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Building Industries by Building Knowledge: Uncertainty Reduction over Industry Milestones

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Abstract. Scholars have long been interested in new industry emergence, highlighting that it could often be impeded by uncertainty across four dimensions: technology, demand, ecosystem, and institutions. Building on the insight that uncertainty stems from partial knowledge, we develop a conceptual framework that utilizes a temporal and a process perspective for knowledge generation and aggregation. Industry emergence through key milestones—commercialization, firm takeoff, and sales takeoff—is made possible by knowledge-generation processes by diverse actors within and across uncertainty dimensions, and knowledge-aggregation processes with appending, selecting, and collective mechanisms at play. Our conceptual framework integrates across disciplinary perspectives to shed light on both the development of an industry poised for future growth, and the bottlenecks that may delay or even impede industries from emergence.

Keywords: industry dynamics • emerging industries • diffusion of innovation • ecosystems • technological change

Introduction

By 2018, a U.S. household owned an average of 1.88 cars, and the roads on which cars are driven spanned over four million miles. Today, mechanical engineering students rely on more than a century's worth of knowledge on cars—a complex technological marvel representing a seamless assembly of internal combustion engines, transmission, fuel systems, and chassis, among other components. Customers expect a smooth car purchase experience, choose among a range of price-quality options for customization to their needs and desires, and have the peace of mind of proximate access to gas stations and repair shops. Efficient supply chains are global in scope, offering expertise, variety, and reliability to car manufacturers. Driving a car is part of the social fabric, and stable regulations support safe integration into streets. This stands in stark contrast to dominant transportation modes in 1885. How did visionaries and entrepreneurs of the past century shape the future that we live in? How did they solve technological problems that pervaded the early gasoline-powered cars, learn what horse carriage drivers expect from a horseless carriage, shift production from craftsman shops to massive factories, and convince society and their legal representatives along the way? In contrast, why did progress in steam and fuel-cell cars halt, and why did electric cars take a century to re-emerge?

Today, another dream captures public imagination in the same realm: the promise of autonomous cars. Yet, the complexity and pace of technical advance led Apple's cofounder Steve Wozniak to pessimistically note that autonomous cars may not be feasible in his lifetime.[1] Customers are skeptical about life without driving: although some cheer the possibility of playing videogames as cars drive themselves, others resist the thought of yielding their passion for driving. Reliable complementary 5G infrastructure for connected cars may be decades away. Crucial questions about social perception and regulation of cyber security of car control and collision incidents remain unresolved. Shaping the autonomous future that looks as taken-for-granted as the modern gasoline-powered cars is far from certain. Future time travelers may well bury them along steam and fuel-cell cars.

This narrative drives our purpose in this article, which is to provide a conceptual framework that delineates how industries emerge over time. Our focus is on nascent industries, defined as industries in the period starting from a technological discovery and/or unmet need, until transitioning to robust commercial activity. Taking a temporal perspective, we build on scholarly work to delineate three distinct stages in nascent industries, each ending with the achievement of a significant milestone: the incubation stage before first commercialization, a monopoly stage before firm takeoff, and low customer penetration before sales takeoff (Gort and Klepper 1982, Agarwal and Bayus 2002, Moeen and Agarwal 2017). In this temporal perspective, the sales takeoff milestone represents industry transition from nascency to robust commercial activity and sustainable growth. Across disciplinary and literature stream silos, there are a range of explanations that privilege alternative factors leading to sales takeoff (Gort and Klepper 1982, Tushman and Anderson 1986, Dosi 1988, Aldrich and Fiol 1994, Golder and Tellis 1997). However, we lack an integrative process perspective about how nascent industries transition in their early stages to achieve specific milestones of commercialization, firm takeoff, and sales takeoff.

This article fills this gap by developing a conceptual framework that links achieving temporal milestones of industry emergence to the process of uncertainty reduction and formation of industry knowledge base. When doing so, we draw on an impressive body of empirical case studies of nascent industries in prior work. We note that each industry case study typically sheds light on only particular aspects of a complex process, often focusing on a singular nascent stage or disciplinary lens, and often without a process perspective. Nonetheless, they collectively provide valuable empirical and theoretical bases, which we weave together in our integrative process framework for fresh insights.

Our conceptual framework starts with coalescing dimensions of uncertainty in nascent industries into a systematic typology: technology, demand, ecosystem, and institutions. As with autonomous cars, high uncertainty in these four dimensions pervades nascent industries. Although enduring uncertainty can impede industry emergence, uncertainty reduction within and across these dimensions paves the way for operation of mature industries such as gasoline-powered cars. However, one cannot assume that uncertainty is reduced on its own. Building on Knight's definition of uncertainty as partial knowledge (Knight 1921), we base our conceptual framework on the foundational insight that reducing uncertainty requires building knowledge (Rosenberg 1982). In turn, we consider formation of an industry knowledge base that addresses key dimensions of uncertainty as fundamental for achieving industry emergence milestones.

What is then the process through which an industry knowledge base is formed, and how does it map into temporal milestones of industry emergence? We define an industry knowledge base as the set of knowledge pertaining to the dimensions of technology, demand, ecosystem, and institutions that is leveraged for economic activity within an industry. In our conceptual framework, an industry knowledge base is formed as a result of recursive engagement of diverse actors in dual efforts at knowledge generation and knowledge aggregation. Through knowledge generation, each actor draws on their prior knowledge and imagination to develop new knowledge that becomes a building block of what can be aggregated in the industry knowledge base. Through knowledge aggregation, actors bring together disjoint and complementary knowledge that is generated by other diverse actors.

Our integrative framework enables us to shed light on how an industry knowledge base may grow or be impeded. Such growth or impediments in turn map onto whether the industry advances through each distinct nascent stage prior to key milestones, namely, the incubation stage preceding first commercialization, the prefirm takeoff stage, and the presales takeoff stage. During the incubation stage, actors often prioritize generating technology and demand knowledge, and aggregate knowledge through open and undercompensated appending mechanisms. If these efforts result in adequate knowledge for developing at least one technical design aligned with at least one customer's demand preferences, the industry achieves the commercialization milestone. During the prefirm takeoff stage, actors' composition and motives change toward economic considerations. They focus on ecosystem and institutional knowledge, and resolve interactions across technology and demand. Such efforts are essential for the culmination to the firm takeoff milestone, when availability of an industry knowledge base and visible commercialization history of existing actors stimulate subsequent entry of a critical mass of firms. However, selecting mechanisms enacted to deter entry may also cause delays and impediments to the firm takeoff milestone. During the presales takeoff stage, the increased number and diversity of commercializing actors correspond to knowledge-generation efforts that are primarily focused on scalability and the interactions across knowledge dimensions. Achieving sales takeoff requires firms to adjust each dimension in response to discoveries or bottlenecks in other interdependent dimensions. Further, in knowledge-aggregation efforts, selection and collective emphasis on particular knowledge trajectories gain prominence. Only if and when a matched set of solutions across all four knowledge dimensions is identified and addresses scalability of the industry, does the industry achieve the sales takeoff milestone.

By shedding light on the dynamics of industry knowledge formation through different milestones, our article contributes at the intersection of industry emergence and firm strategy literatures. To the industry emergence literature, our conceptual framework explicates not only the development of the industry's structure for future scale and growth, but also bottlenecks that may delay or impede industry emergence. To the firm strategy literature, we discern strategic implications of operating in a nascent industry at its different time junctures. By describing knowledge-generation and knowledge-aggregation processes, our conceptual framework provides key insights on the role of actors and firms in this process, and when and how they dedicate their efforts that advance a nascent industry.

Industry Emergence: Temporal and Process Perspectives

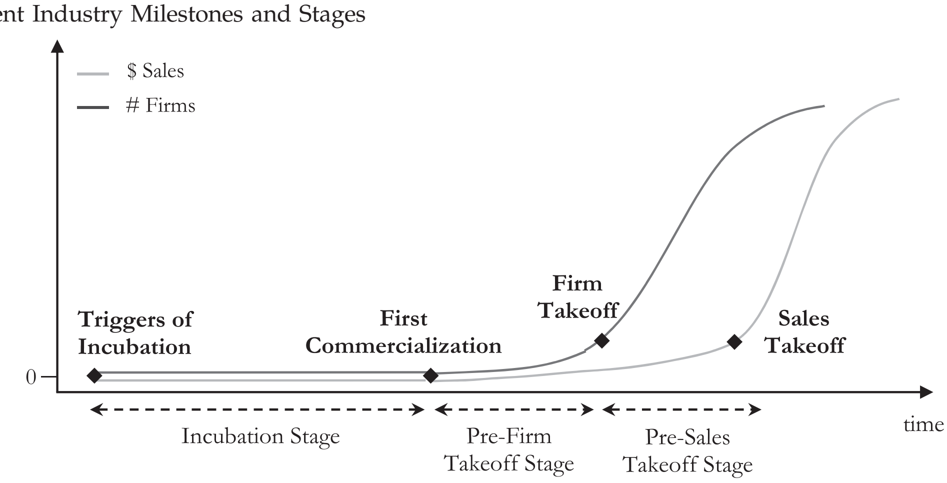
Temporal Perspective: Industry Emergence Through Key Milestones

Sampling on industries that become commercially viable, scholars have identified three distinct stages of nascent industries, each culminating in a milestone for industry emergence: the incubation stage before first commercialization, a monopoly stage before firm takeoff, and low customer penetration before sales takeoff (Gort and Klepper 1982, Agarwal and Bayus 2002, Moeen and Agarwal 2017). Figure 1 depicts trends in the number of firms and industry sales across these stages.

The incubation stage is triggered by technological discoveries or unmet needs (Agarwal et al. 2017). It is characterized by precommercialization investments, and culminates in the first instance of commercialization. This stage can last 26 to 28 years on average, with high variation across industries: some achieve commercialization within four years, whereas others may take more than 60 years (Agarwal and Bayus 2002, Golder et al. 2009). Upon achieving the milestone of first commercialization, industries transition into the next stage of a monopoly with few commercializing firms, which ends when there is a sharp increase or takeoff in the number of firms (Gort and Klepper 1982). The mean duration of the prefirm takeoff stage is 14 years, again with variation within and across chronological periods of time (Agarwal and Gort 2001). Trends for 25 new products show that after industries experience firm takeoff, average annual entry rate increased by 177% (Agarwal and Gort 1996). However, sales and market penetration levels are still low relative to their potential. This final nascent stage ends when there is a sharp rise in sales, with the sales takeoff milestone signaling industry transition to growth and robust commercial activity. At this point, product sales increase by 400%, compared with the preceding year (Golder and Tellis 1997). Surveying across 30 industries, Agarwal and Bayus (2002) show that firm takeoff always precedes sales takeoff. It lasts eight years on average, though the range spans from one year to 25 years across industries (Agarwal and Bayus 2002).

Although these temporal stylized facts about nascent industry stages are robustly documented for industries that successfully emerged, mere passage of time does little to enable industry emergence. Underspecified is the process through which milestones may be achieved, or the impediments to any one of the milestones. Existing research privileging different explanations offers insights in literature silos that require integration. Here, research about incubation stage has recently gathered steam, and it shows how precommercial investments by diverse actors shape subsequent industry trajectory (Greenstein 2015, Moeen and Agarwal 2017). Studies of post-commercialization have a longer history. Evolutionary economists highlight the external knowledge sources leveraged by entrants (Gort and Klepper 1982) and attribute sales takeoff to entry of diverse firms that offer various products for a broad range of customer preferences (Adner and Levinthal 2001, Agarwal and Bayus 2002). Technology management scholars note the initial proliferation in technical designs and the potential ensuing of a dominant design (Tushman and Anderson 1986, Utterback and Suárez 1993) within an emerging ecosystem (Adner and Kapoor 2016). Marketing researchers point to price reductions that motivate majority adopters to purchase products at sales takeoff (Golder and Tellis 1997). Organizational theorists link industry

Figure 1. Nascent Industry Milestones and Stages



emergence to increasing sociopolitical legitimacy (Aldrich and Fiol 1994, Sine and Lee 2009). Across these theoretical explanations, scholars have not explicated an integrative and systematic process for how industries transition over consecutive stages of incubation, prefirm takeoff, and presales takeoff. Indeed, these theoretical explanations often focus on a single industry stage or a single disciplinary lens, resulting in a research gap for a complementary process perspective.

Process Perspective: Uncertainty Reduction and Industry Knowledge Base Formation

In answering the overarching question of how industries transition over their nascent stages to achieve milestones of industry emergence, our conceptual framework adopts a process perspective. Integrating research in different disciplinary lenses reveals that emergence of an industry hinges on reduction in multiple dimensions of uncertainty that are pervasive in its early stages. Knight (1921) defined uncertainty as partial knowledge that restricts entrepreneurs' ability to identify the entire set of choices and probability of each outcome. Drawing on this concept, uncertainty reduction requires actors to build knowledge (Rosenberg 1982). Thus, our conceptual framework explicates processes critical to the progressive formation of an industry knowledge base, absent which uncertainty remains unresolved, and milestones depicted for successful industries remain unachieved.

To shed light on this process, we rely on the premise that reducing uncertainty and building an industry knowledge base require purposeful action. However, such purposeful action is not in the form of an efficient market design that ensures incentive alignment and is enacted by omniscient social planners (Arrow and Debreu 1954). Instead, given lack of knowledge, such action is in the form of purposeful experimentation (Rosenberg 1982) that is aggregated, so that the industry may ultimately emerge. As a result, actors who make a strategic effort to build knowledge in a nascent industry are crucial to our conceptual framework. Faced with a knowledge gap resulting from the uncertain industry state, each actor can exert efforts to generate new knowledge that addresses the gap. Because several actors can concurrently engage in knowledge generation, they can possibly generate knowledge that is different from the others. To build an industry knowledge base that can be utilized in economic activity and/or incorporated in subsequent knowledge generation, actors can engage in aggregating knowledge that is generated by other actors. Moreover, given the nascent context, it is unlikely that knowledge-generation and knowledge-aggregation efforts at one time period are sufficient to address gaps completely. Thus, some actors could abandon efforts entirely, others may iteratively undertake knowledge generation and aggregation, and yet new actors may enter the process at later times. The industry knowledge base continues to be built as long as at any time period, at least one actor perceives engaging in the process to be worthwhile. Next, we elaborate on the building blocks of this process.

Dimensions of Uncertainty. Across theoretical perspectives examining nascent industries, scholars commonly underscore substantial and multifaceted uncertainty in nascent industries, the reduction of which is critical for sales takeoff and industry emergence.

Scholars in evolutionary economics and technology management have noted that a prerequisite for industry emergence is the invention and refinement of technical designs and products (Gort and Klepper 1982, Tushman and Anderson 1986, Utterback and Suárez 1993). However, technological uncertainty, defined as partial knowledge about technical designs comprising technical components and their connecting architecture, is pervasive in nascent industries. Actors often lack information about what existing technical components to rely on, what new components to develop, and how to combine components within an architecture (Helfat and Raubitschek 2000).

Drawing upon economics, marketing, and technology management lenses, scholars have noted that understanding, fulfilling, and shaping customer preferences are critical for value creation and industry emergence (Clark 1985, von Hippel 1986, Golder and Tellis 1997, Adner and Levinthal 2001). Yet, demand uncertainty, defined as partial knowledge about customers' explicit and latent functional and price preferences, is extensive in nascent industries. Not only do firms lack this information, but also customers themselves may be unaware of their preferences (Christensen and Bower 1996).

Economics and strategic management scholars note that without an aligned ecosystem, firms and customers lack intermediate and complement products, impeding the industry's commercial viability (Rosenberg 1972). However, ecosystem uncertainty, defined as partial knowledge about the nature and configuration of ecosystem activities that deliver value to customers, pervades nascent industries. Ecosystem activities include vertical supply chain activities and their associated complementary assets (e.g., procurement, manufacturing, distribution) (Teece 1986, Mitchell 1989), in addition to activities for provision of complement goods and services (Adner and Kapoor 2016).

Scholars utilizing institutional economics and sociology lenses note that because institutions set the rules of exchange, they impact institutional costs and the willingness/ability to sell and buy (North 1990, Ostrom 1990, Aldrich and Fiol 1994).

However, institutional uncertainty, defined as partial knowledge about social and formal institutions that structure exchange of an industry's products, is substantial in nascent industries. Institutional costs often stem from ill-defined product meaning and legitimacy (Aldrich and Fiol 1994, Rao 2004), regulatory ambiguities (Marcus 1981, Langlois 2003), and fuzzy intellectual property scope (North 1990, Merges and Nelson 1994).[2]

Our conceptual framework integrates these perspectives and coalesces dimensions of uncertainty that impede industry emergence into a typology: technology, demand, ecosystem, and institutions.[3] This typology underpins our definition of an industry knowledge base as the set of knowledge pertaining to the dimensions of technology, demand, ecosystem, and institutions that is leveraged for economic activity in a nascent industry. Our focus is on the process of building such an industry knowledge base.

Actors. Drawing upon Schumpeter (1934, 1942), building new knowledge requires purposeful action, at the very least to assess and act on serendipitous or inadvertent discoveries. Thus, actors, defined as agents who are attracted to an industry's potential and exert effort toward building knowledge, play a key role in our conceptual framework. Consistent with Malerba (2002), actors include individuals (e.g., scientists, customers, ex-employees), for-profit firms (e.g., startups, established firms), nonprofit organizations (e.g., public agencies, foundations), and collaborative forms (e.g., alliances, associations, social movements). We additionally recognize that focal actors engage in the process as the primary locus of knowledge generation and/or economic activity, whereas some peripheral actors may not undertake economic activity, but serve as an important channel or knowledge cocreator to a focal actor.[4] Although some actors are economically driven, nonmonetary incentives can prevail. These include the desire to create (Schumpeter 1942) propelled by imagination (Shackle 1979), or the quest for reputation and status (Merton 1973).

Knowledge Generation. Despite their prior knowledge, each actor can face knowledge gaps in a nascent industry. Strategic management scholars note that to address knowledge gaps, an actor can either rely on external knowledge that was already generated by others, or generate new knowledge (Capron and Mitchell 2009). However, the uncertain nascent industry state can be a limiting condition to the availability of external knowledge. Thus, our conceptual framework considers knowledge generation as the essential mechanism through which each actor addresses knowledge gaps that they face. We acknowledge that as an industry knowledge base is accumulated, the balance between new knowledge generation and reliance on external knowledge can change.

Drawing on knowledge-based views, the knowledge-generation process starts with identification of a knowledge gap or a problem (Nickerson and Zenger 2004) and entails searching for solutions (Helfat and Raubitschek 2000). Knowledge gaps can pertain to deficiencies in a single dimension of technology, demand, ecosystem, or institutions. Alternately, when inconsistencies and opportunities in one dimension require revising existing knowledge in another dimension, knowledge gaps can include interactions across dimensions. Each actor can then rely on their prior knowledge and imaginations to find solutions (Felin and Zenger 2009) and pursue iterative experiments to assess efficacy of these solutions in addressing knowledge gaps (Levinthal 1997).

Knowledge Aggregation. The sheer volume of what is not yet known in nascent industries requires division of efforts, thereby leading to multiple actors being involved in knowledge generation. Actors can vary in their focus on knowledge gaps and approaches to knowledge generation, due to their different prior knowledge (Shane 2000) and imaginativeness and interpretation (Gavetti and Levinthal 2000). Thus, newly generated knowledge by different actors can be diverse and nonoverlapping. Although this diverse knowledge provides the building blocks of an industry knowledge base, limits to the public good aspects of knowledge (Teece 1977, Nonaka 1994, Cohen et al. 2000) inhibit it from automatically diffusing to become an industry knowledge base. Instead, as knowledge-based views suggest, aggregation processes are needed to bring together diverse knowledge that is in the possession of distinct actors (Grant 1996). Accordingly, our conceptual framework regards knowledge aggregation as a requisite process for building an industry knowledge base.

Aggregation implies "forming a collection from separate parts" (Thesaurus.net 2011), thereby creating alternatives about what is to be included versus excluded. We consider three distinct, though not necessarily mutually exclusive, mechanisms for knowledge aggregation: appending, selecting, and collective. For particular pieces of knowledge to be included in the industry knowledge base, actors can pursue appending mechanisms, ranging from knowledge spillover channels to market-based channels for knowledge sharing (e.g., licensing, alliances, acquisitions). For particular pieces of knowledge to be excluded, actors can pursue selecting mechanisms that diminish or block relevance of other actors' knowledge for the industry. These selecting mechanisms can be market based (e.g., product selection by customers) or nonmarket based (e.g., lobbying for favorable regulation, shaping social support), or they can build on both market and nonmarket to varying degrees.

Finally, through collective mechanisms, actors can agree on an aligned and coordinated plan about what pieces of knowledge to include or exclude in the industry knowledge base. Collective mechanisms (e.g., technology standard setting, quality control committees, coordinated narratives or lobbying) are distinct inasmuch as they require significant alignment and coordination, often across a large group of actors (Lee et al. 2017b). Yet, they can intersect with appending and selecting mechanisms, as in cases when technology standard setting selects between competing technologies, but specifies knowledge sharing/appending preconditions in patent pooling.

The next three sections outline these processes during each nascent industry stage by integrating across industry case studies and anecdotes to address the following: For each industry milestone to realize, what types of actors are typically involved? What dimensions of uncertainty do actors focus their knowledge-generation efforts on? What mechanisms do actors leverage for knowledge aggregation?

Incubation Stage

Actors and Prior Knowledge

Industry incubation is triggered by scientific discoveries or unmet demand (Agarwal et al. 2017). Scientific discoveries within academic/industrial labs open the potential for their practical applications (Mowery and Rosenberg 1991). Similarly, unmet needs of users (von Hippel 1986, Shah 2003) and mission-oriented challenges defined by nonprofit or government organizations (Klepper 2016) identify the potential for developing novel products. Regardless of the impetus, the incubation stage does not begin as a blank slate because of the prior knowledge base of involved actors.

Academic or industrial scientists build off their basic research to explore practical applications. For example, during the incubation of the solid-state lighting industry, academic scientists at the Massachusetts Institute of Technology (MIT), University of Illinois, and North Carolina State, along with corporate scientists at Bell Labs, RCA, GE, and IBM, leveraged their basic inorganic light-emitting diode knowledge (Sanderson and Simons 2014). Similarly, knowledge from related industries can be redeployed by established firms. The chemical and plant sciences knowledge of Monsanto and DuPont was relevant for the agricultural biotechnology industry (Moeen 2017), as was Corning's glass manufacturing knowledge for the fiber optics industry (Cattani 2005).

Further, users with knowledge of inadequacies in existing products and services often become involved. The incubation of rodeo kayaks was led by enthusiasts and kayak users who identified the opportunity, designed a product, and later founded startups (Baldwin et al. 2006). When public and nonprofit agencies establish a mission-oriented challenge, they leverage their own prior knowledge and that of other actors. For example, NASA and its affiliate agencies such as the Naval Electronics Laboratory and Jet Propulsion Laboratory were involved during the incubation of charge-coupled device sensors to be used in the Hubble Space Telescope. They also worked with myriad firms, including Texas Instruments, RCA, Fairchild, Tektronix, and Sony (Roy et al. 2019).

Focus of Knowledge Generation

During the incubation stage, developing prototypes at the nexus of technology and demand often gains primacy, thereby becoming the focus of knowledge-generation efforts.

Technology Dimension. Technological uncertainty about how to achieve a feasible technical design is at its highest during the incubation stage. Technical designs require identification or creation of component parts for a particular functionality and the linkages between components (Iansiti and Clark 1994). For some components, actors can adjust pre-existing technological knowledge in other sectors to their needs. In an examination of 29 prospective products, Golder et al. (2009) found 59% of technical components had predecessors in other sectors. Other components are designed anew, requiring actors to experiment through laboratory tests, observations, simulations, and physical models (Thomke 2003). For example, when designing the first laser printer at Xerox PARC, components such as spinning drums, paper rollers, and power supply were adjusted from existing facsimile printers. However, the design required components such as a laser scanner and digital control system to be developed from scratch. After linking components, components and linkages may need to be redesigned or refined to address coherence and performance tradeoffs between components.

The need to develop altogether new components and resolve performance tradeoffs across linked components may require additional scientific advancements. This necessitates focal actors to draw upon peripheral actors, such as academic and industrial scientists generating breakthrough knowledge in adjacent spaces. For instance, the presence of dark current was a major impediment in using buried channels in charge-coupled device sensors. It was only when peripheral scientists at the MIT Lincoln Laboratory and the California Institute of Technology's Jet Propulsion Laboratory discovered pinning techniques involving boron that the focal actors overcame dark current and designed a functional sensor (Roy et al. 2019). Such knowledge generation may also require several scientists and inventors to experiment with different approaches. For example, in the quest to develop insect-resistant crops, scientists at Agracetus, Agrigenetics, Plant Genetic Systems, Monsanto, and Professor Chilton's laboratory worked in parallel to embed Bacillus thuringiensis (Bt) genes in plants. Many of these experimental crops did not work, until Plant Genetic Systems succeeded in gene truncations and Monsanto found promoter genes to boost Bt expression (Moeen and Mitchell 2020).

Demand Dimension. Demand uncertainty regarding minimal functional preferences that create enough of a value proposition to entice at least one customer to purchase the product is notable. Generating demand knowledge requires interacting with potential customers to determine price and functional preferences. The challenge in the incubation stage results from the fact that most customers are unaware of their latent preferences (Christensen and Bower 1996) and need to have a real-world experience of a product before offering reliable feedback (von Hippel 1986).

In the absence of functional prototypes, actors assess prospective customers' preferences by presenting them with analogies, descriptions, or visual drawings (Urban and von Hippel 1988, Rindova and Petkova 2007). For example, to assess interest in business computers, IBM described it with a combination of machine and brain analogies (Bingham and Kahl 2013). Apple often circulates rumors as conceptual prototypes, such as the rumor of a secret product named Star that is a hybrid between tablets and laptops (Seidel et al. 2019). Product demos are often displayed, such as L'Oréal's ultraviolet monitoring nail art as a futuristic wearable device in the 2018 Consumer Electronics Show (Wilson 2018). These various methods of interacting with customers provide crucial preliminary knowledge about customers' willingness to buy and preferred functions.

Even when prototypes exist, generating demand knowledge requires trial and error, often marked by jumps across potential customer segments. As an example, although socialite Josephine Cochrane invented the dishwasher to satisfy her own unmet need, interactions with friends and neighbors failed to establish a value proposition for home use. Cochrane had to turn to hotels and restaurants, providing them not only a display but also direct product experience (Agarwal et al. 2017).

Potential customers can approach firms to share demand knowledge, even when the inventors do not actively seek this knowledge. In the case of extreme sport equipment, sport enthusiasts in user communities shared product designs that addressed their personal needs, revealing a large latent demand (Shah 2003). In the motorsport industry, drivers shared their expectations of a prospective sport car in communities such as the British motor clubs (Aversa et al. 2019).

Ecosystem Dimension. Although ecosystem uncertainty is sizeable, resolving this dimension is not the primary focus. None of the studies about the incubation stage, to the best of our knowledge, provide evidence of dedicated ecosystem knowledge generation. This accords with reason. Building an industry-specific ecosystem and complementary assets often requires knowledge of interdependent technical and demand aspects (Teece 1986), which are premature at this industry stage. This does not imply a lack of awareness of ecosystem needs. Firms during the incubation stage of agricultural biotechnology were aware of the need to build and acquire seed breeding divisions as complementary assets. However, they delayed full-scale investment in these assets until achieving modest technological milestones (Moeen and Mitchell 2020). As actors approach product commercialization, they may begin paying attention to this dimension, but more as a prelude to focused development in later stages.

Institutions Dimension. Similar to ecosystems, the need for industry-specific institutions does not seem to be a prime focus of knowledge generation. Although activists may raise safety, social desirability, and ethical concerns about products that are not yet commercialized, it is after widespread product use and visibility that these concerns present outstanding social and regulatory challenges. Before selling products, actors often justify their legitimacy and legal compliance on the grounds of novelty. In personal genomics, for example, firms initially ignored attending to regulatory dimensions, although they anticipated that regulatory pressures could intensify later (Gao and McDonald 2019).

The exception is intellectual property rights institutions, which is consistent with the intense focus on technology development. Actors often attend to whether their technologies are eligible for patent protection. Multiple Supreme Court rulings about patent scopes have historically happened during the incubation stage of their respective industries. For instance, the 1980 Diamond versus Chakrabarty case about patentability of genetically modified organisms was a turning point in favor of biotechnology-related industries. Similarly, the legal battle for patentability of human genes in the 2013 Association for Molecular Pathology versus Myriad Genetics case started during incubation of gene therapy and diagnostic gene sequencing industries.

Interactions Across Dimensions. Given the focus of knowledge generation on technology and demand, interactions across these two dimensions are salient in the incubation stage. To advance the industry, knowledge of demand attributes becomes the focusing device for designing subsequent technical designs and choosing between alternatives. In parallel, every technical design becomes the basis for subsequent demand knowledge generation, as firms assess how the new design aligns with customers' preferences. For example, in developing compression cooling devices, actors used the analogy of a combination of ice pack and bandage to collect customer feedback, even when a prototype was not available and potential customers lacked familiarity with a product that did not yet exist. Multiple decisions about technical components of cooling, power, and transportation systems were then made not just based on technical feasibility, but also on their fit with therapeutic demand attributes and customer feedback (Seidel and O'Mahony 2014).

Knowledge-Aggregation Mechanisms

Because knowledge generation during incubation largely focuses on technological and demand dimensions, so does knowledge aggregation. Further, knowledge aggregation is meaningful, given that the numerosity and diversity in actors imply distribution of newly generated knowledge among them. Not only is there evidence of multiple actors engaging in knowledge generation during the incubation of industries (Moeen and Agarwal 2017, Roy et al. 2019), but also actors are often diverse, for example, in their founder background (Shane 2000), pre-entry industry of origin (Moeen 2017), or affiliation with public agencies (Greenstein 2015). Indeed, their diversity can be linked to different knowledge-generation efforts. In incubation of three-dimensional printing, for example, founders with different educations and employment histories pursued different innovations and targeted nonoverlapping customer segments, even though they licensed the same patent from the same MIT laboratory (Shane 2000).

Appending Mechanisms. Various channels may be at play for appending knowledge during the incubation stage. Alliances and acquisitions to share molecular biology and plant sciences knowledge were prevalent in agricultural biotechnology (Moeen and Mitchell 2020). Knowledge exchange through scientific publications among academic and corporate scientists was pervasive in solid-state lighting (Sanderson and Simons 2014). Knowledge sharing communities were common in probe microscopy (Mody 2006). Geographic proximity between firms in the emerging British Motorsport Valley enabled knowledge exchange during the incubation of the motorsport industry (Aversa et al. 2019).

In these cases, knowledge sharing or spillover in the absence of complete pecuniary rewards is common. This may be in part due to the composition of actors. Actors engaging in the incubation stage are often immersed in contexts that follow norms of open knowledge sharing. Scientists often publish findings in accordance with scientific community norms (Merton 1973). Similarly, users often belong to communities motivated by nonpecuniary benefits from creating novel solutions (Franke and Shah 2003, Mody 2006). For example, rather than financial motives, publication by academic and corporate scientists during the incubation stage of solid-state lighting was a means to establish scientific credibility (Sanderson and Simons 2014).

The other reason relates to knowledge attributes during the incubation stage. Although market-based channels such as licensing, alliances, and acquisitions do occur, they do not always yield full economic value. Market-based knowledge sharing typically entails defining protected boundaries around knowledge and arriving at a shared valuation, all of which are arduous during the incubation stage (Moeen and Mitchell 2020). Difficulties in protecting knowledge may arise due to a lack of reliable and stable patent scope definitions, which may reduce a knowledge source's willingness to share as well as a knowledge recipient's willingness to pay. Hence, undercompensated spillovers are common, as documented for the incubation stage of charge-coupled device sensors (Roy et al. 2019) and solid-state lighting (Sanderson and Simons 2014). Even when market-based channels are employed, accurate knowledge valuation is difficult in the face of an uncertain technology trajectory. Not anticipating the lucrative commercial trajectory of agricultural biotechnology, Monsanto licensed one of its genes for only half a million dollars, a massive ex-post undervaluation (Charles 2001).

Selecting Mechanisms. Product market-based selection by customers is absent during incubation stage. Still, particular knowledge trajectories can be selected out when their relevance to the industry is diminished in knowledge markets. When other actors involved in parallel knowledge-generation efforts do not find a particular knowledge trajectory worthwhile for further investment, they may divert their efforts elsewhere. For example, after persistent technical challenges in generating electricity in experimental nuclear fusion reactors, actors pivoted to harnessing fission (van Lierop 2019).

Nonmarket selecting mechanisms may be at play, too. First, actors involved in parallel knowledge generation may obstruct competing actors. For example, after the National Nanotechnology Initiative supported the incubation of molecular manufacturing in the early 2000s, some scientists' competing motives and status prevailed in races for discoveries. They redefined this mission in ways that hindered parallel and perhaps more ambitious trajectories to the point that industry emergence was jeopardized (Grodal and O'Mahony 2017). Second, external decision makers (e.g., coordinating public actors or funding agencies) may prioritize particular trajectories. This was the case in NASA's choice to use buried channel designs for the charge-coupled device sensors in the Hubble Telescope, which led to temporarily abandoning knowledge relevant to surface channel designs (Roy et al. 2019). It is notable that NASA proceeded with buried channel designs, but several of its technical solutions came from knowledge that was originally developed for the abandoned surface channel designs.

Collective Mechanisms. The salience of generating new knowledge for an industry that does not yet exist implies that collective mechanisms largely involve mobilizing actors toward investing in the industry, rather than coordinated selection of a particular knowledge trajectory. Defining mission-oriented grand challenges is one trigger for industry incubation that encourages a large number of actors to find solutions for a concerning challenge (Agarwal et al. 2017). This is often accompanied by creating norms and stipulating knowledge sharing (Vakili and McGahan 2016), and thus accelerating the use of knowledge appending mechanisms. For example, public-private collective actions coordinated by the Advanced Research Projects Agency for the Internet (Greenstein 2015), Office of Scientific Research and Development for penicillin (Agarwal et al. 2017), and NASA for the space shuttle (Roy 2019) mobilized and promoted knowledge sharing between numerous firms, universities, and government labs, resulting in commercial products.

Commercialization Milestone

The incubation stage can end in one of two outcomes. First, at least one actor may commercialize their product. This is a key milestone that signifies adequate knowledge for establishing at least one feasible technical design that aligns with at least one customer's preferences so that trade can begin within a rudimentary ecosystem and institutional structure. To achieve this milestone, actors devote their knowledge-generation efforts at the intersection of technology and demand dimensions. They rely on appending mechanisms to exchange complementary knowledge, not only reducing redundancy in their knowledge generation, but also diverting efforts to remaining knowledge gaps. The use of open and undercompensated appending channels enhances this knowledge flow. When actors' lack of investment decelerates knowledge-generation and appending processes, collective mechanisms assure that multiple diverse actors are attracted to building the industry knowledge base.

Alternately, the potential industry may be abandoned, temporarily or altogether. No matter how many actors are attracted to the promise of a potential industry, and no matter how much perseverance they show in their knowledge-generation efforts, some cases are fraught with repeated dead-ends. Here, our conceptual framework alludes to potentially systemic factors hindering the first commercialization. First, the commercialization milestone may not be realized if sufficient number of actors do not recognize opportunities to engage with the potential industry. However, this is not about the numbers, but about efforts exerted by actors that yield successful outcomes. Despite attracting numerous actors, grand challenges defined by the National Institutes for Health (NIH) for an artificial heart (Sampat 2012) or the National Nanotechnology Initiative for molecular manufacturing (Grodal and O'Mahony 2017) have not yielded envisioned commercial products. Second, actors may disengage from knowledge generation in a technology-demand nexus due to insufficient progress within and across these dimensions, or divert attention to alternatives for technology development and addressing user needs that gain success or prominence. The cycles of artificial intelligence (AI) winter are representative of technical setbacks that have discouraged actors' knowledge generation in AI (Crevier 1993). Third, actors' knowledge generation may be one-sided, losing sight of the interaction across technology and demand. Left unresolved, achieved technical designs can become collectible artifacts on inventors' shelves, and identified customers' preferences can remain mere fantasies. Finally, actors' lack of reliance on appending mechanisms may slow progress, as each actor needs to independently generate knowledge that might already reside in isolated silos. This would likely result in a sharp increase in the resources and time necessary to create solutions. The inverse is the premature use of selecting mechanisms, as the overall shortage of industry knowledge may not yet allow for evaluating parallel knowledge trajectories.

Prefirm Takeoff Stage

Actors and Prior Knowledge

The commercialization milestone results when one of many potential actors engaged in industry incubation offers a solution at the technology-demand nexus. Some of the others may continue efforts for their own commercial offerings, whereas others may exit or be selected out due to reduced relevance of their knowledge. Commercialization shifts the focus of actors toward economic incentives, and the organization of activities toward for-profit enterprises. Academic scientists and user inventors form startups as they gear toward commercialization entry, and corporate scientists begin to engage with downstream divisions for production and sales in established firms.

New actors who recognize opportunities for applying their prior knowledge also invest in the industry. They may include new academic entrepreneurs, user entrepreneurs, established firms from related sectors, and public agencies. Two factors spur an increased investment rate by new actors, an important prelude to the subsequent sharp increase in firm entry rates. First, the industry knowledge accumulated during the incubation stage encourages investments by new actors who can draw on this knowledge rather than engage in risky and costly knowledge generation from scratch. Across 46 product innovations, knowledge dissemination was key to reduction in barriers to entry during prefirm takeoff (Agarwal and Gort 2001). Second, the first sales of commercial products serve as signals that garner support from stakeholders (e.g., financial sponsors, employees, value chain actors), thereby facilitating additional entry. In the minimally invasive surgical devices industry, financial aid by venture capital and NIH peaked after the first successful surgery (Pahnke et al. 2015).

Knowledge Generation Focus

Post commercialization, actors' knowledge generation targets gaps that still exist at the intersection of technology and demand. Further, economic considerations warrant dedicated efforts toward reducing ecosystem and institutional uncertainty.

Technology Dimension. Some actors focus on the development of technical designs that differ from the commercialized prototypes. Other actors address deficiencies and refine early product offerings, which are often primitive in design (Rosenberg 1982). For example, although the first laser printers could print, they were too slow and bulky, experienced persistent paper jams, and their computing system could not process different sources. Addressing deficiencies requires considerable attention to technical redesigns toward enhanced product functionality. Similar to the incubation stage, the redesign of various components, experimentation with alternate linkages, and continued incorporation of emerging scientific and technical advancement require significant effort.

Demand Dimension. Although first commercialization identifies at least one value proposition, there remains significant uncertainty about functional preferences related to that value proposition (Adner and Levinthal 2001). Knowledge-generation efforts broaden in scope to better understand and affirm preferences of known customer segments. For laser printers, although offices and data centers were known customers, their functional preferences about printing speed, resolution, or fonts were not known. Actors' efforts can mimic the incubation stage processes such as gauging customers' reactions to descriptions of products/features yet to be prototyped. Further, commercialized products afford firms the opportunity to assess customers' revealed preferences through product sales, as is customary in the lean startup practitioner methodology in entrepreneurship (Blank 2005).

Ecosystem Dimension. During this stage, economic value capture hinges on new products reaching customers, thereby increasing the importance of addressing ecosystem uncertainty. Here, there is a need to identify the nature of activities in a vertical value chain, what activities to vertically integrate versus externally source, and the interactions among internal units and/or collaborators.

Initially, although actors may generally know what activities are key for value capture (Teece 1986, Mitchell 1989), their specific nature may not be known. In many cases, firms may transform related industries' supply chains for their own needs, as exemplified by car manufacturers drawing on bicycle wheels and wooden bodies supply chains (Langlois and Robertson 1989), Edison utilizing the gas infrastructure for electricity (Hargadon and Douglas 2001), and agricultural biotechnology firms leveraging elite varieties in conventional seed breeding (Moeen 2017).

In other cases, firms need to design altogether new elements of the supply chain. Supercomputers needed Gate-all-Around (GaA) chips, which implied that silicon producers serving the personal computing industry were not suitable suppliers. Because the GaA chip industry was in its nascent stage, development of a robust supply chain for supercomputers needed advancements in GaA technology (Afuah and Bahram 1995). To generate ecosystem knowledge, firms often interact with potential suppliers to develop the needed expertise, or they support internal units that serve as suppliers. When laptop manufacturers needed to design flat panel displays with specific size-resolution combinations that were not yet in existence, they collaborated with their trusted suppliers (Hoetker 2005). Computer workstation manufacturers that needed reduced instruction set computer technology largely relied on internal units to address this shortage (Afuah 2001).

Although ecosystem knowledge for effective provision of complement goods and services to increase customer adoption is also lacking, existing research has not documented dedicated attention to this aspect during the prefirm takeoff stage. Conceptually, this partly arises from the small number of customers that purchase the product for whom widespread complement availability may not be salient.

Institutions Dimension. Commercialization is predicated on stealth or adequate social acceptance and legal compliance for at least one exchange to occur. In this stage, actors pay more attention to institutional uncertainties that may render the industry far from legitimate or legal.

When establishing social legitimacy, the few firms with a commercialized product are often the industry's visible images and cognitive referents (Santos and Eisenhardt 2005). Thus, the industry social legitimacy is often tightly coupled with the social perception of these early entrants, which is impacted by their rhetorical strategies. In online commerce, an early entrepreneur raised awareness about the industry by storytelling and borrowing familiar labels such as shopping carts (Santos and Eisenhardt 2005). Such efforts also engage peripheral actors. As an example, journalists were key to disseminating and interpreting news releases that computer workstation manufacturers issued (Kennedy 2008).

Regarding regulatory institutions, uncertainty largely pertains to lack of focal regulations about the industry or ambiguity in interpreting existing overlapping regulations. For drones, it was unclear whether pre-existing Federal Aviation Administration regulations that covered manned aircrafts also covered unmanned drones, or whether the same laws or legal authority could be applied. Such lack of knowledge is also correlated to the fact that the few industry firms may not have yet found powerful positions to lobby or mobilize stakeholders for enacting legal changes. Further, limited product use implies it may fly under the radar of regulators or stakeholders who demand industry regulation. Nonetheless, at the face of varying levels of pre-existing and emerging regulations, evidence suggests that early entrants continue to circumvent regulations. For example, personal genomics firms evaded Food and Drug Administration laws by selling products in direct consumer markets or foreign countries (Gao and McDonald 2019). To avoid oversight in pharmaceutical drugs, dietary supplement firms sold their products as food rather than as drugs (Ozcan and Gurses 2018). Similarly, pay cable TV firms designed services as extensions to existing broadcasting services so as to operate outside of the Federal Communications Commission regulated airwaves (Gurses and Ozcan 2015).

Defining intellectual property institutions can continue to occur through court rulings and legal precedents about patentability. The increase in technology development implies that firms may seek patent protection in more instances of complementary innovations. Here, firms, patent prosecution lawyers, patent office examiners, and the judicial system may initially lack the institutional knowledge for specifying each patent's scope. In agricultural biotechnology, overlapping patents were granted to six firms for insect-resistance traits, creating ambiguity about each firm's rights (Graff et al. 2003). Efforts to resolve such issues enable generating associated institutional knowledge.

Interactions Across Dimensions. The interaction between technological and demand dimensions remains focal. Such interactions create recursive knowledge-generation efforts, so that technical designs are revised according to customers' preferences and demand attributes are reassessed for each technical design. Early Internet search engine and portals such as Yahoo! and Excite assessed web traffic and user feedback after each revision of their search algorithm or entertainment content. This information was then continuously incorporated in the next version (Rindova and Kotha 2001).

At times, demand knowledge reveals customers' preferences that conflict with existing technical designs. Instead of revising the design, actors may opt for reshaping demand and customers' perceptions accordingly. Amidst an initial lukewarm reaction to Kodak's first roll-film camera, Kodak identified that customers perceived the simplicity and light weight of roll-film cameras as technical inferior features relative to the precision of professional glass-plate cameras. Before undertaking technical changes for higher camera precision, Kodak focused on identifying other appealing demand attributes. Once it realized that some customers value portability, the increase in demand came from marketing campaigns about the advantages of roll-film cameras for recording vacations and family history (Munir and Phillips 2005).

Actors' incipient focus on generating ecosystem and institutional knowledge implies that their interactions with technology and demand knowledge begin to gain salience. Because technology and demand knowledge are more developed, the first iteration of ecosystem or institution building often prioritizes alignment with these existing elements. Our earlier examples allude to these interactions, where actors generate knowledge about value chain activities and institutions that support production and exchange of products based on the generated knowledge at the technology-demand nexus.

Knowledge-Aggregation Mechanisms

As knowledge generation involves all four dimensions of technological, demand, ecosystem, and institutions, actors' knowledge-aggregation efforts expand in scope to include all four dimensions. Further, because the number and diversity of involved actors continue to increase in this stage, it is possible that they generate novel knowledge that needs to be aggregated.

Appending Mechanisms. Alliances, acquisitions, geographic proximity, and communities continue to be relevant channels to append knowledge. In addition, given the development of industry-specific human capital, employee mobility gains importance. Evidence from 46 product innovations during the prefirm takeoff stage is consistent with employee mobility and shortened job tenure for a single employer (Agarwal and Gort 2001). Product commercialization can enable the flow of demand knowledge. Product exhibits or advertisements can reveal features of new products and reflect a focal firm's knowledge of customer preferences. In addition, media and analyst coverage of each firm's product sales can distribute knowledge about demand trends. Specific to ecosystem knowledge, each firm's ecosystem configuration (e.g., supplier and partner choices) may be visible to others. For example, Genentech's alliance with Eli Lilly in 1982 to leverage the latter's long-standing clinical trial and manufacturing expertise alerted other actors about the ecosystem knowledge that complementary assets in the biotechnology human therapeutics industry take the form of clinical trial expertise. For institutional knowledge, rhetorical strategies and cases for patent prosecution and infringement occur in the public domain and become accessible to other actors.

During this stage, open knowledge sharing is less pervasive. The shifting composition of actors coupled with a focus on economic value changes norms. For example, scientists who published in scientific journals during incubation of solid-state lighting later operated within for-profit norms and filed for patents. This pattern held not just for scientists at IBM and RCA, but also for academic scientists who founded startups such as Soraa and Cree (Sanderson and Simons 2014). Further, efforts to privatize knowledge to enable for-profit actor engagement may be enacted, as was the case with the National Science Foundation after commercialization of the Internet (Greenstein 2015). Such transitions imply actors are less willing to openly share knowledge, even though knowledge spillovers where the knowledge source may be undercompensated continue to diffuse knowledge in all four dimensions.

Concurrently, an increase in market-based channels such as licensing, alliances, and acquisitions is enabled by stronger intellectual property protection and prospects of knowledge evaluation. For technological knowledge, not only have firms advanced to technological findings that can be included in a patent, but also institutional knowledge about patentability and patent scopes have emerged. Thus, firms can divert knowledge flows toward channels that provide economic value capture.

Selecting Mechanisms. Product market-based selection by customers begins in this stage, but it can be limited, given the small number of firms and customers alike. In addition, when actors do not find a particular knowledge trajectory worthwhile for sustained investment and subsequent knowledge generation, they may abandon the trajectory and diminish its relevance.

Some knowledge trajectories may be winnowed out if actors do not have access to the required prior art. When firms utilize patents to enforce intellectual property (IP) rights, they can stall complementary technologies. Wright Brothers litigated innovators who built on their pioneering patent on airplane stabilizing and steering system. Several extensions and airplane systems did not advance until a patent pool was administered by the Manufacturer's Aircraft Association (Merges and Nelson 1994). In the mid-1990s, agricultural biotechnology firms launched an acquisition wave that preempted potential entrants from access to proprietary seed breeding units and complementary assets (Moeen and Mitchell 2020).

The fledging state of industry institutions may enable nonmarket blockage of competing firms' knowledge. Absent a defined industry identity for the air taxi industry, an industry that is yet to experience firm takeoff after two decades, Linear Air likened its operations to an air limousine, thereby trying to exclude firms such as SATSair that defined the industry as on-demand charters (Zuzul and Tripsas 2019). Absent a robust legal institution for the steamboat industry in the 1780s, early innovators used lobbying and subsidies to maintain a monopoly and restrict entry (Cox 2009).

Collective Mechanisms. Public-private partnerships behind grand challenges still play a role, but lose momentum as their objective might have been achieved at the point of commercialization. Absent a sizeable number of firms, coalition building using trade associations is also unlikely. However, activists and nonprofit organizations that recognize the industry's promise may coordinate across actors for enticing additional investments that are needed to address remaining knowledge gaps. Their efforts can take the form of removing investment barriers or aligning stakeholders' divergent interests. For instance, HIV/AIDS advocacy groups were influential in bridging various stakeholders and creating favorable conditions for increased research about treatments (Maguire et al. 2004), similar to the Sierra Club's role in increasing firm entry in wind energy (Sine and Lee 2009).

Firm Takeoff Milestone

The prefirm takeoff stage can end in one of two outcomes. First, it can culminate in firm takeoff, a milestone that heralds the beginning of the wave of commercializing actors. At this milestone, two concurrent forces set the stage for subsequent entry of a critical mass of firms. The accumulation of an industry knowledge base provides new firms with the foundational knowledge to begin their journey, and the few visible commercialization instances are the harbinger of potential economic opportunities. To reach this milestone, actors generate knowledge at the intersection of technology and demand to offer product refinements for extra functionality, and begin addressing ecosystem and institutional uncertainties. The resultant knowledge is disseminated between actors using appending mechanisms. The rise in market-based appending channels creates a viable means for the industry knowledge base not to lose valuable complementary knowledge, and for firms not to lose economic incentives. When nonmarket selecting mechanisms prevail, actors find ways to combat obstacles that hindered fresh knowledge brought by new actors. When divergent stakeholders' interests impede investment in knowledge generation, collective mechanisms come into play.

Alternately, the few first firms may become the only remnants of the industry, remaining isolated tinkerers or eventually divesting. Our conceptual framework illustrates factors that set back firm takeoff. First, there are no golden rules about the absolute number of new firms needed for firm takeoff, though the industry knowledge base behind the momentum in entry rate is revealing. If knowledge generation at the technology-demand nexus creates continually unmet expectations, incoming actors may not find the industry worthwhile for investment. Similarly, this is the time juncture during which, if preliminary efforts to establish ecosystem or navigating institutional environment are aborted, the industry's economic value may be deemed unpromising for incoming actors. For example, despite achievements that led to commercialization, an inability to configure ecosystems for growing and shipping ripe tomatoes haunted transgenic altered-ripening tomatoes. Immense social backlash pervaded vitamin-A-enhanced rice. Both were discontinued, although firms continued genetic modification of other plants (e.g., corn, soybeans, and cotton) for which ecosystem and institutional knowledge was emerging (Charles 2001).

Second, if existing actors' economic value considerations result in excessive and early switches from market-based appending to selecting mechanisms, fewer incoming actors are attracted to the industry. As norms and motives reflective of the composition of actors shift toward economic value, market-based appending and selecting mechanisms alike can enable appropriability. However, selection not only deprives the industry from parallel knowledge trajectories whose value is still uncertain, but also signals impending rivalrous conditions, whereas market-based appending mechanisms contribute to a cumulative industry knowledge for incoming actors to draw on.

Third, nonmarket selecting mechanisms and monopolies that remain unchallenged can persist in preventing subsequent knowledge generation and economic activity. Our earlier examples about delays in firm takeoff in the presence of nonmarket selecting mechanisms are illustrative of this point. They also allude to how other actors can step in to remedy the originating conditions and advance the industry toward firm takeoff. These may be actors that coordinate collective mechanisms, such as the HIV advocacy groups that aligned conflicting motives and expectations, or actors who themselves seek entry. For example, agricultural biotechnology entrepreneurs lacking access to complementary assets entered as upstream technology providers, rather than becoming vertically integrated firms (Moeen and Agarwal 2017). Faced with the steamboat monopoly, entrepreneurs engaged in distribution of public pamphlets, judicial action against monopolists, and illegal ferrying of passengers. They also engaged in the Gibbons versus Ogden landmark legal dispute, which distinguished federal from state jurisdiction on interstate commerce and legalized subsequent steamboat entry (Cox 2009).

Presales Takeoff Stage

Actors and Prior Knowledge

Industries that achieve the firm takeoff milestone experience a subsequent acceleration in entry and commercial activity. Three types of actors engage with the industry. First, firms that were in a preproduction mode during the earlier stages offer commercial products (Carroll and Hannan 2000).

Second, a new set of firms engage in the industry in light of the expanding knowledge base that reduces the cost and scale of new knowledge that entrants need to generate from scratch. Here, in addition to new actors from the same contexts as in prior stages (academics, users, diversifying entrants from related industries, and public agencies), a fresh knowledge context is within-industry itself. Existing actors become knowledge fountainheads from which employee spinouts emerge. For example, whereas IBM and MCI conducted early research on Internet-related technologies, it was their employees who engaged in new venture creation (Greenstein 2015).

Third, firm takeoff and economic value capture by early entrants substantially increase an industry's visibility, which in turn spurs entry by actors exercising an option to wait. Some of these firms may have been waiting to assess the relevance of their preexisting assets to the new industry. For example, Phillips Medical System did not initially enter the nuclear magnetic resonance industry, but the industry's competitive pace of entry during the late 1970s implied that Phillips's window of opportunity for leveraging its downstream assets in medical diagnostics may close soon (Mitchell 1989). Other firms may have had to overcome external or internal resistance. In the case of the new Voice over IP industry, Verizon's investments in the technology were initially opposed by security analysts, although these concerns diminished later (Benner and Ranganathan 2012). Alternatively, revisiting their own resistance, Christie's and Sotheby's changed their initial perspective on the modern Indian art market after success of the newly founded Saffronart (Khaire and Wadhwani 2010).

Knowledge Generation Focus

Before sales can takeoff, industry knowledge needs to enable scalability and cost-effectiveness,[5] along with affordable and desirable products to diverse customers. Further, actors need to attend to how knowledge in any dimension increasingly interacts with other dimensions.

Technology Dimension. The residual technological uncertainty at this stage relates to additional features that not only enhance a product's functionality, but, importantly, reduce cost. Two refinements during the presales takeoff stage of airplanes are exemplar of these efforts. First, former employees of the Wright Brothers company founded Pratt and Whitney and specialized in airplane engines. Their efforts led to radial engines such as WASP and Hornet, which made planes faster and substantially cheaper. Second, parallel efforts focused on finding a lighter, stronger, and less expensive material as a substitute in airplanes' wooden bodies. Whereas steel and aluminum turned unsuitable, Alcoa developed a new aluminum alloy. Using this cheap, light, and strong aluminum alloy, however, implied the need to redesign other technical features in fuselage structure (Miller and Sawers 1970).

Demand Dimension. The presales takeoff stage concurrently signifies two transitions in the customer base. First, beyond the initial group of customers whose needs and preferences were central to the industry thus far, significant uncertainty remains about potential additional customer segments who may find the products relevant. In turn, demand knowledge generation is directed at identifying these customer segments and customers' diverse functional preferences within each segment (Adner and Levinthal 2001, Agarwal and Bayus 2002). For example, as commercial drone applications expanded to aerial photography, precision agriculture, inspection, and mapping, it was important to understand the unique preferences of each customer segment. It turned out that whereas photographers sought stability and no disruptive engine noise, farmers preferred high speed to cover large fields, weight-carrying capacity for crop spraying, and thermal sensors to assess crop health (Shermon and Moeen 2019).

A second transition, irrespective of customer segments, relates to customers' preferences for lower prices. Expansion of the customer base to early adopters/early majority categories brings more attention to price, given its importance in purchase behavior of these customers (Rogers, 1995, Golder and Tellis 1997). Yet, there are knowledge gaps in the specific willingness to pay. In 2G telephony, the price point to attract the mass market was initially ambiguous across different countries, even for firms that already knew the preferences of early customers (Eggers et al. 2019).

Actors use various approaches to generate demand knowledge, many of which mirror the knowledge-generation processes used in the preceding stages. An additional avenue stems from product use by an increasing number of customers, who either themselves tinker or request modifications to tailor the product for their particular preferences (Gambardella et al. 2017). For example, customers who tinkered with their cars often sent letters to contemporary magazines, such as *Horseless Age* and *Ford Owner*. Folding car seats, for instance, emerged from drivers who published pictures of cars in which they had replaced the passenger seat with a bed for a camping trip (Franz 2005).

Ecosystem Dimension. Efforts initiated in the preceding stage expand in scope to improve initial value chains, focus on scalability, and provide complement products that create value for diverse customer sets. After observing the division of labor and efficacy of the initial value chain, new knowledge can reveal incompetent suppliers, shortage of capabilities, transactional misalignments, and missing ecosystem activities (Jacobides and Billinger 2006). Subsequent knowledge generation may then focus on addressing these shortcomings. Of note here is the diversity of patterns that account for each industry's needs and attributes. For example, later entrants in the bioethanol industry emphasized less vertical integration (Qian et al. 2012), in contrast to the aluminum industry, where there was increased vertical integration (Helfat 2015). Laptop manufacturers continued working with their long-standing suppliers of flat panel displays (Hoetker 2005), in contrast to biotechnology firms that switched among downstream suppliers with more relevant expertise over time (Pisano 1991).

Further, efforts to achieve scalable and cost-effective supply chains become pertinent. At times, this can be achieved by expanding ecosystems that earlier catered to smaller segments by increasing the capacity of existing suppliers or bringing in new suppliers and collaborators. At other times, actors have to create novel supply chain activities to accommodate larger scale. For example, isolating insulin was initially possible using alcohol purification, a time-consuming method that worked at small scale. To achieve reliable large-scale production, Eli Lilly discovered isoelectric precipitation as a novel isolation process and modified the supply chain accordingly (Bliss 1982).

Attention to complements becomes salient at this stage, given that customers' value perception and purchase behavior may be tied to the availability of such products. If already available products and services cannot be coadopted as complements, actors need to design altogether new complements or incentivize complement providers. For example, semiconductor firms assisted ecosystem partners that could develop new mask materials, given customers' joint use of lithography equipment and masks (Adner and Kapoor 2016). Developing scalable approaches to provide complement products is also key. To that end, mobile game publishers formed simultaneous ties with multiple game developers (Ozcan and Eisenhardt 2009). Other online game platforms opened their game engine codes so that numerous game enthusiasts can become unpaid complement providers (Boudreau and Jeppesen 2015).

Identifying complement products and their scalable provision entail continued trial and error. Batteries for electric vehicles are a salient example of an ongoing challenge over the past century. In the 1910s, electric car manufacturers set up battery exchange stations for drivers (Kirsch 2000). A century later, although the idea of battery exchange is still around in Denmark's Better Place network, other trials include Tesla establishing numerous supercharger stations, and suggestions of a peer-to-peer charging network that leverages household electricity connections.

Institutions Dimension. In terms of social legitimacy, a critical mass of firm entry can create contradicting forces that require generation of different types of institutional knowledge. On the one hand, firms, customers, and stakeholders can form trade associations and social movements to bring favorable awareness to the industry. Their narratives can define the industry's core purpose and distinguish it from existing industries (Wry et al. 2011). Yet they need to understand what industry identity enhances legitimacy. For example, when grass-fed meat and dairy production was portrayed as an agriculture method without industrial feeding, it failed to gain attraction. But, after actors portrayed it as healthy diet, the message was accepted (Weber et al. 2008).

The contradicting force arises when increased product use and visibility present social desirability and ethical concerns, accompanied by advocacy groups and opposing social movements that either resist the industry or demand adjustments. Actors then need to generate institutional knowledge to alleviate these concerns. For example, as biotechnology drugs gained dominance, the green movement questioned their legitimacy as unethical interferences with nature or unsafe release of invasive genes to the environment (Weber et al. 2009). The availability of more cars on the streets of Chicago and New York in the 1910s raised concerns about their safety and speed (Rao 2004).

A range of stakeholders and peripheral actors engage in this legitimizing process. Amplification of stories in the media along with media's own interpretive frame help disseminate the industry identity and opposing ideas. For example, the media's frequent portrayal of Amazon impacted its reputation, and contributed to the e-commerce industry identity (Rindova et al. 2007). In Indian art and fashion, museum curators and fashion magazines were instrumental (Khaire and Wadhwani 2010).

The shaping of regulatory institutions becomes central at this stage. Some regulations seek to advance the industry. The Renewable Portfolio Standard policies aimed to incentivize renewable energy industries (Fabrizio 2012). Railroads often received public funds and land (Dobbin and Dowd 1997). Yet institutional knowledge of what regulations can serve this purpose and avoid unintended consequences is often lacking. Concurrent to regulators' sensemaking, the critical mass of firm entry enables lobbying to build legal support. For example, the increase in the number of solar panel manufacturers in Europe influenced feed-in tariff regulations to support long-term contracts for renewable electricity (Georgallis et al. 2019). Such support may also come from social movements. The National Recycling Coalition, for example, was the mobilizing advocate behind the 1976 Resource Conservation and Recovery Act (Lounsbury et al. 2003).

Other regulations at this stage define legal and restricted activities and specify oversight entities. These regulations typically respond to social or safety concerns noticed due to increased product use, or reflect opposing efforts by actors in threatened industries. The 1906 Pure Food and Drugs Act was enacted, after lack of hygiene in drugstores and drug-related adverse effects or deaths became known to the public and regulators. Due to gaps in institutional knowledge, regulatory revisions are frequent. Industry experts become key in communicating the industry's operations to regulators, as was the case in the regulatory approval of genetically modified crops (Hiatt and Park 2013). Trade associations and powerful firms can also engage in lobbying and political contributions, though often accompanied by organizing legitimizing public campaigns.

Several aspects of the IP institutional environment are already established by this stage. However, residual institutional gaps about patent boundary ambiguities arise. Revisions to pioneering patents' scope in the presales takeoff stages of multiple industries, including automobiles, airplanes, electric lamps, and razors, were prevalent and changed their institutional landscape (Merges and Nelson 1994). A notable example is Ford's challenge to the Selden patent scope that enabled scalable innovations.

Interactions Across Dimensions. Attending to interactions across all four dimensions of uncertainty prior to sales takeoff is crucial. Not only do these interactions allow for resolving inconsistencies between solutions for different dimensions, they also enable actors to use knowledge generation in one dimension to address unmet expectations in another dimension. Some inconsistencies and unmet expectations may arise from specific attributes of the presales takeoff stage, such as scaling and cost-effectiveness, whereas others may come to the surface due to concurrent attention to all four dimensions.

The interactions between technology and demand have continually been the focus of knowledge generation. During this stage, the addition of new customer segments with different price and functional preferences calls for revising technical designs. For example, the technical design of early cars achieved mobility and endurance, whereas subsequent efforts were directed toward customer preferences for smoothness of ride and comfort (Clark 1985). New customer segments for touring and speed racing resulted in technological redesign of cars and engines for higher speed (Kirsch 2000).

The focus on ecosystems implies that ecosystem opportunities and constraints can create and simultaneously need to account for interactions with technological and demand knowledge. To align with ecosystem activities, actors often reconsider their technological solution. For example, when digital video recorders revealed incompatibility with a scalable TV ecosystem, TiVo redesigned its technical platform (Ansari et al. 2016). In photovoltaic solar panels, particular downstream assets for deposition surfaces were available in the ecosystem, encouraging generation of technological knowledge that could use these ecosystem assets (Kapoor and Furr 2015). It is also likely that advancements in ecosystem knowledge open opportunities for novel technical designs that were not previously considered. In car manufacturing, the rise of new materials and a new production technique paved the way for designing semiautomatic car transmissions (Clark 1985). The interaction also works in the other direction. As actors pivot to new technical designs, new ecosystem knowledge may be warranted. Flat panel display manufacturers, for example, needed to reconfigure their vertical value chain once they switched from plasma to liquid crystal display designs (Eggers 2016).

At the intersection of ecosystem and demand, knowledge of customer preferences can reveal demand attributes that require adjustments in the ecosystem. This was the case for mobile operators, who initially considered text messaging as a communication mode between their technicians. But, after the broad demand for text messaging by the general population was understood, firms included text message billing as an activity in their value chain (Ansari and Phillips 2011). Moreover, reconfiguring ecosystems may be a solution to demand bottlenecks. In residential solar panels, because households generally recognized the need for solar panels, marketing techniques reached diminishing return in encouraging more customer adoption. Ecosystem reconfiguration to include financing as a complement activity, though, increased demand (Hannah and Eisenhardt 2018). An attribute of presales takeoff is expansion of customer segments to early adopters and majority, whose differential preferences call for ecosystem reconfiguration. For example, majority adopters of game consoles differed from early adopters in their preferred games, thereby requiring new complement games in the ecosystem (Rietveld and Eggers 2018). Finally, changes in the ecosystem have implications for assessing and reshaping demand. In rodeo kayaking, one way to achieve cost efficiency in manufacturing was to use plastic rather than fiberglass. However, these changes in value chain configuration necessitated assurance that use of plastic did not violate customer preferences (Baldwin et al. 2006).

The rising attention to generate knowledge about institutions does not happen in isolation of technological, demand, and ecosystem knowledge. The interaction with technology means that the emerging institutional knowledge provides feedback for subsequent efforts in generating technological knowledge. In particular, when stakeholder feedback reveals safety or social concerns about existing technical designs, instead of imposing regulatory restrictions or reversing perceptions of illegitimacy through rhetoric strategies, actors can reconsider technical designs. For example, recent disruptions to airports and privacy violations have resulted in social legitimacy hurdles for drones as "trespassers in the sky" (*Washington Post*, 2016). In response, a technical solution in the form of virtual fences is being explored. Further, revisions to technical designs need to account for the solution's coherence with institutions. For example, in organic farming, to harvest fresh vegetables in cold weather, the technological shift from cover cropping and composting to applying sodium nitrate required revising the organic certification process (Lee et al. 2017a).

Interactions between institutions and demand require resolving institutional concerns from potential uses in broader demand segments that emerge during presales takeoff. For example, the early demand segments for the Internet consisted of the military and scientific communities. With the opening of the Internet for commercial use, multiple regulatory and supporting institutions had to be developed or adjusted (Greenstein 2015). Further, when institutions face bottlenecks, demand knowledge can allow for identifying untapped customer segments for whom institutional concerns are less impeding. The cannabis industry, for instance, was initially illegal and stigmatized. To overcome this, firms assessed demand potential in customer segments interested in medical cannabis (Lashley and Pollock 2020).

Institutions also need to respond to and shape the evolving ecosystem. In electric lighting, Edison's envisioned ecosystem included a centralized lighting system, and needed regulatory support for burying electric lines underground. Vanderbilt's envisioned ecosystem included an isolated system of small generators in individual houses, and needed social legitimacy for home storage of a flammable device (Hargadon and Douglas 2001). Further, knowledge generation about an ecosystem needs to consider the implications for social and regulatory institutions. For green buildings, as the social pressure for Leadership in Energy and Environmental Design certification intensified, actors needed to overcome the shortage of ecosystem knowledge and inadequate availability of environmentally sustainable material suppliers, real estate agents, and commercial builders (York et al. 2018).

Knowledge-Aggregation Mechanisms

Knowledge aggregation during presales takeoff involves all four knowledge dimensions. The increase in the number and diversity of actors additionally intensifies generation of nonoverlapping knowledge. For instance, the divergence in technical design of digital cameras is linked to differences in firms coming from consumer electronics, analog camera, and computer industries (Benner and Tripsas 2012). In the case of cochlear implants, scientists with different views about safety and efficacy developed different routines to assess their knowledge-generation progress (Garud and Rappa 1994). Drone manufacturers diversifying from user contexts identified market-specific demand attributes and customer segments (Shermon and Moeen 2019). Founder background in the residential solar industry had implications for the configuration of ecosystem activities (Hannah et al. 2019).

Appending Mechanisms. Most channels used in the preceding stages for appending knowledge maintain their relevance and importance. Actors continue to use alliances, acquisitions, geographic proximity, open communities, and employee mobility along with channels specific to particular dimensions. New channels may also arise. For example, suppliers and ecosystem partners who garner industry-specific ecosystem knowledge may use it in collaboration with others (Saxenian 1996). Trade associations or lobbying firms can share institutional knowledge with their stakeholders and clients.

Although unintended knowledge spillovers can be present, open knowledge sharing diminishes. This may partly reflect actors' quest for value capture, so that even knowledge revealing can have for-profit motives (Alexy et al. 2013). For example, disclosure of communication equipment technologies considered economic boosts from nondisclosed knowledge (Toh and Miller 2017), and lack of patent enforcement in pharmaceutical drugs was a means to discourage the rise of competing technologies (Polidoro and Toh 2011). In parallel, the cumulative building of knowledge can strengthen the conditions for knowledge protection and appropriability, thereby amplifying the use of market-based appending channels. These conditions are reinforced by the increased understanding of industry that makes evaluating emerging knowledge and leveraging alliances and acquisitions easier.

Selecting Mechanisms. By this stage, the rise in the number of customers is accompanied by customers' preferences for lower prices. Thus, they play a stronger role in product market-based selection of firms on the basis of price and features, and as a consequence, select knowledge trajectories. Concurrently, actors' lack of successive knowledge generation in a trajectory can result in it being selected out.

Nascent industry firms also become increasingly rivalrous, as they seek to establish knowledge dominance. To block rivals' technologies, firms continue to use patent infringement lawsuits. These lawsuits then base firms' reputation for litigiousness and restrict employee mobility (Agarwal et al. 2009). For the demand dimension, since commercial products embody both technological and demand knowledge, patent rights often spill over to blocking rivals' products drawing on similar demand attributes. Potential bilateral investments by ecosystem partners enable imposing barriers on rivals. For example, in the flat panel display industry, Samsung and Sony formed proprietary ecosystems and alliances with a multitude of electronic firms, effectively blocking each other's expansion (Gnyawali and Park 2011). Institutions can also enable rivalrous action through nonmarket approaches. In the music synthesizer industry, firms used differentiating identity claims, even when product features were similar (Anthony et al. 2016). Finally, as some firms become powerful, they initiate regulatory changes that adversely impact rivals.

The potential attraction of majority customer segments can also increase pressure from actors in threatened industries who seek to winnow out the nascent industry knowledge altogether. These latter firms often accelerate investments in existing technologies that are at risk for obsolescence, as was the case in carburetor manufacturers' responses to technological changes in fuel injection (Furr and Snow 2014), or pursue ecosystem extensions that revive value-creating potential of threatened industries (Adner and Kapoor 2016). They can restrict access to value chain assets that overlap the threatened and nascent industries. In pharmaceuticals and wireless telephony, firms threatened by technological discontinuities used their complementary assets as competitive tools (Rothaermel and Hill 2005). Further, threatened firms can leverage institutions and nonmarket approaches to question legality or legitimacy of nascent industries. Taxicab drivers strongly opposed ridesharing mobile apps, asking local governments to ban them (Paik et al. 2018). Similarly, with the rise of chain retail stores in the 1930s, threatened independent retailers organized antichain movements, attacked their societal impact, and succeeded in imposing extra taxes (Ingram and Rao 2004).

Collective Mechanisms. During this stage, earlier collective mechanisms that mobilize actors toward investing in the industry often shift their emphasis toward coordinating the use of existing industry knowledge. This may in part arise from the increase in attention to the industry accompanied by the rise in the number of firms and customers that no longer requires external incentives. Further, it may arise from the need to contain competing knowledge trajectories and redundant efforts, in light of the expansion in size and scope of knowledge under control of diverse actors.

To coordinate technological efforts, standard-setting bodies and concomitant patent pools often bring together coalitions of actors consisting of firms, advocacy groups, and public agencies (Shapiro and Varian 1999). Faced with multiple competing technical designs that are cumulatively generated until this stage, the collective standard-setting process selects one design to be adopted by members, as documented during presales takeoff of the flight simulators (Rosenkopf and Tushman 1998), wireless telecommunication (Leiponen 2008), and commercial Internet (Simcoe 2012) industries. Its joint use with patent pools then allows members to append and license technologies that are compatible with the standard, yet owned by others (Joshi and Nerkar 2011, Vakili 2016). Not only do these collective efforts select out competing technologies, they also exhibit rivalry from inside. For example, firms participating in standard setting for computer peripheral interfaces were more favorable toward collective outcomes that secured their competitive position (Ranganathan and Rosenkopf 2014).

Similar collective mechanisms work for coordinated efforts targeted as ecosystem configuration. A coalition of firms and value chain suppliers can agree on downstream practices or manufacturing specifications that follow consistent interfaces (Rosenbloom and Cusumano 1987) or quality control (Benner and Tushman 2002). They can additionally extend to the demand and institutional dimensions, as actors form trade associations and social movements (Lee et al. 2017a). To shape demand, trade associations can engage in joint advertisement and education about an industry's product (Wry et al. 2011). Many forms of knowledge-generation efforts about social and regulatory institutions in the earlier sections already noted their collective nature, in that the unit of analysis for actors addressing an industry's social legitimacy, building support for regulations, or lobbying is at the collective level.

Sales Takeoff Milestone

The presales takeoff stage can end in one of two outcomes. First, industries can achieve a sharp increase in sales. The sales takeoff milestone is often hailed as the turning point between the nascent and embryonic state of an industry and its established growing state. The large number of customers being attracted to the industry reflects the cumulative knowledge about how to develop technologies for products that cater to varying functional and price preferences of wide customer segments, how to deliver and supply products and complements at scale, and how to arrange institutions for smooth exchange. For this milestone to realize, actors generate knowledge that accounts for the interactions between all four dimensions, with an eye on scalability and cost-effectiveness. Continued reliance on market-based appending mechanisms brings together different pieces of knowledge under control of different actors. Actors need to withstand selecting mechanisms exerted from threatened industries. When the balance between appending and selecting mechanisms does not consolidate divergent knowledge trajectories, collective mechanisms become useful in aligning actors' efforts.

Alternatively, the early few customers may become the only champions of the industry, keeping it alive as a small niche or lamenting its disappearance. Our conceptual framework points to factors that can impede sales takeoff. First, failure to achieve scalability with cost-effective solutions is a major barrier to sales takeoff. Scalability does not simply imply producing and delivering the same product at scale, rather, it also entails broadening the industry's appeal to a wide range of potential customers. It thus permeates all four dimensions of knowledge, and requires targeted knowledge generation. It can be finding technical solutions, offering complements, or alleviating social concerns for an expanding and often increasingly heterogeneous customer base. Second, inadequate knowledge in any dimension can slow the industry, but the inconsistencies across them are notably damaging at this time juncture. Addressing interactions allows for identifying a matched set of solutions across all four knowledge dimensions. A case in point is bioresorbable orthopedic implants, yet to reach robust customer adoption. Although almost every orthopedic manufacturer had commercialized a bioresorbable implant by 2004 (Ambrose and Clanton 2004), the dominance of their metallic implant offerings, coupled with nontrivial concerns of regulatory and legal fallout, have cast a shadow on bioresorbable implants. Third, another obstacle for sales takeoff is when a turf war between competing knowledge trajectories creates doubts about prospective winning or losing trajectories. Customers may delay purchase, and firms may defer investments. These industries may not advance, unless selection by powerful actors or collective mechanisms succeeds in narrowing the field. Fourth, in some cases, the emergence of a nascent industry can threaten obsolescence of an established industry. If actors in a threatened industry orchestrate a comeback by generating new knowledge or obstructing the nascent industry, it is the nascent industry that risks obsolescence.

Salient Themes Across Nascent Industry Stages

Several themes emerge regarding endogenous changes across nascent industry stages in actors and in knowledge-generation and knowledge-aggregation processes. Figure 2 illustrates the cumulative development of the industry knowledge base, and Figure 3 summarizes processes at each stage.

Theme 1: Transition of Actors in Terms of Knowledge Context and Organizational Form

The knowledge context of the actors and their organizational forms evolve over stages. Incubation actors largely comprise inventors within academic and corporate labs, individual users, or mission-oriented public/nonprofit agencies, and they draw from communities with norms of open knowledge sharing with a relatively higher focus on nonmonetary incentives (status and reputation within their communities). During prefirm takeoff, these actors often create for-profit enterprises or increase engagement with (downstream) corporate divisions, with concurrent increase in the relative focus on profitability. Further, commercialization represents profitability opportunities for a new set of actors who can build on their own or accumulated industry knowledge. Post firm takeoff, actors undertaking the form of for-profit enterprises are even more marked. This is in part because the next wave of entrants

Figure 2. Cumulative Building of Industry Knowledge Base

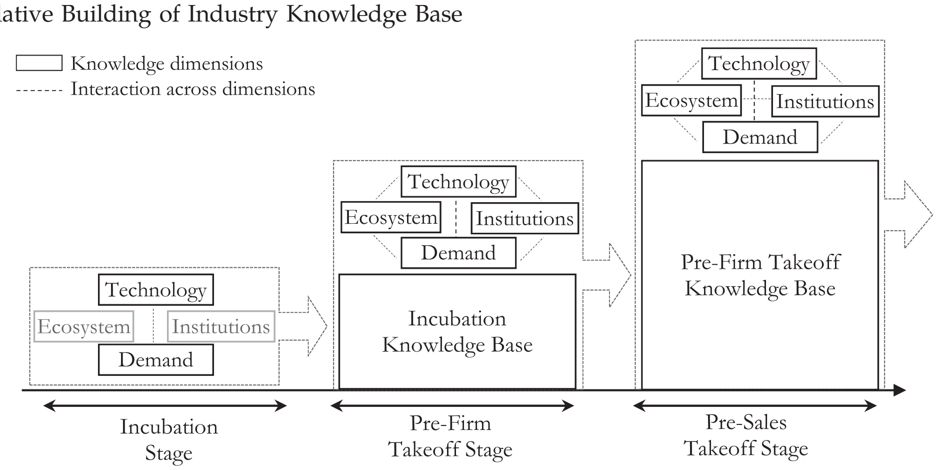
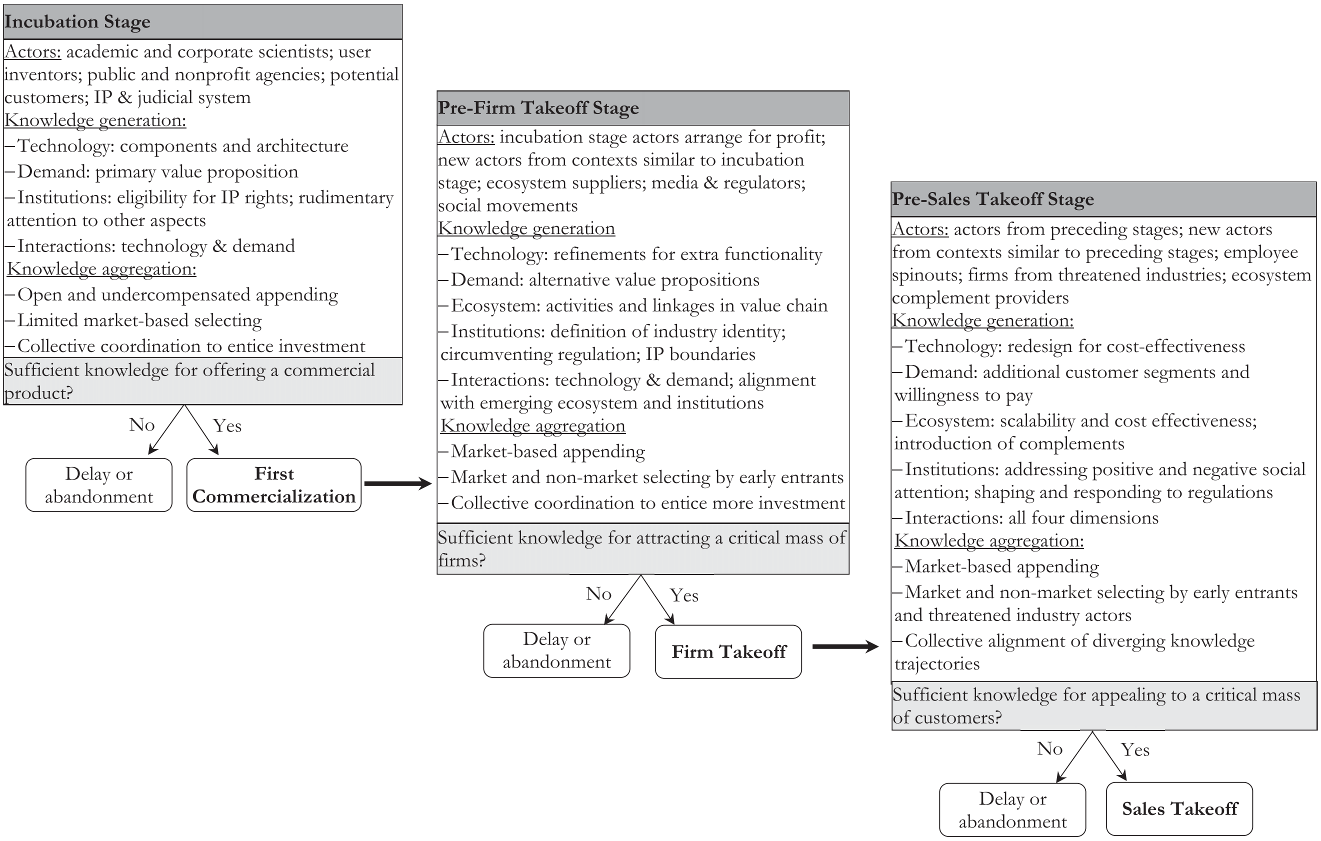


Figure 3. Conceptual Framework for Industry Emergence Processes



consists of new venture formation (e.g., spinouts) that builds on knowledge developed in preceding stages, or firms in obsolescing/threatened industries.

A similar transition is noticeable for peripheral actors. Although the majority of peripheral actors in the incubation stage stem from relevant demand and technological (including IP and judicial institutions) contexts, actors with relevant knowledge of value chains, media, financial analysis, and regulation are leveraged during the prefirm takeoff stage. The latter peripheral actors become more critical for scaling efforts during presales takeoff through trade associations, standard-setting bodies, and social movements.

Theme 2: Sequenced Focus in Knowledge Generation to Address Dimensions of Uncertainty

All four knowledge dimensions represent "unknown unknowns" at the onset of industry incubation. Nonetheless, the focus on dimensions of knowledge is not equal across stages. Actors sequence efforts and focus on a circumscribed set of issues, rather than being overwhelmed by tackling all uncertainties at the same time. In the incubation stage, consistent with the prior knowledge context of focal actors, knowledge generation focuses on the technology-demand nexus. On the technological dimension, this requires adapting existing components, creating new components, and linking components. On the demand dimension, this requires identifying a primary value proposition. Although there exist significant knowledge gaps in ecosystem and institutional dimensions, expending effort on them is premature (other than attention to technology-related IP institutions).

After commercialization, a better understanding of the most promising technological solutions and demand segments creates two concomitant shifts. First, the nature of technological and demand knowledge generation shifts to deepening of technological paradigms developed during incubation and identifying and discerning among additional value propositions. Second, such understanding is a critical base for actors to begin attending to ecosystem and institutional knowledge generation, to develop customized vertical value chains, create social legitimacy, and navigate regulatory regimes.

After firm takeoff, technological and demand knowledge-generation activities shift to refinements for scalability and cost-effectiveness. Attention to ecosystem and institutional knowledge dimensions accelerates as firms invest in developing vertical value chains for scaled production and offering complement goods and services for enhanced demand. Simultaneously, increased positive attention provides opportunities to utilize social movements, lobbying, and standard setting for increased legitimacy and legal support, whereas negative attention results in efforts to generate knowledge to offset resistance from actors in threatened industries, and address social and regulatory concerns.

Theme 3: Interactions of Knowledge Dimensions Increase in Successive Stages, and May Become Bottlenecks that Impede or Delay Industry Emergence

Consistent with the previous expansion in focus on knowledge dimensions, issues at the interface of knowledge dimensions also increase in salience. Although only interactions between technology and demand serve as feedback for generating knowledge in the incubation stage, the prefirm takeoff stage begins to encompass interactions between demand, technology, ecosystems (e.g., configuring vertical value chains), and institutions (e.g., social legitimacy and regulatory hurdles). The relevance of interactions accelerates in the presales takeoff stage, given the need to create scalable technology and production ecosystems that cater to diverse customer needs with high social and regulatory legitimacy. Often, it requires actors to revisit and reconfigure choices made in preceding stages in any one dimension, given bottlenecks or knowledge-generation efforts in other dimensions.

When bottlenecks from interactions stifle knowledge generation, they can impede transition from one stage to another, potentially leading to abandonment of the fledgling industry. During incubation, inconsistencies between technology or demand may impede commercialization efforts. Prior to firm takeoff, vertical value chains and institutions that are incompatible with technological and/or demand knowledge often suppress the industry. Prior to sales takeoff, interactions between regulatory boundaries, social legitimacy concerns, ecosystem conflicts, unpredictability in demand, and inadequacies in technical designs may thwart knowledge generation in any one or multiple dimensions.

As much as resolving these inconsistencies is key to industry emergence, the multifaceted and interdependent nature of an industry knowledge base can also enable actors to address bottlenecks. Actors identifying a problem or a gap in one knowledge dimension are not limited to finding a solution in the same dimension. Instead, adjustments in other dimensions may offer remedies.

Theme 4: Appending and Selecting Aggregation Mechanisms Shift Toward Market-Based Exchange and Appropriability

Another key theme emerges from the comparisons of appending and selecting mechanisms in each stage. Whether and how actors undertake these mechanisms largely stem from three interrelated changes: norms of actors, difficulty in protecting knowledge, and difficulty in arriving at a shared understanding of the valuation of knowledge. During incubation, actors' norms commonly exhibit low desire for capturing economic value, and competition among actors within academic and user communities accords with noneconomic factors such as status and reputation. Thus, appending mechanisms in the form of open sharing or undercompensated spillovers become common. Although there may be some selecting mechanisms to eliminate parallel knowledge trajectories, these are limited in scope. The reliance on open and undercompensated appending mechanisms stimulates knowledge flows across actors, allowing them to build on each other's achievements.

Commercialization heralds shifts in the composition of actors and their focus on economic value and profitability. It also enables valuation in the form of price of end products and thereby of relevant underlying knowledge, resulting in increased tendencies to engage in market-based appending mechanisms to capture economic value from each actor's shared knowledge. These tendencies are reinforced by the enhanced conditions for IP protection and appropriability, and development of shared understanding and valuation of industry knowledge. The same factors increase a focus on selecting mechanisms by creating incentives for actions toward blocking rivals and their access to relevant knowledge. These selecting mechanisms include the use of markets for technology and corporate control to gain favorable positions relative to rivals, as well as the use of regulatory and legal barriers by early entrants to extend monopoly positions in product and resource markets.

Post firm takeoff, markets gain even more relevance as exchange mechanisms. This is because industry norms are reflective of the organization of actors as firms engage in both resource and product markets, institutional structures strengthen conditions for knowledge protection, and increased specificity of roles within ecosystems helps create a shared understanding of potential value creation and potential hazards of economic exchange. In tandem, selecting pressures are the most dominant. Additionally, both early entrants and incumbents in threatened industries intensify efforts for the use of institutional factors to limit entry or gain competitive advantage in markets. This can manifest in the first wave of exits by firms unable to compete.

Although market-based selecting mechanisms are increasingly observed in industries that successfully transition from one stage to another, it is notable that such transitions may be impeded through the use of regulatory and institutional pressures (often through nonmarket strategies of lobbying and seeking legal recourse) by early entrants or threatened industry incumbents. In the extreme, such strategies may result in the industries never reaching the milestones of firm and sales takeoff altogether, and thus limiting the size of the overall market.

Theme 5: Collective Aggregation Mechanisms Are Increasingly Used to Create Constellations of Coordinating Actors that Compete with Each Other

The previous shifts in appending and selecting mechanisms are complemented by changes in the use of collective mechanisms across stages. Collective aggregation mechanisms in the incubation stage are limited to the coordination and mobilization of actors to invest efforts in knowledge generation, often by organizations that define mission-oriented grand challenges. These collective mechanisms are often accompanied by efforts to append knowledge of involved actors. Greater attention to the nascent industry due to the first commercialization creates a concomitant use of collective processes that engage more actors and call for even more investment in the industry. These collective mechanisms also seek to respond to the increased premature selection between actors, and coordinate aligning divergent industry views. Post firm takeoff, the cumulative knowledge generation along with persistence of competing knowledge trajectories brings about the need for collective coordination about which paths to pursue, and which knowledge trajectories to focus on. These collective processes begin to create constellations of actors who engage in collective action, yet compete within and across these constellations. Thus, there is an increase in competition among collectives of actors who seek to promote their technologies, demand, ecosystems, and institutional structures.

Discussion

Our conceptual framework unifies knowledge-generation and knowledge-aggregation processes through which industry knowledge is built (or impeded), and sheds light on how industries have emerged (or are abandoned) across distinct stages of incubation, prefirm takeoff, and presales takeoff. In doing so, we integrate across disciplinary silos, examining industry emergence with a focus on different dimensions of uncertainty, levels of analysis, and temporal stages. Our framework reveals evolutionary economics, strategic technology management, and entrepreneurship lenses that help explain the evolution of strategies in resolving technological, demand, and ecosystem uncertainty from incubation through sales takeoff. Institutional economics and organizational theory lenses are critical to understanding strategies utilized for creating social and institutional knowledge. All lenses provide insights for different pieces of the puzzle, and taken together, help provide a holistic view of the proverbial elephant.

In adopting an explicit process perspective, our framework abstains from the linear determinism of structure-conduct-performance models (Bain 1956). Instead, given its focus on partial knowledge that can only be addressed through a trial-and-error process, it highlights the endogeneity of industry and market structure, in line with Schumpeter's (1934, 1942) view of innovation and entrepreneurship, Rosenberg's (1992) view of economic experiments, and Gort and Klepper's (1982) view of endogenous changes in knowledge compositions. Similarly, on an epistemological level, it eschews end-state first-best market design solutions offered by omniscient and infallible social planners (Arrow and Debreu 1954).[6] Rather, it is in line with cognitive research emphasizing imagination (Shackle 1979), sensemaking (Weick 1995), and interpreting (Porac and Thomas 1990) by decision makers for shared understanding within evolving interpretative environments (Rindova and Fombrun 1999). This is not to say that the Marshallian market analysis is not relevant for nascent industries. Actors' focus on building knowledge necessitates participation in markets for knowledge starting in the incubation stage. However, industry-specific markets do not just emerge. Our framework explicates how knowledge generation and aggregation help build underlying technological, demand, ecosystem, and institutional knowledge, so that markets for an industry's products and services have the requisite features of thickness, efficient and effective transaction mechanisms, and constraints to minimize repugnancy (Roth 2008).

Limitations and Future Research

Our framework assumes that actors engage in purposeful action to reduce uncertainty. Two important caveats are in order. One, we neither suggest that economic incentives strictly increase over time, nor that uncertainty strictly decreases over time. Although we focus on uncovering endogenous processes, we acknowledge the importance of exogenous shocks on actors' incentives and industry uncertainty. Two, we acknowledge serendipity, in addition to purpose and deliberation. Serendipitous findings may spark revelation, and coupled with perseverance and diligent experimentation can speed uncertainty reduction. The interplay of exogenous shocks, serendipity, and endogenous processes is outside the scope of our article, and we hope future research will shed light on how and why the endogenous processes and temporal changes within nascent industries are impacted by shocks and serendipity.

Our framework also notes that industries may fail to emerge altogether, or experience significant delays. Here, we are limited by the literature on industry evolution itself suffering from success bias, inasmuch as it draws disproportionately upon retrospective analysis of industries that ultimately achieved commercial viability and transitioned to become mature. When discussing impediments and delays, we accordingly had to glean information from variance in length of each nascent stage. We urge scholars to study industry nonemergence and failure, because evidence from these contexts will provide important counterfactual insights. This is especially crucial for might-have-been industries that do not advance beyond the incubation stage, as lack of commercial products leaves little traceable evidence behind, and leads to systematic scholarly omission. Doing so will also shed light on whether selecting mechanisms that create institutional barriers through the use of regulation or legal restrictions create greater impediments and result in a greater likelihood of industries being abandoned prior to a milestone than selecting mechanisms that rely on voluntary trade among actors.

Our framework describes how a nascent industry advances to robust commercial activity. However, we do not assert that industry emergence is a universally desirable outcome. In this timeline, other threatened industries may begin their decline to obsolescence, and some competing knowledge trajectories within the nascent industry may be pushed to the sidelines. Thus, future research needs to assess strategic outcomes and implications separately for different scenarios or actors.

We also acknowledge that our focus on industry-specific institutions is predicated on actors in developed countries benefiting from strong general-purpose institutions such as a functional judicial system, property rights, and financial system. This sets a boundary condition to our framework. In developing countries, there are significant challenges created by a lack of effective institutions or the presence of dysfunctional institutions. Moreover, many of today's industries are born global. Future research can help shed light on how nascent industries in developing and global contexts may require different processes, or different sequence in which uncertainty dimensions are addressed.

Conclusion

Industries of the future will certainly have to navigate many of the uncertainties that existing industries do not have to grapple with, by virtue of past investments in building knowledge to provide novel technical solutions, tap into demand, and create robust ecosystems and institutions to facilitate coordination and exchange. Our conceptual framework itself builds on the impressive and cumulative body of knowledge generated by past innovative efforts of diverse scholars, who were armed by their imagination and prior knowledge, and engaged in sensemaking and interpretation of nascent industry contexts. In doing so, we hope we have helped contribute toward a shared understanding of the processes through which uncertainty is reduced within and across milestones of nascent industries. We also hope such a shared understanding will inspire future empirical work and theory building, so our scholarly endeavors may continue on the growth path for a robust knowledge base.

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Endnotes

[1] Noted by Steve Wozniak in his keynote speech at the J.D. Power Auto Revolution conference on October 23, 2019.

[2] Our focus is on industry-specific institutions, as scholars have predominantly studied industry emergence in developed countries. Country-level differences in strength of general institutions (e.g., property rights; regulatory, judicial, and financial systems) are outside our article's scope (Levy and Spiller 1994, Khanna and Palepu 1997, Henisz and Zelner 2001).

[3] Our focus is on industry-level dimensions of uncertainty. We abstract away from business models or transactional behavioral uncertainty, as these two dimensions operate at the actor level. Actor-level business model uncertainty implies partial knowledge about an actor's approach to the business (Zott et al. 2011), whereas transactional behavioral uncertainty indicates partial knowledge about opportunism in partnership relationships (Williamson 1975).

[4] It may well be that these roles are on a continuum rather than a binary distinction, both at a point in time based on the level of effort exerted, and also over time as actors increase or decrease their level of effort investment.

[5] Evolutionary economics and technology management scholars allude to how economies of scale and process innovations may operate during industry shakeout (Utterback and Abernathy 1975, Klepper 1996). Our references to scalability during presales takeoff indicate

attempts to build scale, and not economies of scale or the most efficient scalable operation.

[6] Such a market design approach could seek to answer the question, "What sets of incentives would be optimal for inducing individuals and organizations to invest in ways that will yield the optimal set and range of industries?" Such an approach presupposes knowledge of incentives, options, and even what constitutes optimality. However, as Rosenberg (1997, p. 97) notes, when there exists uncertainty along multiple dimensions, "the decisionmaker does not have information about the joint distribution of all the relevant random variables, then we have little reason to believe that a 'rational' decision is possible or that a well-defined 'optimal' investment or adoption strategy will be found."

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