.g., source criticism, contextualization, and hermeneutics for narrative construction)). This enables us to develop each firm's unique historical narrative that causally links events and allows for comparison of both within- and across-firm-type pattern generation (Online Appendix D). These narratives are essentialized in Table 5 for the general patterns that we believe are most important in terms of each firm's prior knowledge and intent for technological entry (panel A of Table 5), technological investments for the creation of the bionic prosthetic technological system (panel B of Table 5), and value capture strategies (panel C of Table 5).

Prior Histories of Technological Entrants

Turning first to start-ups (panel A of Table 5), the prior histories of cofounders for each start-up reveal rich and hybrid backgrounds (academic, user, and corporate), sometimes even within the same founder. For all but one, at least one cofounder had an immediate prior affiliation to an academic or hospital setting, conducting research in advanced prosthetics, biomechtronics, or artificial intelligence. For each of these four, the founders' intent was to capitalize on their basic research, and in two cases, the founding team included an amputee whose intent was to address needs unmet by conventional prosthetics. For four start-ups, although the founding team and early recruits in each represented complementary technological or user knowledge, none of the founders had direct experience of prosthetics manufacturing, marketing, or sales. The exception, Orthocare, was created by amputee-lawyer Doug Cormack, who convinced bioengineer cofounders Kim Coleman and David Boone to fold their prior venture (Cyma) into Orthocare at its inception. Cyma provided Orthocare with knowledge in product design, clinical evaluation, regulatory support, transition to manufacturing, and machine design. iWalk provides an illustrative example of how the founder's intent and experience influenced why it was created and what its technological focus was. Lead founder Hugh Herr was a prodigy mountain climber who lost his legs to frostbite. Herr subsequently chose a career in engineering, conducting basic research and rising to a leadership position in the Massachusetts Institute of Technology's laboratory over a 25-year period. In the early 2000s, Herr developed and sublicensed his laboratory's bionic "Rheo Knee" technology to prosthetics incumbent Össur. Partially because of his dissatisfaction with the technology transfer process, Herr founded iWalk in 2006 to consolidate the Rheo Knee license with opportunities arising from a new bionic ankle technology developed in his research laboratory.

Panel B of Table 5 reveals that four established firms from other industries (DEKA, Honda, Kobe Steel, and Samsung) had diverse technological and downstream capabilities related to (auto-)motives, electrical engineering, computers, or robotics. Liberty Mutual Insurance lacked prior relevant technological capabilities, but its intent arose from economic gains from enabling injured workers with better-performing bionic prosthetics to return to work relative to paying long-term disability claims. In contrast, Honda's and Samsung's intent stemmed from their long-standing strategy of growth and diversification strategy into humanoids or assistive technology dating back to the 1980s. Kobe Steel had a century-long history of medical technology investments through local hospitals and its "keiretsu" group firm affiliations. It was motivated by its collaboration partner, Hyogo Rehabilitation, to make technological investments in bionic prosthetics. DEKA was invited by The Defense Advanced Research Projects Agency (DARPA) to participate in its Revolutionizing Prosthetics 2007 grand challenge to help develop upper-limb smart prostheses for wounded veterans through grant funding of $18 million dollars.

The intent of all incumbents (Blatchford, Össur, Ottobock, Steeper, and Willow Wood) was aligned with the purpose of bionic prosthetics, and they possessed technological capabilities in mechanical prosthetics (panel C

Table 5. Historical Analyses of the Start-up Sample, Established Firms in the Other Industries Sample, and the Prosthetic Industry Incumbents Sample

Panel A: Historical analysis of the start-up sample			
Name/founding year	Founder knowledge context/motivation	Key technological investments and creation of technological system (year)	Value capture strategies
iWalk (2007)	• Hugh Herr, amputee professor, Biomechatronics research group at MIT; cofounders: Nicholas Negroponte, MIT Media Laboratory; Richard Greenwald, Bioengineering Dartmouth ○ Prior experience of developing Rheo Knee with Össur (2000–2004) • Intent of addressing unmet needs through applications of academic research; created firm to reduce technology transfer inefficiencies	• Developed bionic ankle BiOM (by licensing MIT technology at founding; 2007–2010) • Developed algorithms for analyzing user surroundings, gait optimization (2007–2017) • Created architectural design for motor, sensor, and spring components (system; 2007–2017) • Developed neural interface using targeted muscle reinnervation for lower-limb device controls (2007–2017)	• iWalk utilized revenues from Herr's license of Rheo Knee technology to Össur (incumbent; 2005) • Entered market with BiOM Ankle (announced 2008; available in 2010); reimbursed by U.S. Department of Defense (DoD) and The United States Department of Veterans Affairs (VA) • Acquired by Ottobock (incumbent; 2017)
Motion Control (1974)	• Stephen Jacobsen, PhD at MIT (adviser: Professor Mann of Boston Arm); bioengineering professor at University of Utah ○ Developed technology for artificial arm, heart, and kidney • Intent of developing academic invention	• Developed upper-limb prosthetics technology by licensing University of Utah technology (1974–1997) • Developed myoelectric control system for upper-limb prosthetics (1974–1997) • Created Utah Artificial Arm in 1981 and the improved version, the Utah Arm 2, in 1997 (system; 1974–1997)	• Acquired by Fillauer Companies, Inc. (incumbent) in 1997
Orthocare Innovations (2007)	• Doug McCormack, an amputee lawyer • Cofounders through Cyma acquisition: Kim Coleman, prior founder/director of research of Cyma; David Boone, director of research at Cyma • Intent of translating cutting-edge technology into commercial products	• Created iPed, a computer-controlled prosthesis (2008–2010) ○ Acquired Martin Bionics, academic start-up after McCormack met Jay Martin as his prosthetist patient at Sabolich; Martin continued within Orthocare ○ Partner: College Park industries for the iPed development • Developed components for robotic arm (2008) ○ Participated in DARPA's 2009 Revolutionizing Prosthetics (2008) ○ Licensed small-scale hydraulic technology from Oak Ridge National Laboratory (2009) ○ Collaborated with Johns Hopkins' APL for robotic arm development (2008)	• Entered market with Compas (component; 2009) • Licensed iPED to College Park Industries (incumbent; estimated around 2012) • Partnered with Ottobock to commercialize a bionic ankle Magellan (2013)
Touch Bionics (2005)	• David Gow, clinical director, NHS, United Kingdom ○ Specialized in rehabilitation engineering services and powered upper-limb research and development • Intent of addressing lack of product variety and technological progress and commercializing Gow's inventions at NHS	• Utilized Gow's bionic inventions i-Limb and i-Limb digits in NHS (2005–2009) ○ Partners: clinics including Advanced Arm Dynamics, Benchmark Orthotics and Prosthetics, Hanger Prosthetics, LIVING SKIN, and Sabolich Prosthetics and Research ○ Partner: LIVINGSKIN and ARTech for high definition covering solutions ○ Acquired LIVINGSKIN for covering resembling the dermal layers of natural skin (2008)	• Entered market with i-Limb (2007) • Launched i-Limb digits (2009); Biosim (software tool; 2010) • Acquired by Össur (2016)

Table 5. (Continued)

Panel A: Historical analysis of the start-up sample			
Name/founding year	Founder knowledge context/motivation	Key technological investments and creation of technological system (year)	Value capture strategies
Victhom Human Bionics (2002)	• Stephane Bedard, PhD in bioengineering at Laval University ○ Dissertation focused on AI applications to bionic leg • Intent of applying Bedard's AI research to bionic leg products	• Developed a bionic arm system and functional upper-limb components (e.g., individually controllable digits; 2005) • Utilized Bedard's AI research to develop bionic leg operations ○ Acquired Neurostream for its neurostimulation technology (2004) • Developed a bionic product line, including the Power Knee, for 3–6 years (2003 and 2005) • Codeveloped with Össur	• Licensed Power Knee technology to Össur (2004) • JV with Ottobock to commercialize neurostimulation (2009) • Sold Neurostream to Ottobock (2011) • Acquired by Ergoresearch (other established firm; 2013)
Panel B: Historical analysis of established firms in other industries sample			
Name/technology entry year	Firm knowledge context and motivation	Key technological investments and participation in knowledge aggregation (year)	Value capture strategies
DEKA (2006)	• R&D firm in medical devices and personal mobility (Segway; iBOT wheelchair) • Intent shaped by invitation to participate in DARPA's Revolutionizing Prosthetic Project to develop bionic arm system for wounded veterans (2006)	• Developed a system-level prototype and components, including the neural interface and actuators (2006–2009) ○ Partners: Liberating Technologies, Rehab Institute of Chicago, UNB, Northwestern, etc. • Entered clinical trials and improved usability for prosthetic arm for FDA approval (2009–2014) ○ Collaboration with VA	• Partnered with Mobius Bionics (start-up) in 2016 to commercialize DEKA Arm (Luke Arm) developed in DARPA project ○ Initial sales largely purchased by DoD/VA
Honda (1999)	• Diversified businesses in automotives, motorcycles, engines; power equipment ○ Prior knowledge in humanoid robots, including ASIMO (the 1980s) • Intent shaped by bionics R&D strategy (1999) ○ Develop assistive technology for the elderly/disabled by leveraging automobile/humanoid technology • Human mobility assistance to alleviate worker fatigue	• Applied existing automobile and robot technology to develop AI, control CPUs, motion-sensing tech, battery, etc. for human mobility (1999–) • Developed brain-machine interface technology (2007) ○ Partner: Advanced Telecommunications Research Institute International • Developed/tested control systems for walking (2008–2018) ○ Partner: Shinseikai Medical (2008) and Rehab Institute of Chicago (2014) • Developed bionic motorcycle arm prototype for amputees for communication between rider and bike (the 2010s)	• No value capture in prosthetics industry to date • Outside prosthetics: Launched an exoskeleton, the Honda Walking Assistive Device (early 2000)
Kobe Steel (early 1980s)	• Diversified businesses in steel manufacturing and machine controls • Intent shaped by collaboration with Hyogo Rehabilitation in Kobe's local community, founded by Seishi Sawamura, orthopedist whose father was a user-prosthetist	• Developed the first ever prototype of microprocessor-controlled prosthetic knee and obtained three patents (1980s–1992) ○ Leveraged machine controls/materials capabilities in research partnership with Hyogo Rehab • Conducted clinical trials at Hyogo Rehab Center (1989)	• Licensed technology to Blatchford (incumbent; 1993) and Nabtesco (Nabco; "diversifying entrant" affiliated with Kobe's keiretsu group; 1990s)

Table 5. (Continued)

Panel B: Historical analysis of established firms in other industries sample			
Name/technology entry year	Firm knowledge context and motivation	Key technological investments and participation in knowledge aggregation (year)	Value capture strategies
Liberty Mutual (1961)	• Large worker's compensation insurance provider in the United States since founding (1912) • Intent of helping injured policy holders to return to work; reducing disbursements. • Established Liberty Mutual Research Center for Safety/Health to help industrial accident victims (1954)	• Under Melvin Glimcher's leadership, Liberty funded the MIT research to develop prototype of myoelectric prosthetic elbow (later the Boston Elbow; 1961) • Hired MIT researchers (e.g., Amar Bose and Norbert Wiener) to further develop the elbow prototype (1960s) • Hired physicist T. Walley Williamson for commercial development (1973) ○ Partners: Harvard Medical School and Mass General • Bill Hanson (founder of Liberating Technologies) joined (1984)	• Sold some of the prosthetic research division to Bill Hanson's Liberating Technologies (employee spin-off; 2001) • Completely shut down the research center (2017)
Samsung (2014)	• Diversified businesses in semiconductors and electronic products • Intent driven by mobility assistive technology as a strategic growth to address needs of aging population	• Samsung Science & Technology Foundation funded research projects on medical robots at universities (2014) ○ Follow-on internal research and 10+ clinical trials in Korea and the United States • Invested in mobility assistive technology (2014–) • Invested in Pillo, an AI medical robot start-up (2018)	• No value capture in prosthetics industry to date • Outside prosthetics: Obtaining an FDA approval for an exoskeleton, GEMS hip assistive robot (2022)
Panel C: Historical analysis of the prosthetic industry incumbents sample			
Name	Firm knowledge context (intent aligned with purpose of the system for all incumbents)	Key technological investments and participation in knowledge aggregation (year)	Value capture strategies
Blatchford	• Founded by Chas A. Blatchford (1890) • Specialized in O&P ○ Major provider to NHS (since 1948) ○ Created the Modular Assembly Prosthesis (1970s) ○ Applied carbon fiber material for aircraft to limb prosthetics (1980s)	• Developed Intelligent Prosthesis & Adaptive Knee (integrating microprocessors, hydraulics, pneumatics technologies) ○ Licensed technology from Kobe Steel (1993) ○ Combined pneumatic/hydraulic controls with microprocessors (1990s) • Developed Elan microprocessor foot (integrating bionics, hydraulic ankle technology, and aerospace carbon materials; 2010s) • Developed intelligent and adaptive prosthesis by integrating new technologies/functions with existing prosthesis	• Entered market with Intelligent Prosthesis+ and Adaptive Prostheses in 1998 • Launched Elan Ankle (2011); Orion Knee (2014); the LiNX system (integrating Elan and Orion for above-knee amputees; 2015)
Össur	• Founded by Össur Kristinsson, a prosthetist (1971) • Specialized in O&P ○ Developed the silicone prosthetic liner called Iceross (1986) ○ Developed carbon fiber and hydraulic technology by acquiring Flex-Foot (2000)	• Developed Rheo Knee integrating bionics and hydraulics (late 1990s) ○ Collaborated with MIT's Herr, and licensed his technology • Developed Power Knee by incorporating AI ○ Partnered and licensed technology from Victhom (2003 and 2005) • Developed "smart structures" (integrating electronic, mechanical components for "user-extension" functions) ○ Partnered/purchased powered prosthetic ankle technology from SpringActive (2015 and 2019) • Developed mind-controlled prosthetics and neurointerface	• Entered market with the Rheo Knee (2005) • Launched the Power Knee and the Proprio Foot (2006); symbionic leg (integrating a bionic knee and bionic ankle; 2012); i-Limb and i-Limb Digits of Touch Bionics (2016)

Table 5. (Continued)

Panel C: Historical analysis of the prosthetic industry incumbents sample

Name	Firm knowledge context (intent aligned with purpose of the system for all incumbents)	Key technological investments and participation in knowledge aggregation (year)	Value capture strategies
		○ Research Trust Fund with Ottobock at the University of Iceland (2016) ○ Licensed from Alfred E. Mann (2019) • Developed wearable technology/exoskeleton for mobility ○ Partner: COMAU (part of Fiat-Chrystler) to invest in IUVO for wearable robot technology (2017) • Extended to bionic upper-extremity technology and prosthetics ○ Acquired Touch Bionics (start-up; 2016) • Strengthened mechanic prosthetic product lines and technology • Strengthened sales, marketing, and distribution in prosthetics ○ Acquired Medi Prosthetics (2016); small prosthetic players (2012), distributors and service providers (2014) ○ Funded Össur Running and Mobility Clinics partnered with Challenged Athletes Foundation; 2012)	
Ottobock	• Founded by Otto Bock (1919) and succession to son-in-law Näder • Specialized in O&P ○ Jupa Knee with a brake mechanism (1949) ○ Pneumatic hand (1962) ○ Pyramid design and modular system (1969)	• Early experiments in myoelectric hands ○ Partner: Viennatone for electronics (1967–1977) • Developed C-Leg (integrating bionics and hydraulics controls) ○ Licensed technology: Kelly James (University of Alberta/biomechanical engineering; 1992–1997) • Developed bionic hand by adding sensors (early 2000s) ○ Partners: NHS, clinics for test fitting • Developed Michelangelo Hand (integrating electrodes/electromyography software) ○ Partner: Advanced Arm Dynamics for clinical tests (2008) • Enhanced bionic upper-limb line; gripping patterns/finger movement ○ Acquired BeBionics from Steeper; Freedom Innovation (2017) • Developed Axon-Bus system (fitting interface) with self-contained data transmission system • Participated in DARPA Revolutionizing Prosthetics (2007) ○ Partner: JHU APL for research on tissue engineering and neural interface • Acquired Neurodan (2005) and licensed neurostimulation technology from Victhom (2005); acquired Victhom's division (2011) • Developed mind-controlled prosthetics and neurointerface	• Entered market with C-Leg, the first bionic prosthetic knee (1997) • Launched Myo (Arm) Systems and Dynamic Arm (2003); Michelangelo Hand (2010); Genium Leg (integrating a bionic knee and ankle; 2011) and Kenevo Knee (2015); BiOM (of iWalk) and BeBionic Hand (of Steeper; 2017) • Outside prosthetics: Entered occupational exoskeleton in partnership with Volkswagen (2022)

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Table 5. (Continued)

Panel C: Historical analysis of the prosthetic industry incumbents sample

Name	Firm knowledge context (intent aligned with purpose of the system for all incumbents)	Key technological investments and participation in knowledge aggregation (year)	Value capture strategies
		○ Research Trust Fund with Össur within the University of Iceland (2016) • Developed wearable technology/Eksoskeleton technology ○ Licensed from Ekso Bionics (University of California Berkeley spin-off; 2014); partner: Volkswagen; acquired SuitX (Berkeley spin-off) for robotic exoskeletons (2021) • Strengthened carbon fiber composite technology ○ Acquired Spring Lite (2001); Freedom Innovation (2017) • Developed fitting technology ○ Acquired BioPortrait (fitting; 1998); Tech Interface Systems (start-up) for volume management technology (fitting; 2003); Respecta (fitting and clinical tests) and Pohlig (fitting; 2013) ○ Partner: UNYQ (start-up) for covering (2015) • Enhanced prosthetic sales, marketing, distribution ○ Acquired VASI for its presence in pediatrics market (2005) • Strengthened prosthetics manufacturing • Acquired Danforth (2002)	
Steeper	• Founded by Hugh Steeper • 1921 • Specialized in O&P; owned Steeper Clinics, through which it distributed devices in the United States and the United Kingdom	• Started research program on powered upper-limb components (e.g., electric hands, electrodes, battery, and cabling) in early 1980s • Developed BeBionic Hand (integrating bionics, novel materials (e.g., aerospace alloys), and design principles; 2014) ○ Licensed bionic upper-limb technology from BeBionic inventor Mark Hunter (2008) • Acquired the Espire Elbow from College Park Industries (2020)	• Entered market with BeBionic Hand in 2010 • Sold BeBionics to Ottobock (2017)
Willow Wood	• Founded by William E. Arbogast, an amputee (1907) • Specialized in prosthetic and orthotic manufacturing ○ SACH Foot (1961) • Carbon Copy II Foot (1984)	• Developed robotic knee (integrating titanium, thermal alignment, internal electronics, and extended power sources; 1999) ○ Collaborated with Sandia National Laboratory and Chelyabinsk 70 laboratory • Developed pattern recognition technology for prosthetic arms ○ Collaborated with the University of Michigan, Cleveland University, and Coapt (Rehab Institute of Chicago spin-off) • Launched Willow Venture to invest in new technology	• Entered market with Limblogic (an accessory; 2007)

Note. APL, Applied Physics Laboratory; ASIMO, Advanced Step in Innovative Mobility; It's the product name of a humanoid robot developed by HONDA; CPU, Central Processing Unit; DoD, Department of Defense; GEMS, Gait Enhancing & Motivating System; Samsung's wearable robotic exoskeleton; MIT, Massachusetts Institute of Technology; IUVO, a spin-off company of The BioRobotics Institute; NHS, The National Health Service; UNB, the University of New Brunswick; VA, Veteran Affairs.

of Table 5). All five firms specialized in orthotics and prosthetics rather than being diversified in other medical devices or industries. All were recognized as technological leaders in the industry as each had pioneered critical innovations in component elements of materials, alignment designs, or mechanical controls. They also possessed downstream capabilities related to marketing, sales, and manufacturing for orthotic and prosthetic devices. For example, Össur (2000, pp. 6–7) explicitly sought to build on its capabilities in materials, marketing, sales, and distribution by "[securing] technological developments."

Technological Investments for the Creation of New Bionic Technology Systems and Competencies

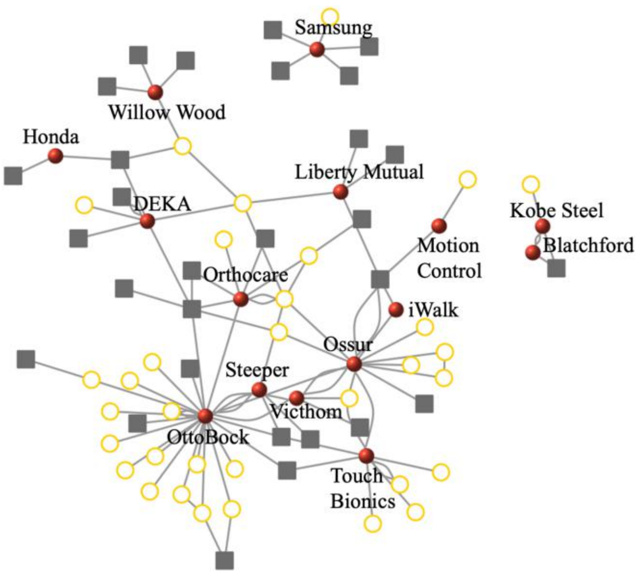
Panel A of Table 5 depicts how start-ups' technological investments leveraged their founders' research expertise and insights, including through licensing of patents assigned to academic institutions. Each start-up's path-dependent technological investments focused on bionic components through use of computer algorithms, sensors, robotics, or artificial intelligence. For example, iWalk's Hugh Herr built on his insights regarding a need for improvement not only in the human nervous system interface and use of data for enhanced performance but also, in the physical connection to the body. iWalk pieced together these capabilities in its efforts to develop a bionic ankle. Orthocare grew its functionally diverse business and technology team for enhance bionics expertise through a key early acquisition of Martin Bionics and forging ties with and hiring personnel from Johns Hopkins' Advanced Prosthetics Laboratory. To fill gaps in hydraulics capabilities, it licensed a small hydraulic subtechnology from Oak Ridge National Laboratories. All five start-ups focused initially on single products, which contrasts with the more diversified strategies of the other firm types.

Panel B of Table 5 showcases that three of the other established firms' investments in bionic prosthetics technologies (Kobe Steel, Honda, and Samsung) were an offshoot of their development of bionics subtechnological systems for problems other than prostheses. As an example, Honda leveraged existing robotics capabilities developed as part of a human mobility assistance technology designed to alleviate factory worker fatigue. Honda invested in AI, motion sensing for human mobility starting in 1999, and brain-machine interface technology starting in 2007, and it experimented with a prototype arm that permitted an amputee to ride a Honda motorcycle. All five firms' investments were fueled by partners with prosthetics-related capabilities and motivations. For example, as an early entrant in 1961, Liberty Mutual funded basic research in universities and subsequently hired several of these researchers to internally develop the "Boston Elbow" in the 1960s. Similarly, DEKA's development of system prototypes heavily relied on a consortium of university laboratories and rehabilitation centers.

All five incumbents developed and sourced bionics knowledge and combined it with their own capabilities in traditional prosthetics subtechnologies, such as materials, hydraulics, and prosthetic design (panel C of Table 5). Some built on their historical investments, such as Ottobock in powered limbs and Steeper in electric/battery-powered hands and hooks. To complement internal knowledge, each engaged in a deliberate strategy to acquire start-ups and partner with universities, start-ups, and other established firms. In particular, Blatchford, Össur, and Ottobock explicitly note this to be their technology strategy, and Willow Wood also had a robust Corporate Venture Capital program. For example, Össur (1999, p. 7) started developing new bionic technology "through internal development and strategic investment in other companies" and especially, by looking for "small firms with only one product line [who] will find it increasingly more difficult to comply with official regulations while conducting research and development." Many, if not all, leveraged internal knowledge related to clinical testing, fitting, and customer engagement to increase effectiveness of prototypes and move the technologies into development and application stages, although Ottobock also acquired several companies that specialized in fitting and clinical tests.

Collaborative Ecosystems for the Creation of the Bionics Prosthetics Technological System. Figure 4 provides a visualization of each of the 15 firms in our historical sample as a node and licenses, alliances, and acquisitions as ties across them and other actors (representing uni- or bidirectional flows). Taken together with panels A–C of Table 5, it shows the internal technological investments of each of the 15 firms in our historical sample leveraged nonmarket collaborative networks and market channels to create bionic prosthetics technological systems. Several interrelated insights emerge from the historical analyses represented in Table 5 and Figure 4. First, from a capability perspective, the knowledge of various components was distributed across numerous actors. Start-ups, other established firms, and incumbents in our historical sample (the red spheres in Figure 4) not only leveraged each other's knowledge and capabilities but also, that generated by at least 33 other firms (the white circles with yellow outlines; or hollow circles in Figure 4) and 29 universities, rehabilitation centers/clinics, or government programs (the gray squares in Figure 4). Second, the historical analysis reveals that in addition to "science-push" investment by inventors and firms with requisite capabilities, the clusters represent fostering of technological investments through "demand pull" engagement by users with unmet needs, ranging from amputees (e.g., Herr and McCormack) to firms (e.g.,

Figure 4. (Color online) Technological Ecosystems for Value Creation



Notes. Red spheres: 15 historical sample firms, Hollow circles: 33 other firms, gray squares: government agencies, universities, clinics, and nonprofit research labs. Gvmt, government; Univ, universities.

Liberty Mutual) and public agencies (e.g., DARPA's 2007 and 2009 Revolutionizing Prosthetics Challenges).

Third, within each of the technology clusters of Figure 4, some relationships were based upon one party building on another's knowledge (often through market-based licensing or acquisition), whereas others represented active codevelopment and alliances that brought complementary knowledge and component technologies together. These "small-world" clusters reveal path dependencies that link the actors' prior knowledge and affiliations to their choices of technological investments and collaborative relationships. Fourth, within each cluster, the technological system was created through continued investments in improving all components. Here, start-ups spawned from research institutions. All firms created critical component knowledge, early "system" prototypes, and patents. Fifth, incumbents played a key role in technology convergence and creation of usable applications from prototypes. Their R&D efforts consisted of "upstream research" initiatives for integration of "old" and "new" technologies to create entire technological systems and "downstream development" initiatives that transformed research and prototypes of other actors into effective and usable applications through additional integration of materials, mechanical, and design innovations.

Value Capture Strategies in the Bionic Prosthetics Industry

Panel A of Table 5 highlights that one start-up, Orthocare, first sought to capture value by commercializing components (Compas). Two start-ups, iWalk and Touch Bionics, launched complete products (BiOM Ankle and i-Limb, respectively). However, licensing and alliances (often with different incumbents) were dominant forms of value capture for iWalk, Orthocare, and Victhom. Moreover, only Orthocare, the sole start-up with a founder with operational and marketing experience, remains independent. All other start-ups ultimately sought acquisition (three incumbents and one other established firm were on the "buy" side of these transactions). Notably, Motion Control's acquisition by an incumbent occurred in 1997, the year of the industry's inception.

Among other established firms, two (Honda and Samsung) have no record of market entry, alliances, or divestitures of capabilities to date; rather, they focused on adjacent value chains (exoskeletons and robotics, respectively). Only DEKA entered the market, doing so by leveraging downstream capabilities of start-up Mobius Bionics to commercialize its Luke arm prototype and targeting The U.S. Department of Defense (DoD) and The United States Department of Veterans Affairs users (given initial funding from DARPA). Kobe Steel licensed its technology to incumbent Blatchford and Nabco, a diversifying entrant into bionic prosthetics with the keiretsu group affiliation with Kobe. Liberty Mutual, the earliest of technology entrants, sold parts of its prosthetic research division to employee Bill Hanson's spin-off Liberating Technologies before shutting down its research center in 2017. Remarkably, all five other established firms' patents were extensively cited in follow-on bionic prosthetic patents.

All five incumbents in our sample entered bionic prosthetics: three with functional bionic limbs and two providing bionic accessories. Otto Bock commercialized the C-Leg bionic prosthetic for industry inception in 1997 (aided by technology licensed from start-ups Biomech and Victhom), and Blatchford followed shortly thereafter with their Intelligent Prosthesis+/Adaptive Prostheses that built on licenses of Kobe Steel's patents. This pattern also holds for the market entry of other incumbents in the historical sample; each commercialized functional system was created by integrating component knowledge or honing/further developing technologies and prototypes created by start-ups or individual inventors. Within this process, the individual firm histories reported in Online Appendix D reveal that the incumbents' downstream capabilities related to clinical testing, regulatory approvals, production, and marketing/sales were important to create products that optimized across trade-offs encountered in the functionality and use of their innovations.

Inference to Best Explanation

Panel A of Table 6 summarizes the central facts and their supportive evidence from preceding sections. Foundational Fact 1 showcases bionic prosthetics as a radical

Table 6. Summary of Facts and Supporting Evidence and Virtues of Considered Explanations

Panel A: Summary of facts and supporting evidence

Facts	Supporting evidence
Bionic prosthetics as a radical technological system. What were the component subtechnologies, and what new base principles were added relative to mechanical prosthetics?	
1. Integrated technological system. Artificial limbs that served the need for mobility required the creation of a technological system utilized new bionic base principles while also leveraging existing subtechnological systems and components (mechanical controls, materials, and design)	Tables 1, 3, and 5 and Online Appendices B and D
Value creation. Who incubated the bionic prosthetics system and why? How did they do so?	
2. Firms of all types invested in incubating the bionic prosthetics system 2.1. Incumbent firms in mechanical prosthetics made technological investments because their businesses served the focal purpose of providing artificial limbs for increased functionality 2.2. Start-ups were formed by individuals with intent to address their own unmet needs or leverage knowledge/inventions created in their roles within universities, public agencies, nonprofits, and existing firms 2.3. Established firms in other industries made technological investments with the intent to develop bionic technology in alignment with their strategic direction and needs	Tables 2, 3, and 5 and Table C6 in Online Appendix C
3. Active ecosystems of value creation during incubation 3.1. All investing firms invested in internal R&D efforts; they (particularly incumbents) also build on patents of other firms, engaged in technological alliances (markets for technology), and acquired patents and tech capabilities (markets for corporate control) 3.2. Vibrant clusters of value creation started being formed during incubation 3.3. Clusters were codeveloped among actors with complementary/component knowledge created by path-dependent links (using formal and informal channels) between the actors	Figures 2–4; Tables 2, 3, and 5; Table C6 in Online Appendix C, and Online Appendix D
4. Component knowledge creation 4.1. All firm types invested in critical new component knowledge, system prototypes, and patents 4.2. Key technological knowledge was found in universities, government agencies (e.g., DARPA), existing firms, and start-ups (founded by individuals embedded in these knowledge contexts) 4.3. Incumbents continued investing in critical component knowledge, such as new materials and mechanic control	Tables 3 and 5
5. Technological system creation. Incumbents played a key integrator role in bringing components together for the purpose of improving artificial limb functionality	Figure 4 and Tables 3 and 5
Value capture. How do the prior histories and technological investment of the firms affect their value capture strategies?	
6. Different value capture strategies 6.1. Incumbent pioneered and had leadership in bionic prosthetic products 6.2. Start-ups were acquired by or allied with incumbents 6.3. Other established firms did not enter bionic prosthetics but focused on adjacent value chains that utilized underlying technological investments consistent with their strategic direction	Tables 4 and 5 and Online Appendix D

Panel B: Virtues of considered explanations

Explanation	A. Consilience (facts in 6A)	B. Coherence (with prior work)	C. Parsimony (underlying assumptions)	D. Precision (of mechanisms)
Creating radical systems effects. Incumbents, other established firms, and start-ups engage in a cocreation process of technological systems and organizational competencies; their intent/evolving capabilities impact choice of value capture strategies	Yes: Facts 1, 2, 3, 4, 5, and 6	Technological systems as a nexus of base principles and purpose (Rosenberg 1982, Arthur 2009) Incubation of industries by creating/reconfiguring diverse knowledge bases through internal development and formal and informal channels for sharing knowledge (Moeen and Agarwal 2017, Moeen et al. 2020) *Representative context: Agricultural biotechnology; bionic prosthetics*	1A1: Creation of radical technologies from novel base principles requires building/integrating subtechnologies into systems to serve a specific purpose 1A2: Prehistories define initial distribution of relevant knowledge and locus of technological investments 1A3: Prehistories define intent (use of technological investments) for focal/alternative purpose	1.1: Investment by actors a function of a. system's purpose and actors' intent b. distribution of tech capabilities c. distribution of component capabilities 1.2: Complementarity across actors leads to a. value creation through component and system knowledge development and leverage of markets for technology and corporate control

Table 6. (Continued)

Panel B: Virtues of considered explanations

Explanation	A. Consilience (facts in 6A)	B. Coherence (with prior work)	C. Parsimony (underlying assumptions)	D. Precision (of mechanisms)
				b. value capture through alternative strategies (commercialization, alliances, acquisitions, adjacent value chains)
Organizational effects. Incumbents are less likely than entrants to invest in radical technology that renders existing competencies obsolete, resulting in entrant advantage	No: Fact 5 Yes: Fact 6.1 if competence-enhancing innovation Silent: Facts 1, 2, 3, 4, 6.2, and 6.3	Knowledge spillover externalities; incentives for investments (Arrow 1962, Reinganum 1983) Tech discontinuities (Tushman and Anderson 1986) *Representative context: Cement, airlines, minicomputers*	2A1: (Unitary) radical technology changes price-performance parameters 2A2: New technology requires new organizations with new tech capabilities 2A3: Value capture by product market entry.	2: Incumbent obsolescence and entrant advantage in product markets a function of a. lack of incentives for incumbent investments in radical technology b. lack of capabilities to create radical technologies that are ushered as exogenous shocks by entrants
Organizational inertia effects. Incumbents fall behind entrants in product markets in the face of radical technological change because of cognitive or organizational inertia	No: Fact 1 (cognitive), Facts 3, 4.1, 5, and 6.1 Yes: Fact 1 (structural), Fact 2.1 Silent: Facts 2.2, 2.3, 4.2, 6.2, and 6.3	Inertia of organizational capabilities (Henderson and Clark 1990, Leonard-Barton 1992) Inertia of managerial cognition (Tripsas and Gavetti 2000) *Representative context: Photolithography; digital imaging*	3A1: (Unitary) radical technology changes price-performance parameters 3A2. Prehistories define distribution of capabilities; core competencies become core rigidities to inhibit adaptation 3A3: Prehistories shape managerial cognition and belief misalignment inhibits adaptation 3A4: Value capture by product market entry.	3: Incumbent obsolescence and entrant advantage in product markets a function of a. rigidities in organization structures b. rigidities in managerial cognition in terms of perceived purpose of technology and organizational intent
Complementary assets effects. Incumbents leverage downstream complementary assets to trade with entrants that possess technological capabilities for radical technology	No: Facts 1, 2.1, 3, 4, 5, and 6.1 (not pioneering) Yes: Fact 6.2 Silent: Facts 2.2, 2.3, and 6.3	Profiting from innovation (Teece 1986, Mitchell 1989, Tripsas 1997, Rothaermel 2001) Markets for technology (Gans and Stern 2000, Arora et al. 2001) *Representative context: Biopharmaceuticals, diagnostic imaging, typesetters*	4A1: (Unitary) radical technology changes price-performance parameters, introduced as an exogenous shock to focal industry through product commercialization 4A2: New technology requires new technological capabilities 4A3: Comp. assets are required to profit from innovation 4A4: Value capture by product market entry 4A5: Value capture in markets for technology	4: Incumbent obsolescence and entrant advantage in product markets a function of continued importance and relevance of incumbent complementary assets
Organizational adaptation effects. Incumbents adapt their devalued technological capabilities through acquisition, assimilation, and reconfiguration to exogenous, radical technology	No: Facts 1, 2.1, 3, 4, 5, and 6.1 (not pioneering) Silent: Facts 2.2, 2.3, 6.2, and 6.3	Organizational adaptation (Hill and Rothaermel 2003, Eggers and Park 2018) *Representative context: Biopharmaceuticals*	5A1: (Unitary) radical technology changes price-performance parameters, introduced as an exogenous shock to focal industry through product commercialization 5A2: New technology requires new technological capabilities 5A3: Value capture by product market entry	5: Incumbent obsolescence and entrant advantage in product markets a function of incumbent ability to respond to technological change through reconfiguration, assimilation, and acquisition of tech capabilities

technological system that required the integration of a new subtechnology with simultaneous reconfiguration of old subtechnologies. Facts 2–5 document value creation for development of the bionic prosthetic technological system and requisite technological capabilities of investing firms. Fact 6 documents the subsequent value capture strategies for each type of investing firm. Panel B of Table 6 lists the alternative explanations and their consilience with facts (column (A)), coherence with prior research (column (B)), parsimony in terms of central assumptions (column (C)), and precision in terms of predicted cause-effect mechanisms (column (D)).

Virtues of the Emergent Explanation: Creating Radical Systems Effects

Our explanation, which we label *Creating radical systems effects*, highlights the endogenous process wherein organizations with different prehistories invested in creating components of the radical technological system and their evolving capabilities and intent shaped how they captured value through different strategies. This explanation is consilient with bionic prosthetics as a radical technological system (Fact 1), where value creation was enabled by technological investments by firms whose intent and prior capabilities were shaped by their prehistories (Facts 2.1–2.3). During incubation, such investments created the new technological system and its components through informal (e.g., knowledge sharing/diffusion) and formal (alliances and acquisitions) collaboration channels for the formation of vibrant clusters (Facts 3.1–3.3) within which firms interacted with each other, nonprofits, and government agencies to build on their varied knowledge capabilities (Facts 4.1 and 4.2). This also infused new technological capabilities in start-ups and existing organizations through reconfiguration efforts (Facts 4.1, 4.2, and 6.2). Incumbents were 20% of the organizations investing in bionic prosthetics but played a crucial role of "system integrators" by actively leveraging markets for technology and corporate control (Fact 3.1) to combine their own knowledge with that gained from other firm types to create and reconfigure components which fit together seamlessly for workable solutions (Fact 5).

In terms of value capture, the explanation is consilient with the use of alternative markets and value chains (Facts 6.1–6.3). Prosthetic incumbents were not only naturally positioned because of their system integrator roles to commercialize bionic prosthetic products, but this positioning also aligned with their core intent and the purpose of their technological system (Fact 6.1). Start-up founders generally sought to capture value in markets for technology by leveraging their (bionics) component knowledge either in alliances with prosthetics incumbents or in markets for corporate control by being acquired after introducing early prototypes and products (Fact 6.2). Critical also is our (surprise) discovery that investments in the radical technology are not necessarily indicative of an intent to commercialize bionic prosthetic end products as most starkly observed for other established firms. Not only did the novel component of bionics have applications beyond prosthetics, their integration with other component technologies of bionic prosthetics (materials and design) could be leveraged in related alternative uses (e.g., other wearable medical technologies, exoskeletons for manufacturing workers, and robotics; Fact 6.3). Even though other established firms represented 50% of the firms investing in bionic prosthetic technology, they rarely entered the emergent bionic prosthetics industry to realize their investment value; rather, they focused on adjacent or related value chains.

Turning to coherence (column (B) in panel B of Table 6), *Creating radical system effects* builds on prior work on the nature of a radical technology (Arthur 2009) and its incubation (Moeen et al. 2020) as described in Building Blocks 1 and 2. Together, these building blocks imply three parsimonious premises or underlying assumptions (column (C) in panel B of Table 6). An incubation period is necessary for the process of creating radical technologies by building and integrating subtechnologies (Premise 1A1). Prehistories of the organizations (and founders in the case of start-ups) matter because they define the initial distribution of knowledge required to build out the subtechnologies and overall system (Premise 1A2) and also, because they shape organizational intent (Premise 1A3).

For precision (column (D) in panel B of Table 6), *Creating radical systems effects* builds on technological investments of actors being a function of the system's purpose and actors' intent and the distributed structure of technological capabilities (Precision Mechanism 1.1). For value creation, the critical mechanisms are internal development *and* collaborative dynamics resulting from informal knowledge sharing and formal leverage of markets for technology and corporate control (Precision Mechanism 1.2a). Importantly, value capture strategies of organizations consist of various modes, which depend not only on differences in emergent *technological* capabilities but also, on differences in intent and distribution of complementary capabilities. This explains the persistence and dominance of incumbents in *product markets*, the active engagement of start-ups in *markets for technology and corporate control*, and the remarkable *absence of diversifying entrants* in bionic prosthetics. Instead, firms in related industries focused on adjacent value chains where they had requisite complementary capabilities. Taken together, the emergent explanation accounts for the observed anomaly of interorganizational dynamics when industries evolve because of radical technological change.

Virtues of Alternative Explanations Within the Existing Literature

All four existing explanations are not able to reconcile the joint patterns of incumbent pioneering and dominance (Fact 6.1)[7] and distribution of technological capabilities across the three organizational types (Facts 1, 2.2, 2.3, 3, 4, 5, 6.2, and 6.3). We find no evidence that incumbents lacked incentives to innovate (*Organizational effects*) or evidence of rigidities in structure or cognition (*Organizational inertia effects*). Additionally, although complementary assets were no doubt relevant to intent and ability of the three organizational types to capture value through alternative strategies, these assets did not *compensate* for the incumbent's intent and ability to create (rather than merely adapt to) the radical technology (*Organizational adaptation effects*).

Column (B) in panel B of Table 6 summarizes the coherence of these explanations with the prior literature, and column (C) in panel B of Table 6 showcases them as variants stemming from the three assumptions noted in the conceptual backdrop. Abstracting from the incubation period creates the notion that the radical technology is (an implicitly unitary) exogenous shock to the focal industry, which changes price-performance parameters (see Premises 2A1, 3A1, 4A1, and 5A1). The tautological correspondence between the radical technology and entrants possessing requisite capabilities necessitates the premise that incumbent core competencies are rendered obsolete (Premise 2A2 in *Organizational effects* and Premise 4A2 in *Organizational adaptation effects* and *Complementary assets effects*) or become core rigidities (Premise 3A3 in *Organizational inertia effects*). Even in instances where the organization may have the requisite capabilities, cognition may inhibit adaptation (Premise 3A3 in *Organizational inertia effects*). Moreover, the focus of the explanations is on value capture through entry (commercialization) in product markets (Premises 2A3, 3A4, 4A4, and 5A3) and sometimes, in markets for technology (Premise 4A5). As noted in column (D) in panel B of Table 6, *Organizational effects* results in a definitional entrant advantage and incumbent obsolescence in industries affected by radical technology. *Organizational inertia effects* links outcomes to underlying rigidities in organizational structures or cognition. *Complementary assets effects* states that outcomes are a function of the incumbent ability to leverage (nontechnological) complementary assets. *Organizational adaptation effects* links outcomes to incumbent reconfiguration, assimilation, and acquisition of their technological capabilities *in response* to the exogenous technological shock.

Creating the Radical Systems Process Model: A Generalized Theory

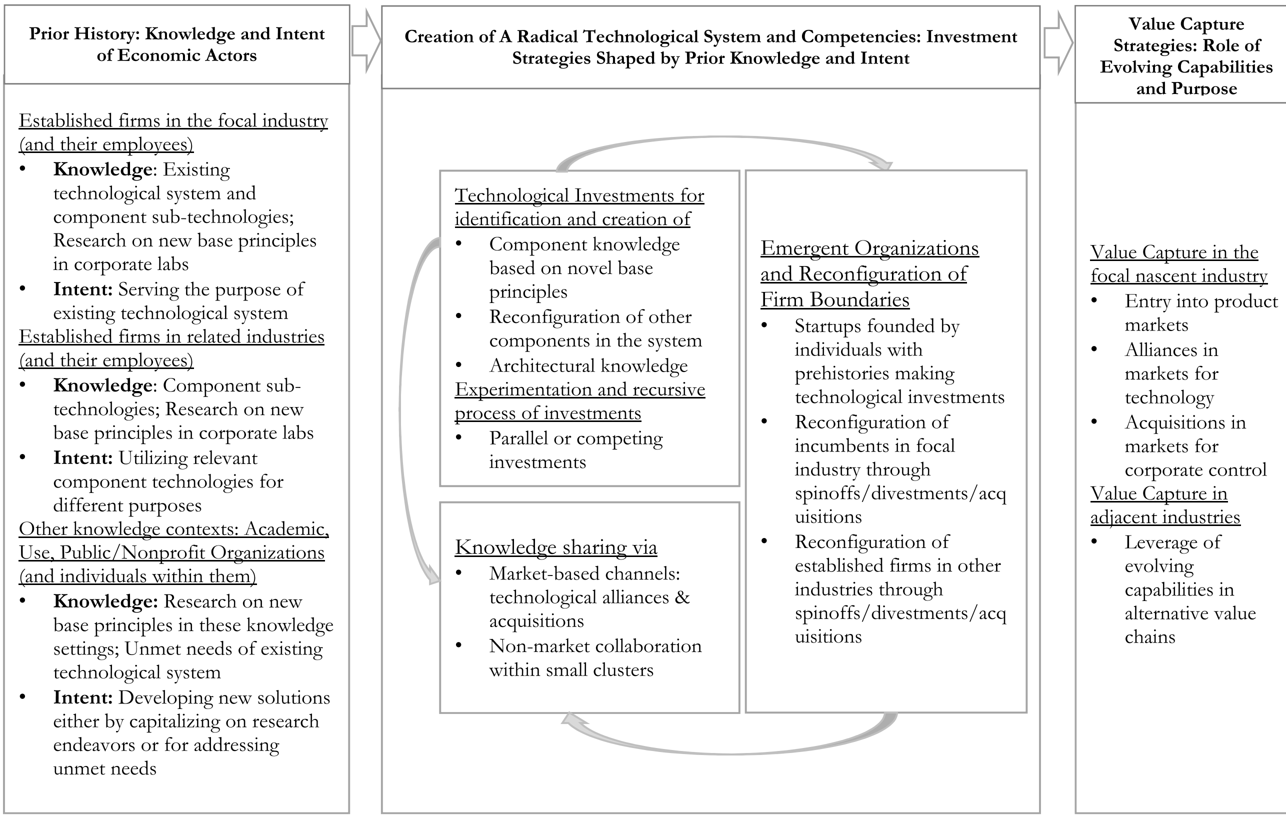
Although the above discussion focuses on the emergent explanation in the context of bionic prosthetics, we now articulate its generalizability to other contexts by explicating the logic of an endogenous *creating radical systems process* model (Figure 5). This logic relies on underlying mechanisms that have been invoked in prior explanations to merely explain value capture and competitive interorganizational dynamics. Within CRSP, however, they play a first-order role in collaborative interorganizational dynamics for creating technologies and organizational capabilities. Accordingly, we highlight how interorganizational dynamics in representative industry contexts (see panel B of Table 6) dictated by *Organizational effects*, *Organizational inertia effects*, *Complementary assets effects*, and *Organizational adaptation effects* are special cases of the generalized model.

Heterogeneity in the Prior History of Economic Actors

Incubation of radical technological systems requires actors to have relevant knowledge (Moeen et al. 2020) and intent to engage in a recombination process of creating novel components and reconfiguring existing components (Xiao et al. 2022). Prior histories shape *who* invests in incubating radical technologies and *why*. In terms of capabilities, there is little reason to expect that *all* requisite knowledge for developing radical technologies and their subcomponents resides within singular organization types. It is more likely that such knowledge is distributed across academic and research organizations that may discover or invent solutions that leverage new base principles, user contexts that provide knowledge of focal purpose and unmet needs, and organizations with knowledge of existing technological systems that embody existing base principles for focal or alternative purposes (Agarwal and Shah 2014, Moeen et al. 2020). Prior histories also shape intent—the *why*—of actors, which may be a desire to commercialize inventions, satisfy unmet needs, or create and capture value by combining the radical technology with downstream complementary assets for focal or alternative purposes. Prior histories thus imply different vantage points for envisioning and enacting a radical technological system and its subtechnologies, resulting in differences in both (a) opportunities/constraints posed by existing capabilities and (b) the intent of economic actors for engaging in technological experimentation.

Industry contexts represented in prior work (see column (B) in panel B of Table 6) vary in the extent to which component and subcomponent technologies draw upon prior histories of incumbents, other established firms, and start-ups. Thus, CRSP accommodates industry contexts where one organizational type's prior history may be more germane than others. Importantly, when studying technological discontinuities in cement, airlines, or minicomputers (Tushman and Anderson 1986) or in typesetters (Tripsas 1997), the theory removes the

Figure 5. Creating Radical Technological Systems and Competencies for Subsequent Modes of Value Capture



need for definitional correspondence of radical technologies and organizational capabilities or subcategorization of radical technologies as competence enhancing or destroying.

Creation of a Radical Technological System and Organizational Competencies

The development of a radical technology is endogenous to and will coevolve with capability investment of diverse actors that bring prior knowledge (Moeen et al. 2020, Goldfarb and Kirsch 2025). Economic actors must engage in the process of building the knowledge base for a new technological system by identifying or creating subtechnologies and linking them into a working system. Capabilities and intent stemming from prior histories direct actors' efforts at creating component and system integration. These pathways include parallel or competing investments by individual or groups of economic actors (Benner and Tripsas 2012), nonmarket collaboration within small clusters (Franke and Shah 2003, Mody 2006, Aversa et al. 2022), and formal market-based alliances and acquisitions (Moeen and Mitchell 2020) to create, combine, and reconfigure knowledge. Another important pathway is knowledge spillovers across efforts in the development of a technological system around different purposes (Rosenberg 1982, Bresnahan and Trajtenberg 1995), particularly for "general-purpose technologies" embodying novel base principal components that have alternative uses in multiple value chains (Goldfarb 2005, Gambardella and McGahan 2010, Conti et al. 2019).

Collectively, for new products to emerge, these investments must coalesce through system integration efforts for workable prototypes and commercialized products, which also has implications for emergent and reconfigured organizational forms. Individuals may leave existing organizations (e.g., academic institutions or established firms) or leverage user innovation to create new ventures (Agarwal and Shah 2014). Such startups may actively leverage markets for technology and corporate control to ally with, merge, or be acquired by other organizations (Arora et al. 2001, Capron and Mitchell 2010). Simultaneously, existing organizations may use the same markets to reconfigure business units through spin-offs or acquisitions for changes in firm boundaries (Karim 2009, Sanderson and Simons 2014, Moeen and Agarwal 2017). Together, incubation period investments and associated formation/reconfiguration of organizations through collaboration and competition simultaneously result in the creation of the radical technology and position firms (start-ups, incumbents, and other established firms) to leverage their resultant capabilities for value capture.

Which organizational types play the key integrator role and pioneer products using the radical technology will be context dependent. In bionic prosthetics, incumbents played this critical role. However, firms in related industries or start-ups may become system integrators if key knowledge is rendered obsolete as in agricultural biotechnology (e.g., Moeen and Agarwal 2017) or if incumbent firms exhibit structural inertia as in photolithography (Henderson and Clark 1990) or cognitive inertia as in digital imaging (Tripsas and Gavetti 2000). Importantly, radical technologies may be complementary to existing technologies in end use as in diagnostic imaging (Mitchell 1989). In such contexts, radical technologies need not obsolesce existing ones, enabling *both* incumbents and entrants to serve as system integrators.

Value Capture Strategies of Investing Organizations

Prior histories and technological investments shape organizational value capture strategies not only because they result in differences in the organization's technological capabilities but also, because they impact organizational intent. Here, it is entirely feasible that organizations with knowledge embodying novel base principles may not be interested in commercializing end products that serve a particular focal purpose. Rather, they may choose to either specialize in generality (Conti et al. 2019) or leverage the knowledge in alternative value chains (Gambardella and McGahan 2010). Together, capabilities and intent will dictate the value capture strategy chosen by an organization. For the focal purpose, value capture strategies include commercialization of end products, licensing or selling component knowledge in upstream markets, selling the entire firm, or divesting relevant units (Moeen and Agarwal 2017, Moeen and Mitchell 2020). Zooming out, this menu may also include value capture in adjacent value chains for alternative purposes (Rosenberg 1982, Bresnahan and Trajtenberg 1995). Here, possession of downstream complementary assets plays an important role as these affect intent and ability to leverage technological knowledge within specific value chains to profit from innovation (Teece 1986, Conti et al. 2019). For start-ups, consideration of complementary assets may cause them to focus on markets for technology or corporate control (Teece 1986, Gans and Stern 2003). Complementary assets may also influence incumbents' intent and ability to pursue value creation and capture from developing radical technological systems for focal industry use. Consistent with this logic, a lack of complementary assets in the focal industry may cause established firms in other industries to *not* become diversifying entrants and instead, leverage investments in adjacent value chains where they possess these assets (Gambardella and McGahan 2010).

Industry contexts will dictate which organization captures value through which mode. In bionic prosthetics, the endogenous process model resulted in incumbents capturing value in product markets, start-ups capturing value in markets for technology and corporate control, and other established firms capturing value in adjacent value chains. CRSP also explains processes in other contexts that dictate value capture strategies. In biotechnology-related industries, start-ups and other established firms pioneered radical technologies, but incumbents benefited by being on the sell side of acquisitions in markets for corporate control (Moeen and Agarwal 2017), adapting their technological capabilities in postindustry emergence stages (Rothaermel and Boeker 2008), or leveraging complementary assets to ally or acquire with entrants possessing upstream technology (Rothaermel 2001). Similar patterns are observed in medical diagnostic imaging (Mitchell 1989, 1991) and in typesetters (Tripsas 1997), where incumbent response to entrants was shaped by intent (protecting core business) and ownership of specialized complementary assets needed for *downstream* integration of technology with market capabilities.

In summary, the CRSP model separates what a radical technological system is from its potential disruptiveness. Its broader range in precision is possible because of a greater parsimony in underlying assumptions. Specifically, and as discussed above in our inference to the best explanation, CRSP does not assume (a) the exogeneity of an (implicitly unitary) radical technology, (b) a definitional correspondence between technology and organizational capabilities, or (c) that product market entry is the only mode of value capture. Interorganizational dynamics dictated by the *Organizational effects*, *Organizational inertia effects*, *Complementary assets effects*, and *Organizational adaptation effects* are then subsumed cases; organizational prehistories define how capabilities and intent (including those based on complementary assets) are aligned with the use of novel base principles for a purpose to determine who develops which components and who serves as a system integrator. Thus, the CRSP model accommodates the range of observed interorganizational *competitive* dynamics in product markets from dominance of incumbents (e.g., bionic prosthetics) or entrants (e.g., agricultural biotechnology) to coexistence of both firm types (e.g., diagnostic imaging and biopharmaceuticals). It also uncovers *collaborative* dynamics among different firm types both in developing the focal radical technological system and in leveraging knowledge (through formal and informal channels) for alternative systems serving a different purpose.

Discussion

Our focus on how prior histories shape interorganizational dynamics in industries experiencing radical technological change contributes to existing literature and enables managers and entrepreneurs to perceive a broader set of strategic options and constraints as shaped by prior capabilities and informed by intent.

First, we shift attention from competitive dynamics after radical technological change to the antecedent processes and sever the "*organizational effects*" definitional correspondence between radical technologies and the obsolescence of incumbent technological capabilities. This recasts interorganizational dynamics away from whether and when entrants will disrupt incumbents. By allowing relevant capabilities at subcomponent and system levels to be distributed across different types of organizations, our model accommodates the possibility that some incumbents may perceive growth opportunities in the use of novel base principles and actively engage in creation of new capabilities and reconfiguration of existing capabilities. Doing so contributes to existing work on industry evolution and incumbent-entrant dynamics postshock (Eggers and Park 2018) by incorporating the budding literature on industry incubation (Moeen and Agarwal 2017) and the related literature on the nature of technological systems (Arthur 2009, Goldfarb and Kirsch 2025).

Second, by challenging the assumption that all incumbents lack incentives or capabilities, we address selection bias in this literature at both industry and firm levels. At the industry level, we address the disproportionate sampling of industries where entrants usher in radical technologies to highlight industry settings triggered by radical technologies where the forces of creative destruction on incumbents may be relatively weak.[8] At the firm level, we address the selection bias in studies of interorganizational dynamics sampling on firms that entered through commercialization that miss firms that capture value through alternative modes of alliances, acquisitions, and adjacent value chains (e.g., Klepper and Simons 2000, Bayus and Agarwal 2007, Sosa 2013). This also highlights how and why established firms in other industries that make technological investments may not necessarily become "diversifying entrants." Novel base principles have a "general-purpose technology" attribute and may be leveraged for the creation of multiple radical technological systems, each developed as different applications that serve distinct purposes. As founders of start-ups and managers of established firms determine investment strategies, their intent has to map onto and to some degree, shape the purpose served by each radical technological system. For founders of start-ups, intent may stem from their own unmet needs or a desire to apply prior knowledge, leading them to invest in creating radical technology systems (or components thereof). For managers of established firms in related industries, intent may stem from applications of novel base principles for different purposes where they already possess downstream complementary assets in adjacent value chains. Both firm types may well be constrained by the lack of complementary assets in their ability to capture value through commercialization of products for the focal purpose. This contrasts with incumbents that may well pioneer and dominate product markets through complementarity between their newly reconfigured technological capabilities and downstream complementary assets. However, broadening the modes of value capture to include markets for technology implies that founders of start-ups and managers of established firms in related industries may benefit by collaborating with other firms that possess requisite complementary capabilities should commercialization capabilities preclude them from becoming (diversifying) entrants in product markets. Start-up founders with the intent to serve their own unmet needs or leverage scientific knowledge may additionally benefit by seeking to be acquired in markets for corporate control.[9]

We thus highlight the endogenous processes of radical technology creation and realized value capture strategies of *all* firms that invested in its creation (Moeen et al. 2020), not just established firms in related industries or start-ups (Cattani 2005, Sanderson and Simons 2014, Moeen and Agarwal 2017, Aversa et al. 2022). Additionally, we expand the menu of value capture options beyond product commercialization (Tushman and Anderson 1986), alliances, and acquisitions (Moeen and Mitchell 2020) to include value capture in adjacent value chains. Altogether, this allows us to position received explanations of interorganizational dynamics within a generalized, parsimonious framework of creating and capturing value from radical technological systems. Our study also enables a stronger connection between industry evolution and the corporate innovation literature (Katila and Ahuja 2002, Xiao et al. 2022). In this context, our findings extend the notion of "entrepreneurship in the large corporation" (Ahuja and Lampert 2001, Katila and Ahuja 2002) as well as "recombinant capabilities" (Fleming 2001, Yayavaram and Ahuja 2008, Arthur 2009). The literature on incumbent-led innovation has abstracted away from the industry life cycle aspects (Xiao et al. 2022). Similarly, the studies on "recombinant capabilities" are silent about important factors, such as the economic actors' characteristics (i.e., only examining technology-level factors) as well as when the recombination of old technologies is necessary to create solution systems. By focusing on prior histories and the distribution of knowledge for the radical technological system in the nascent period of the industry, we connect the literature to conditions under which entrepreneurship in the large corporation may become salient and also, confirm that such efforts may be particularly advantageous when the recombination of old and new technologies is useful.

Our "nature of technological system" approach extends the "profiting from innovation" framework that has largely focused on complementary assets as a key mechanism for value *capture* (Teece 1986, Gans and Stern 2000) in two ways. First, it highlights the *complementarity* in the development of component and system *technological* capabilities as a different (and understudied) concept than complementary assets (i.e., *nontechnological* capabilities, such as managerial or distribution capabilities). This implies that profiting from innovation requires first-order attention to the complementarity in the value *creation* of the radical technology and organizational competencies. Second, it highlights how prior knowledge and the systemic structure of technological solutions—the way that firm competencies are developed and fit for value creation—constrain and influence firm strategic choices by shaping *intent* as well as *capabilities*. Ownership of downstream assets in adjacent value chains may well shape the intent of organizations to coinvest in the focal technology development and collaborate with each other upstream and then, choose the most appropriate mode for value capture (product market entry in focal or alternative value chains, alliances, or acquisitions). This creates a stronger connection between studies of emergent technologies and studies of general-purpose technologies by linking the relevance of a firm's technological and complementary capabilities in alternative value chains to their strategic decisions for value creation and capture (Gambardella and McGahan 2010, Conti et al. 2019).

Finally, our study showcases the value of a single-industry study to infer the best of possible explanations by judging each's explanatory virtues in terms of its consilience with observed patterns, coherence with prior knowledge, and explication of mechanisms through parsimony and precision (Douven 2022, Pillai et al. 2024). It also enables the identification of key assumptions and critical cause-effect mechanisms for the development of a generalizable, parsimonious theory with sufficient explanatory precision for use in other settings, contingent on the mapping of these assumptions and mechanisms to those contexts.

Limitations and Future Research Opportunities

In our current study, we sufficed in demonstrating that considering the use of *novel base principles* in the new technological system for the focal purpose led to a powerful explanatory theory. Much is left to be explored. A new base principle may impact many parts of the system, and how this impact determines the degree of radicalness was outside the current study's scope. It may also be fruitful to map the radicalness of an innovation onto architectural versus modular innovation (Henderson and Clark 1990). For example, a continuous measure based on two potential dimensions ((a) the novelty of *each* base principle employed at either a component (modular) or system (architecture) level and (b) the number of novel base principles employed across components within the system (i.e., the novelty of the entire system given the interdependencies across multiple novel base principles)) may lead to more subtle insights into variation in interorganizational dynamics in terms of collaboration and competition among organizations with different prehistories and in terms of whether incumbents are ultimately disrupted by entrants. Similarly, it was sufficient for us to show that advancing the application of novel base principles for *alternative purposes* in adjacent value chains created spillovers for the *focal purpose*. Examining relatedness of alternative purposes and fungibility of established firms' capabilities across value chains was outside the study's scope. A future research opportunity lies in extending early work by Rosenberg (1982) and later, Goldfarb (2005) by examining the sequence of development of technological systems for different purposes and how endogenous processes of *who* invests, *why*, and *how* they do so affect the evolution of general-purpose technologies and their sociotechnological structures within an economy.

Relatedly, as true of all single-industry studies, our understandings may be influenced by idiosyncratic factors that determine observed outcomes. In the present case, the bionics market is limited by the size of the amputee population and in the United States, by regulation and insurance reimbursements for expensive bionics. A larger market prize, alternative regulatory regimes, or pricing structures may have induced start-ups or other established firms to build out their complementary capabilities and commercialize products. These socioeconomic factors represent important contingencies that are deserving of future research.

Finally, our study focused on differences *across* organizational types (i.e., prehistories), but it is also important to examine the role played by *within variation* among organizational types in interorganizational dynamics and the continued use of existing versus adoption of radical technologies.[10] Future research may examine how within variation may drive observed differences in cluster formation and the extent to which organizations with similar or different prehistories compete to occupy complementary roles within a technological system. How may simultaneous development of alternative clusters affect overall knowledge creation, diffusion, and resultant interorganizational dynamics for value capture? Here, our study is also limited because although we identified different modes of value capture, we could not discern or rank order among the strategies in terms of relative shares of value capture. We hope that future research will dig deeper into these issues.

Conclusion

The insights from our historical methods and abductive study of bionic prosthetics enable us to develop a generalized theory that departs from most prior work that treats a radical technology as an exogenous starting point of a new industry. We frame a radical technology as a product of an endogenous process that coevolves with the capabilities of heterogenous economic actors that invest in its creation. Moreover, value capture strategies are neither random nor uniform but endogenous to prehistories and technological investments in the incubation period. Thus, there cannot be a general and precise rule, even theoretically, as to how a radical technology will impact existing market players across settings. Rather, interorganizational dynamics in industries experiencing radical technological change can best be understood by applying a contextual lens for the process model of *who* invests in creating the radical technology, *why*, and *how* they do so.

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Endnotes

[1] The theory accommodates the possibility of "competence-enhancing" discontinuities that do not create disruption, but here too, the definition is based on the effect of the radical technology on incumbent capabilities and who pioneered it.

[2] To illustrate definitional comparisons, Eggers and Park (2018) classify biotechnology, generational shifts in disk drives, and digital photography as radical technologies based on the above *organizational effects* definition that links entrants to the introduction of radical technologies. However, only biotechnology and digital photography are radical per the nature of technology; biotechnology uses biological rather than chemical principles to develop therapeutic drugs, and digital photography stores image information digitally as opposed to chemically. That is, the base principles are new. The shift across disk drive generations is not radical because storage continued to employ magnetic principles.

[3] Thus, a new base principle may spawn several new industries through the development of various radical technological solutions that usefully apply a new base principle to different human needs or problems (Goldfarb and Kirsch 2025).

[4] Of the 66 firms identified as mechanical prosthetics incumbents based on our search of the Medical Device Register during 1983–1998, 42 firms had no record of technological investments in bionic prosthetics.

[5] Because our analyses were not prespecified, we describe our results in terms of precision and consistency with explanations (King et al. 2021), with smaller standard errors of coefficients being interpreted as a greater likelihood of consistency.

[6] Technology-investing firms—particularly start-ups—also drew upon knowledge generated in academic and government laboratories as reflected in the descriptive patterns of backward citations in Table C7 in Online Appendix C and the historical analysis below.

[7] The organizational effects explanation reconciles Fact 6.1 if one classified bionic prosthetics as a competence-enhancing radical technology. However, even for Fact 6.1, we note important discrepancies within the organizational effects definition when viewed through this study's insights. As an illustrative example, Tushman and Anderson (1986) classify electric typewriters as a competence-enhancing discontinuity relative to mechanical typewriters. This may be because some features of the typewriter's architecture were retained (e.g., QWERTY keyboard) or because retrospection revealed that electric typewriters were dominated by incumbents (e.g., IBM and Remington Rand) by the 1940s. However, archival reports (IBM Education Department, 1949/1951, as cited in IBMTypewriters.com, n.d.) indicate that electric typewriters were first introduced by Northeast Electric Company (a diversifying entrant) based on licenses of patented technology created by an independent inventor John Smathers. Northeast Electric initially contracted with Remington to produce the Remington Electric Typewriter in 1925, and when subsequent negotiations fell through, Northeast Electric entered the product market in 1929. When Northeast Electric was acquired by General Motors, its typewriter business was spun off as Electromatic Typewriter Co. Subsequently, IBM acquired Electromatic Typewriter Co. and introduced its own first electric typewriter—the IBM Electromatic—in 1933. Thus, this early history of electric typewriters underscores that the competencies were *not* developed in house by incumbents rather by other actors and subsequently acquired through alliances or acquisitions.

[8] As another example, Kang (2023) shows that pharmaceutical firms were able to move into new market spaces for cancer drugs when genome mapping resulted in a shift of underlying base principles from tissue similarity to gene similarity.

[9] In addition to bionic prosthetics, such proactive investment and collaborative dynamics within and across markets for technology and corporate control seem to be at play in AI-related technologies. In their nascent stages, the creation of new technological systems was spurred by investments and cocreation efforts of established firms in multiple industries and start-ups through small group collaboration networks (e.g., Microsoft and OpenAI, Google and Character.AI (start-up created by ex-Google employees), and the AI alliance by IBM and Meta that includes several other partner organizations).

[10] As a case in point, coronavirus disease 2019 (COVID-19) vaccines were developed using both messenger RNA (mRNA) technologies and conventional methods relying on vaccines that inject antigens (a piece of the virus) into the body (Loftus et al. 2020). Both Pfizer (an incumbent) and Moderna (a start-up entrant) announced variants of mRNA technologies in quick succession of each other. Meanwhile other organizations—incumbents and entrants alike—used conventional technologies for COVID-19 vaccines too. Thus, this question would focus on what alternative base principles were used by organizations of either prehistory for collaborative or competitive dynamics.

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Seojin Kim is an assistant professor of management at Drexel University's LeBow College of Business. Her research explores the emergence of new firms, technological systems, and industries, focusing on how the heterogeneous prior experiences of individuals and firms shape their strategic decisions under uncertainty.

Rajshree Agarwal is the Rudolph Lamone Chair in Strategy and Entrepreneurship at the University of Maryland's Robert H. Smith School of Business. She is interested in the role of innovation and enterprise in the evolution of individual careers, firms, industries, and economies.

Brent Goldfarb is the Dean's Professor of Entrepreneurship at the University of Maryland's Robert H. Smith School of Business. He studies new firms and industries as well as technological innovation and works at the intersection of empirical methods and the philosophy of science to improve the reliability of social science.