© *Academy of Management Annals*
2023, Vol. 17, No. 1, 141–180.
https://doi.org/10.5465/annals.2021.0086

THE EVOLUTION OF TECHNOLOGY

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The evolution of technology is a central theme for management theory due to the transformative effect of technological change on societies, markets, industries, organizations, and individuals. Over the last decades, scholars from a broad range of theoretical and methodological traditions have generated a vast yet dispersed body of literature on technology evolution. We offer a comprehensive synthesis of the major streams of scholarship on technology evolution by dividing the literature into four perspectives: technology-realist, economic realist, cognitive interpretivist, and social constructionist. We further show that each perspective offers a divergent account of three central mechanisms—variation, selection, and retention—that drive discrete, continuous, and cyclical patterns of technology evolution. We integrate these perspectives by highlighting that they all emphasize recombination, environmental fit, and path dependence as central drivers of those three mechanisms. This integration opens paths toward a more complete account of technology evolution than that offered by the currently scattered state of the extant literature. We emphasize the need for a coevolutionary framework that cuts across the four perspectives to push the literature forward. Subsequently, we outline the foundation of this framework and propose future research opportunities by which the literature on the evolution of technology can advance.

The evolution of technology is a core topic in management theory (Abernathy & Clark, 1985; Kaplan & Tripsas, 2008; Pinch & Bijker, 1984; Suarez, 2004; Yates, 2005). Technology evolution lies at the heart of most industries (Christensen, 1997; Utterback & Abernathy, 1975), shapes competitive forces (Argyres, Bigelow, & Nickerson, 2015; Utterback & Abernathy, 1975), drives differentiation and cost reduction (Porter, 1997), and forms a material basis for the practices of consumers (Mick & Fournier, 1998) and professionals (Leonardi & Barley, 2010).

There is an extensive body of literature on technology evolution scattered across several research streams such as management, technology studies, economics, sociology, and psychology (Buenstorf & Klepper, 2010; Garud & Rappa, 1994; Grodal, Gotsopoulos, & Suarez, 2015; Kennedy, 2008; Rosenberg, 1982; Andriani & Cattani, 2016). Yet scholars within many of these research streams are not in conversation with one another because they tend to adhere to fundamentally different core assumptions about the nature of technology as well as the mechanisms that drive technology evolution (Kaplan & Tripsas, 2008). The lack of communication among scholars from these different streams has meant that knowledge of the evolution of technology has developed in semi-separate silos. Even within the discipline of management, sub-perspectives on the evolution of technology often do not communicate with one another. This has generated a fragmented and scattered literature although the literature on the evolution of technology has long since matured beyond its infancy. The time is ripe for a unifying synthesis.

The literature on technology evolution concerns how technology changes over time. While the literature encompasses a wide array of definitions, technology can broadly be defined as a form of knowledge that can be applied to solve problems (Dosi, 1982). However, such a wide definition of technology makes it difficult to distinguish among distinct concepts

We would like to thank Andrew J. Nelson, Victor Seidel, and Fernando F. Suarez for their comments on the paper. We would also like to thank Hannah Nivar for her invaluable work as a research assistant.

such as science, technology, and knowhow (Nelson & Winter, 1982). Therefore, most scholarly work on the evolution of technology has traditionally focused on the evolution of artifacts that encompass this knowledge (Basalla, 1988) by studying technological changes in product categories such as personal computers (Baldwin & Clark, 2000; Bingham & Kahl, 2013), automobiles (Rao, 2004), synthesizers (Anthony, Nelson, & Tripsas, 2016), or digital cameras (Tripsas, 2009). In line with Basalla (1988), we therefore define technology as the incorporation of knowledge into artifacts that can be used to solve problems, and we view the evolution of technology as the change in these artifacts over time.

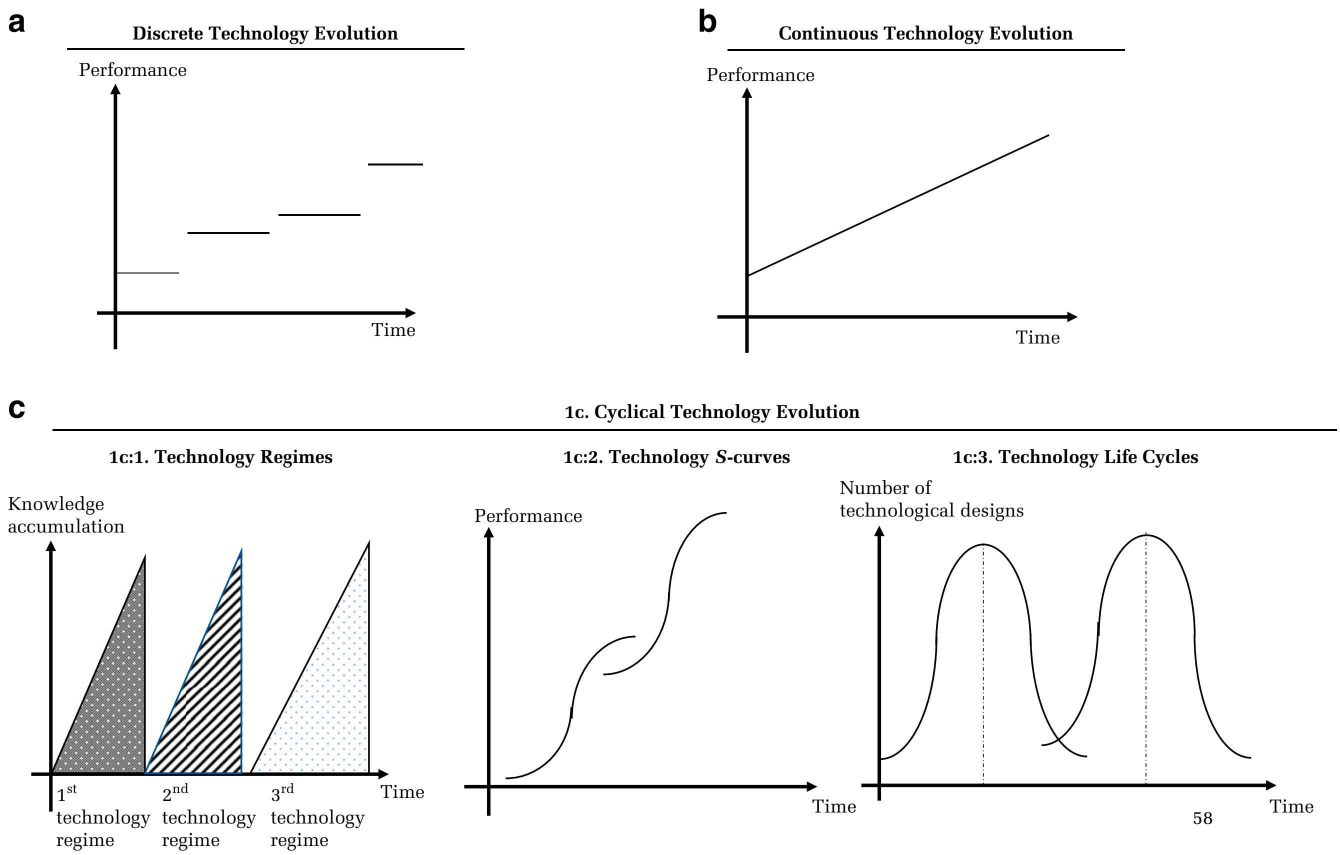
Scholars from a variety of research traditions have found that the evolution of technologies shows category-wide patterns (Abernathy & Clark, 1985; Anderson & Tushman, 1990; Kaplan & Tripsas, 2008; Schilling, 1998). It is therefore meaningful to discuss the technological evolution of the bicycle (Bijker, Hughes, & Pinch, 1987), automobile (Hannan, Carroll, Dundon, & Torres, 1995; Klepper, 2002; Rao, 2004), or personal computer (Eisenman, 2017) in general rather than merely the evolution of different producers' technology products. To study these macro-level changes in the evolution of technology, we must focus on changes in technologies at the market level, in contrast to the micro-adaptations that occur as a technology is implemented within organizations (Barley, 1986; Carlile, 2002) or the evolution of a single producer's work with a technology, such as the process from basic research and development (R&D) to product development and product extensions (Seidel & O'Mahony, 2014; Van de Ven & Polley, 1992). Although these types of technology evolution on the micro and firm levels are important due to their influence on the nature of work (Barley, 1986; Bechky, 2020; Leonardi & Barley, 2010), technology dynamics at the market level has the most profound impact on the actual shaping of technology evolution, such as by dictating which designs become dominant. Hereinafter, when we refer to *technology evolution*, we refer to the evolution of sets of physical artifacts that can be applied to solve a problem, for it is the patterns in the evolution of such artifacts and mechanisms that drive the evolution of technology, which is the subject of this review.

PATTERNS OF TECHNOLOGY EVOLUTION

The literature has described three patterns of technology evolution: discrete, continuous, and cyclical (Anderson & Tushman, 1990; Basalla, 1988) (see Figure 1 for an overview). Early works on the evolution of technology viewed technological change as the outcome of individual geniuses who invented novel artifacts, such as the steam engine or the automobile. Such inventions were viewed as creating discrete changes in the nature of technologies and were not seen as continuations of prior technologies (see Figure 1a) (Basalla, 1988). Inspired by Darwinian thought, some scholars in the late 19th century questioned this view and suggested that technology, like biological organisms, evolves through a continuous process of mutations termed "variation" (Butler, 1880). Producers continuously create slight variations of prior technologies, some of which are then selected and retained until they are challenged by yet another technological variation (see Figure 1b) (Basalla, 1988). The design of bicycles, for example, has been fairly stable, without major technology cycles and disruptions since the safety bicycle came to dominate the bike market over 130 years ago.

In contrast, most recent studies have depicted the evolution of technology as a cyclical pattern wherein periods of continuous incremental change are occasionally punctuated by discontinuous disruptive changes (Abernathy & Utterback, 1978; Adner & Kapoor, 2016; Christensen, McDonald, Altman, & Palmer, 2018; Suarez, 2004). For example, in contrast to the relative stability of bicycle designs, rigid disk drives were characterized by continuous turbulence (Christensen, 1993). Incremental technological change is defined as changes that introduce only slight variations to existing technologies (Anderson & Tushman, 1990; Suarez, 2004). Authors have offered divergent definitions of discontinuous technological change. Some emphasized the inputs—mostly a new knowledge base—that went into the creation of the discontinuous technology (Dosi, 1982; Nelson & Winter, 1982), whereas others have defined discontinuous technological change as the introduction of a technology with a radically different price-performance potential than that of the prior generation (Schumpeter, 1934). Still others have defined discontinuous technological change in terms of whether its outputs or consequences are aligned or misaligned with incumbent existing competencies—termed "competence-enhancing" and "competence-destroying," respectively (Tushman & Anderson, 1986). The stable period between two discontinuous changes is called the "duration of a technological regime" (or "technological paradigm") (Dosi, 1982; Nelson & Winter, 1982), a "technology S-curve" (Adner & Kapoor, 2016; Foster, 1986), or a "technology

FIGURE 1
Patterns of Technology Evolution: Discrete, Continuous, and Cyclical Models



life cycle" (Abernathy & Utterback, 1978; Suarez, 2004).

The concept of a technological regime is inspired by the Kuhnian idea of scientific paradigms (Kuhn, 1962) and refers to a pattern of technology evolution in which knowledge accumulation within successive technological regimes is disrupted by a change in the scientific knowledge base of the technology (see Figure 1c:1) (Cattani & Malerba, 2021; Dosi, 1982; Nelson & Winter, 1982). As a new knowledge regime is introduced and applied to technological problem solving, a technology's knowledge regime becomes further elaborated until it eventually stagnates due to exhaustion (Dosi, 1982; Kuhn, 1962).

The concept of an S-curve focuses on the level of technological performance gained from investments in technology over time (see Figure 1c:2) (Adner & Kapoor, 2016; Christensen, 1992; Foster, 1986). Initially, after the introduction of a new disruptive technology, the performance of that new technology is low, but once early investments in the technology cross a threshold, the maturation of that technology takes off as further investments lead to steep improvements in its performance. However, once all feasible performance improvements via incremental innovation have been achieved, performance improvements begin to taper off and the technology is said to have become "mature." The shape of the technology's performance graph, therefore, resembles an S-curve. At some point in time, a new type of technology is introduced. Initially, this new technology may—but does not always (e.g., Adner & Kapoor, 2016)—perform more poorly than the existing technology. As was the case with the technology that came before it, investments will rapidly improve the performance of the new technology until it surpasses that of the old technology, thereby spurring users to adopt the new technology, which eventually results in "technology substitution."

Another cyclical model is the technology life cycle (see Figure 1c:3) (Abernathy & Utterback, 1978; Suarez, 2004; Utterback & Abernathy, 1975).

In contrast to the S-curve, which tends to focus on a general manifestation of a technology, theories of the technology life cycle also focus on explaining which of several competing technological designs will become dominant over time, and why. A technological design is a configuration of technological components assembled within an overall technological architecture (Baldwin & Clark, 2000; Henderson & Clark, 1990); a dominant design is "a single architecture that establishes dominance [within an industry]" (Anderson & Tushman, 1990: 13; see also Abernathy & Utterback, 1978). The notion of a technological design is important in the study of technology evolution because it allows the comparison of technological variations over time as well as across producers (Anderson & Tushman, 1990; Clark, 1985).

The technology life cycle depicts technology evolution as cyclical waves between high levels of design variety and periods of design convergence (Anderson & Tushman, 1990; Christensen, Suarez, & Utterback, 1998). A technology life cycle begins when a technological discontinuity spurs producers to experiment with the new technology, resulting in a plethora of new technological designs (Abernathy & Utterback, 1978; Agarwal & Bayus, 2002; Anderson & Tushman, 1990; Eggers, 2012; Von Hippel, 1988). This early period of the technology life cycle is termed the "era of ferment," as an array of technological designs compete for dominance. Eventually, a single technological variation tends to be selected; this technology will be retained and become the dominant design within its industry, at times even in the face of technologically superior alternatives (David, 1985; Suarez, 2004). The emergence of a dominant design marks the onset of the shakeout among firms within the industry and the initiation of the period characterized by incremental technological change within the confines of the dominant design (Schilling, 2002; Suarez, 2004).

A comparison of these models highlights a pattern wherein technology evolution is characterized by periods of discontinuous and continuous change. The most recent literature emphasizes that technology evolution is cyclical with continuous evolution repeatedly being punctuated by discontinuous change. Over time, the *mean performance* of technology design variations within a category will follow an S-curve. However, at any given point in time, there is design variation, and not all versions of the technology perform at the same level. Many technology variations are spurred by a technological discontinuity. Simultaneous with the rapid performance improvements, we also observe a decrease in the *variance* of technological designs.

While many different scholars have identified discrete, continuous, and cyclical models of technology evolution, they have differed in their explanations for how these patterns arise. In particular, they have examined these patterns of technology evolution through the lens of four different perspectives, which we present below.

INTRODUCING FOUR PERSPECTIVES ON TECHNOLOGY EVOLUTION: TECHNOLOGY-REALIST, ECONOMIC REALIST, COGNITIVE INTERPRETIVIST, AND SOCIAL CONSTRUCTIONIST

What accounts for the patterns of technology evolution? We identified four perspectives that adhere to a different set of fundamental assumptions: technology-realist (Abernathy & Utterback, 1978; Rosenberg, 1982), economic realist (Klepper, 1997), cognitive interpretivist (Grodal et al., 2015; Kaplan & Tripsas, 2008), and social constructionist (Callon, 1986; Hargadon & Douglas, 2001). See Table 1 for an overview. The perspectives overlap and are intertwined. They are, thus, ideal types rather than discrete buckets that encompass specific papers. Many papers combine more than one perspective, but papers tend to foreground one perspective more than the others. The contrast between each of these perspectives provides clarity to the mechanisms underlying the evolution of technology—that is, the forces scholars use to explain how technologies change over time.

Authors across all four perspectives have identified the mechanisms of variation, selection, and retention as driving the evolution of technology, regardless of the patterns of technology evolution they advocate (Aldrich, 1999; Anderson & Tushman, 1990; Basalla, 1988; Bijker, 1987; Kaplan & Tripsas, 2008; Miner, 1994; Murmann & Frenken, 2006; Pinch & Bijker, 1984; Tushman & Murmann, 1998). We define *variation* as the introduction of technological alternatives (Basalla, 1988), such as the creation of new technological designs, but also the continuous introduction of more marginal, incremental changes. For example, in tracing the evolution of bicycles, Bijker et al. (1987) showed that producers initially introduced a broad array of bicycle designs. Early bicycles, such as the "hobby-horse," did not have pedals and chains; instead, riders propelled them forward by pushing their feet on the ground. Over time, other types of bicycles were introduced, such as the "high wheeler" and the "safety bicycle," which, despite being deemed

TABLE 1
Overview of the Four Perspectives on Technology Evolution

Perspective	Literature Examples	Definition of the Perspective	Definition of Technology	Focus of Literature	Data and Methods	Core Assumptions About Technology Evolution	Temporal Scope
Technology-realist	Abernathy and Clark, 1985; Tushman and Anderson, 1986; Schilling, 2002; Suarez, 2004	Technological evolution is driven by technological factors. *Includes:* S-curve theory, industry life cycle theory, technology life cycle theory	Technology as knowledge, predominantly stored in artifacts	Explaining competitive advantage and industry evolution. Focus on technological design.	Secondary data to trace key technological parameters. Quantitative data of markets, market share and entry-exit data, patent data. Focuses mostly on firms.	*Technological realism*: Actors' cognitive representations of the technology reflect the technology *Technological determinism*: Inherent properties of a technology have a fixed application and affect industries and organizations	Macro-cycles of economic growth; Industry life cycles; Technology life cycles
Economic realist	Gort and Klepper, 1982; Klepper, 1997	Technological evolution is driven by economic factors. *Includes:* Evolutionary economics, industrial economics, industry life cycle theory	Technology as knowledge, predominantly stored in artifacts	Explaining competitive advantage and industry evolution. Focus on R&D investments and economies of scale.	Secondary data to trace key technological parameters. Quantitative data of markets, market share and entre-exit data, patent data. Focuses mostly on firms.	*Technological realism*: Actors' cognitive representations of the technology reflect the technology *Economic determinism*: The application and effect of a technology on industries and organizations are determined by economic factors, such as firm size, market share, and R&D capacity.	Macro-cycles of economic growth; Industry life cycles
Cognitive interpretivist	Clark, 1985; Garud and Rappa, 1994; Tripsas and Gavetti, 2000; Kaplan and Tripsas, 2008; Kahl and Grodal, 2016	Technological evolution is driven by actors' cognitive representations. *Includes:* Socio-cognitive theory, frame	Technology as the interplay between knowledge, artifacts, and ways of evaluating	Firm adaptation to technological change, the commercialization of new technology, arbitrariness of the path of	Qualitative archival studies, cases studies, interviews, textual linguistic analysis to capture beliefs and "frames."	*Technological interpretivism*: Actors' cognitive representations do not directly represent the technology in itself due to	From emergence to taken-for-grantedness; Organizational adaptation pro-cesses; Conver-gence between

TABLE 1
(Continued)

Perspective	Literature Examples	Definition of the Perspective	Definition of Technology	Focus of Literature	Data and Methods	Core Assumptions About Technology Evolution	Temporal Scope
		theory, categorization theory		technological change. Focus is on categories and frames.	Focuses on firms and users.	interpretative ambiguity *Interpretative flexibility*: Ambiguity about applications and performance criteria of a technology affords multiple paths of application and effects, why technological evolution is not given prior to the fact	diverse cognitive representations
Social constructionist	Yates, 1993; Hargadon and Douglas, 2001; Akrich, Callon, Latour, & Monaghan, 2002; Dokko, Nigam, and Rosenkopf, 2012; Grodal, 2018	Technological evolution as shaped by social forces, such as power, networks, and politics. *Includes:* Institutional theory, actor–network theory, institutional economics	Heterogenous assemblage of technical and social linkages, resources embedded in social and power relations	The locus of innovation, coevolution between technology and social forces. Focus is on social structure.	Historical case studies, quantitative data on technologies, organizational fields and eco-systems. Focuses on multiple audience members.	*Social constructionism:* Actors' interactions with technology cannot be reduced to the technology itself but include the interests, network position, and power of the actor *Influence*: The application, path, and effect of a technology is shaped by its surrounding social structures	The process of reconciling contestation; The emergence of industries or fields

both ugly and uncool, became the dominant bicycle design (see Figure 2 for examples of early bicycle designs).

We define *selection* as the mechanism through which a subset of technological variations gains the favor of their environment, such as customers or regulators (Rosenkopf & Tushman, 1998; Schilling, 2002; Simcoe, 2012). In the case of bicycles (Bijker, 1997), consumers began to select the technological designs of the boneshaker, the high wheeler, and the safety bicycle over other designs. Finally, we define *retention* as the consistent recreation and reselection of a technological variation over time (Anderson & Tushman, 1990; Miner, 1994). Even though variation occurs continuously, most elements of a technology variation are retained across the flow of technological change. For bicycles, retention occurred when, over time, the safety bicycle was recreated and reselected, thereby shaping the future trajectory of incremental changes in bicycles, whereas other technological designs, such as the boneshaker and the high wheeler, disappeared.

The four perspectives offer different views on the three mechanisms (variation, selection, and retention) and their consequences for technology evolution (see Table 2 for an overview). In its ideal form, the

FIGURE 2
Technological Designs During the Evolution of the Bicycle

Name and Year	Technological Designs
Hobby-horse (1820s) The hobby-horse was one of the first bicycles created. It consisted of a wooden beam with two wheels and a fixed handlebar attached. Riders would propel themselves forward by pushing on the ground with their feet. Due to this method of riding it was often referred to as a "running machine" (Bijker, 1997; Minetti, Pinkerton, & Zamparo, 2001).	
The boneshaker (1860s) The boneshaker elaborated on the hobby-horse by adding pedals and a crank to the front wheel. The original boneshakers had wooden wheels and metallic rims. Later models (called velocipedes) had rubber tires which greatly increase riding comfort and was the most important technological improvement (Bijker, 1997; Minetti, Pinkerton, & Zamparo, 2001).	
The high wheeler (1870s) The iconic high wheeler came on the market about 10 years after the boneshaker. The rationale for the new design was that with a larger front wheel, each turn resulted in a larger distance. The high wheeler was very difficult to ride as both getting on and off was difficult and the bike could be unstable. Riders would impress bystanders by their high speed and control of this daring machine (Bijker, 1997; Minetti et al., 2001).	
The safety bicycle (1890s) The bicycle that ultimately became dominant within the industry was the safety bicycle. It featured a chain-driven rear wheel and had equal sized wheels. This design made it easier to get on and off the bicycle and made riding the bicycle available to a larger part of the population (Bijker, 1997; Minetti et al., 2001).	

Photos provided by courtesy of The Bicycle Museum of America: https://www.bicyclemuseum.com/

TABLE 2
The Four Perspectives' Views on the Variation, Selection, and Retention of Technology

Perspective	Technology-Realist	Economic Realist	Cognitive Interpretivist	Social Constructionist
Variation	***Variation is Driven by Recombination***			
	Somewhat random variations in technological design due to technological uncertainty. Different resources among firms spawn technological variations. Producers recombine technological resources.	Somewhat random variation in technological designs due to market uncertainty. Firm-level variation in capabilities and R&D capacity.	Different cognitive frames (often rooted in prior experiences, such as industry affiliation) spur different takes on technological opportunities and different technological designs. Producers recombine cognitive concepts, such as categories.	Different actors launch technological variations due to their different socio-political interests and distinct placement in social networks, institutional structures, and power relations. Producers form bricolage of resources across actors and social structures.
Selection	***Selection is Driven by Environmental fit***			
	Technological variations face a selection environment with certain needs in terms of price/performance relationships. Selection is determined by fit between a technological variation and the performance needed by users and other selecting stakeholders.	Consumers select technological variations based on their preferences. Selection is determined by the fit between technologies and consumer preferences in particular cost.	Technological variations face a selection environment in which a range of cognitive representations of a technology circulate. Selection is determined by the fit between the interpretative cues of technological variation's tangible features and discursive representation and the cognitive categories of users and other selecting stakeholders.	Technological variations face a selection environment in which actors possess conflicting interests and different degrees of power. Selection is determined by the fit between a technological variation and the interests of the stakeholders with the strong market influence.
Retention	***Retention is Driven by Path-Dependence***			
	Technological lock-in of dominant design: Commitment to past investments, regulatory standard settings, network externalities.	Economic lock-in in terms of economies of scale. Technologies that sold in bulk in prior years will be cheaper to produce and they will therefore be re-selected by consumers.	Taken-for-grantedness among both producers and consumers about which technologies to offer and purchase, typically rooted in assumptions about consumer demand or technological possibilities.	Technological variations are retained if they support or reinforce the network positions of powerful actors or network positions capable of mobilizing superior resources.

technology-realist perspective holds that technical factors—such as performance enhancements, correspondence between technical features, and user needs—are the main drivers of variation, selection, and retention (Abernathy & Clark, 1985; Anderson & Tushman, 1990; Mueller & Tilton, 1969; Utterback & Abernathy, 1975). An assumption of technological realism is that actors' cognitive representations of a technology mirror the actual technological artifact. Works adhering to the technological perspective have often implied technological determinism (i.e., the idea that a technology is fixed in its applications and effects, and its social and economic impact will mirror the inherent features of the technological artifact) (Allen, 1983; Colfer & Baldwin, 2016; Henderson & Clark, 1990; Schumpeter, 1934; Smith & Marx, 1994). Authors adopting the technological perspective have focused mainly on how changes in the maturation of the technology along the S-curve or technology life cycle shape the variance of technological designs.

The economic perspective emphasizes that economic factors, such as R&D investments and economies of scale, are the main factors that influence the variation, selection, and retention of technology (Klepper, 1997, 2002; Klepper & Simons, 1997; Murmann & Frenken, 2006). This perspective tends to adhere to realist assumptions about technology but holds that economic factors, such as firm scale, often overrule technical factors. In its purest form, the economic perspective implies a different materialistic determinism than the technological perspective, namely economic determinism, which assumes that as technologies are traded in the marketplace, technology evolution is governed by the competitive dynamics of markets, rather than being primarily the outcome of technological factors.

The theoretical point of departure for the cognitive perspective is a rejection of technological realism, instead holding that actors' cognitive representations of a technology are not one-to-one with the actual technological artifact (Kaplan & Tripsas, 2008; Navis & Glynn, 2010; Pinch & Bijker, 1984). The core tenet of cognitive interpretivism is that cognitive factors drive the direction of technology evolution (Bijker, 1987; Garud & Rappa, 1994). Empirically, studies adhering to the cognitive perspective have rarely focused on explaining long patterns of technology evolution and have instead focused more narrowly on transition periods and the competition between technological variations.

The social perspective builds on both the economic and the cognitive perspectives (Hsu & Grodal, 2021; Pontikes & Barnett, 2015). The core tenet of social constructionism is that understanding actors' interactions with technology cannot be reduced to the technology's inherent properties and rather social factors, such as interests, network position, and power, must be taken into account (Callon, 1986; Powell & Grodal, 2005). Compared to the technological and economic perspectives, this perspective does not adhere as strongly to materialistic determinism, but rather it asserts that technological evolution is heavily influenced by social dynamics that cannot be reduced to technical and economic factors. Superior technologies tend to be deselected if they are not aligned with the surrounding social structures (Callon, 1986; Croidieu & Kim, 2018; Dokko, Nigam, & Rosenkopf, 2012; Hargadon & Douglas, 2001; Pontikes & Barnett, 2015; Rao, 2004). The social perspective is heterogeneous with regard to the patterns of technology evolution that the studies have explained. However, in contrast to the technological and economic perspectives, the social perspective emphasizes consistency in the social and institutional structure across technology life cycles, which in turn creates continuity in technological development across discontinuities (Grodal, 2018).

Together, the four perspectives emphasize that technological, economic, cognitive, and social factors shape technology evolution. Although early works in the technology evolution literature emphasized the importance of the coevolution of these interconnected factors (Clark, 1985; Murmann, 2003), contemporary literature has largely abandoned this notion, diverging into distinct branches. As an attempt to reignite the coevolutionary approaches to examining technology evolution, we offer a unified model of the mechanisms that drive technology evolution (see Figure 3 for an overview). Several insights emerge from our unified model. We argue that recombination, environmental fit, and path dependence are aggregate, cross-perspective drivers of variation, selection, and retention. Drawing on this insight, we provide a schematic framework of how the technological, economic, cognitive, and social factors together shape each phase in technology evolution through recombination, environmental fit, and path dependence. Based on this framework, we discuss several areas of differences and similarities across the perspectives, and we identify avenues for future research by expanding current research methods to include mixed methods and archival historical analysis (Kahl & Grodal, 2015; Ventresca & Mohr, 2002).

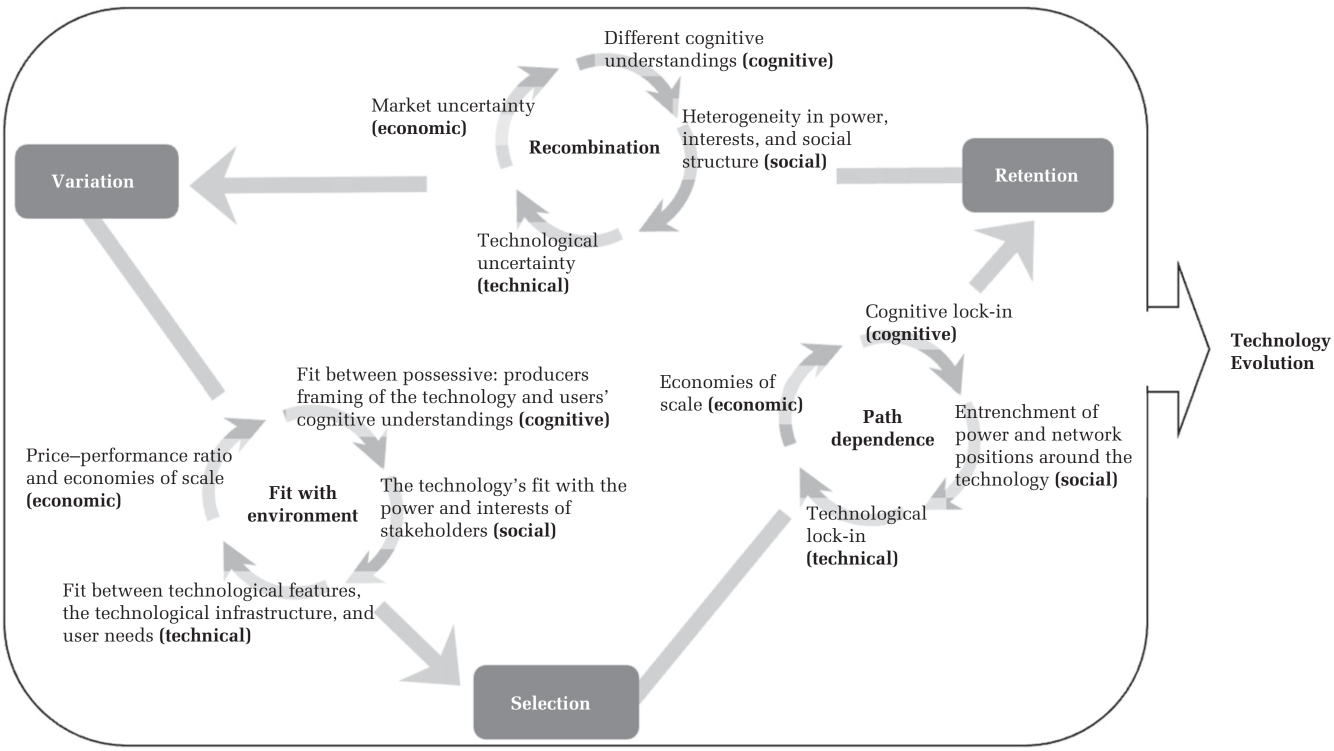
In what follows, we are first going to introduce the methods that we used to review the literature on the evolution of technology. We will then introduce the four different perspectives on the evolution of technology that we identified during our review. Lastly, we will provide an integration of the four perspectives and offer suggestions for future research.

METHODS

Selection of Relevant Literature

We sought to include articles in our review that could inform us about the drivers of technology evolution. Therefore, we excluded articles that neither empirically nor theoretically informed us about this topic. We conducted a broad search in journals across management, economics, sociology, and psychology, among others. We identified journals associated with each of these disciplines by drawing on lists in other *Academy of Management Annals* reviews (Hannigan, Haans, Vakili, Tchalian, Glaser, Wang, Kaplan, & Jennings, 2019; Lehman, O'Connor, Kovács, & Newman,

FIGURE 3
Model of Technological Evolution



2019; Zhang, Wang, Toubiana, & Greenwood, 2021) and included additional journals when necessary (see Table 3 for an overview of the journals that we included in our search). To identify relevant articles from these journals, we systematically searched these journals for a set of keywords related to technology evolution ("techn* evolution" or "techn* emergence" or "innov* evolution" or "innov* emergence" or "evolution of techn*" or "techn* change"), which yielded a total of 1,059 articles (see Table 3 for an overview of these articles across topic areas). By reading through the abstracts of these papers, we identified 257 articles related to the evolution of technology within markets (Adner & Kapoor, 2016; Anderson & Tushman, 1990; Croidieu & Kim, 2018; Garud & Rappa, 1994; Grodal et al., 2015). For example, if an article was related to the influence of technological change on competition within an industry, it was included in the sample. However, if an article examined the role of technological change on macroeconomic indicators in a country or technological change related to intraorganizational phenomena, it was excluded. This led us to exclude work that focused solely on intraorganizational innovation (Barley, 1986; Barrett, Oborn, Orlikowski, & Yates, 2012; Benner & Tushman, 2002; Carlile, 2002; Feldman, 2000; Hargadon & Douglas, 2001; Leonard-Barton, 1992; Murray & O'Mahony, 2007; Zbaracki, 1998), the evolution of process technologies and service industries (e.g., Carroll & Hannan, 2004; Hannan & Freeman, 1977), the diffusion of specific technological variations (Naumovska, Gaba, & Greve, 2021; Rogers, 1985), and the evolution of science (Kuhn, 1962; Nelson, 1962). We excluded the majority of papers in disciplines outside of core management (e.g., economics, sociology) because most of them were focused on labor dynamics and innovation activities across a national economy rather than within a market or industry (Lerner & Stern, 2012).

We conducted a second round of screening on the remaining papers by reading through the full texts to determine whether a paper examined technological evolution or offered information that shed any light on the mechanisms driving technological change. For example, many papers studied only technological discontinuities as a shock to another variable of interest that did not shine light on technology evolution. This screening left 135 articles.

TABLE 3
Research on Technology Evolution

	Total	Management: Strategy & Entrepreneurship	Management: Organization Theory	Economics	Marketing	Psychology	Sociology	FT50	Technology
Pre-1980	2 (82)	1 (2)	0 (1)	1 (48)	0 (2)	0 (3)	0 (2)	0 (8)	0 (16)
1980–1989	7 (70)	6 (14)	0 (1)	0 (12)	0 (0)	0 (3)	1 (7)	0 (2)	0 (31)
1990–1999	47 (212)	28 (73)	11 (22)	2 (35)	0 (2)	0 (2)	2 (13)	3 (24)	1 (41)
2000–2009	85 (284)	46 (127)	35 (39)	4 (52)	3 (8)	0 (2)	0 (11)	0 (27)	3 (18)
2010–2019	105 (370)	45 (181)	46 (60)	4 (56)	3 (4)	0 (2)	0 (17)	1 (29)	3 (21)
2020–2021	11 (41)	3 (21)	4 (7)	1 (7)	0 (0)	0 (0)	0 (4)	0 (1)	0 (1)
Total	**257** (1,059)	**129** (418)	**96** (130)	**12** (210)	**6** (16)	**0** (12)	**3** (54)	**4** (92)	**7** (128)

Notes: The search words were: "techn* evolution" OR "techn* emergence" OR "innov* evolution" OR "innov* emergence" OR "evolution of techn*" OR "techn* change." A lower percentage of papers were included from outside of core management because the papers yielded by the systematic search in these disciplines tended to be at a different unit of analysis, such as macroeconomic variables. For example, 66 studies among the 210 economics articles addressed labor economics questions, such as how technical changes affect labor markets and wage inequality. Most of the studies we found in the sociology literature addressed inequality-related subjects. Other studies we found in the economics literature mostly discussed the impact of macroeconomic variables on the level of innovation across the whole economy, not a specific industry or a class of products.

Management—Strategy & Entrepreneurship: *Strategic Management Journal, Management Science, Research Policy, Industrial & Corporate Change, Journal of Business Venturing, Entrepreneurship Theory and Practice, Strategy Science, Strategic Entrepreneurship Journal.*

Management—Organizational Theory: *Organization Science, Academy of Management Journal, Academy of Management Review, Administrative Science Quarterly, Organization Studies, Academy of Management Annals, Journal of Management Studies, Journal of Management Inquiry, Journal of Management, Organization, Academy of Management Discovery, Research in the Sociology of Organizations,* and *Strategic Organization.*

Economics: *American Economic Review, Quarterly Journal of Economics, Journal of Political Economy, Econometrica, Journal of Financial Economics, Journal of Financial and Quantitative Analysis, Review of Economic Studies, Review of Finance,* and *Review of Financial Studies.*

Marketing: *Journal of Consumer Psychology, Journal of Consumer Research, Journal of Marketing, Journal of Marketing Research, Journal of the Academy of Marketing Science,* and *Marketing Science.*

Psychology: *Advances in Experimental Social Psychology, Annual Review of Psychology, Cognitive Science, Journal of Applied Psychology, Journal of Cognition and Culture, Journal of Experimental Psychology (Applied), Journal of Experimental Psychology (General), Journal of Experimental Social Psychology, Journal of Occupational and Organizational Psychology, Journal of Occupational Health Psychology, Journal of Personality and Social Psychology, Personality and Social Psychological Bulletin, Personnel Psychology, Psychological Bulletin, Psychological Review,* and *Psychological Science.*

Sociology: *American Journal of Sociology, American Sociological Review, Annual Review of Sociology, Social Forces, Sociological Quarterly, Sociological Review, Sociological Science,* and *Sociology.*

FT50 journals (excluding the ones listed above): *Accounting Organizations and Society, Harvard Business Review, Human Relations, Human Resource Management, Information Systems Research, Journal of Accounting Research, Journal of Business Ethics, Journal of International Business Studies, Journal of Management Information Systems, Journal of Operations Management, MIS Quarterly, Operations Research, Production and Operations Management,* and *Sloan Management Review*

Technology-related journals: *Journal of Product Innovation Management, Science Technology & Human Values, Social Studies of Science,* and *Technology and Culture.*

Journals identified in the second-round search (60 additional papers): *Technology Review, Business History Review, The Journal of Economic History, California Management Review, Research Management, NBER working paper series, Rand Journal of Economics, The Economic Journal, Canadian Journal of Economics, Research in Organizational Behavior, Cambridge Journal of Economics,* and *Social Studies of Science.*

In addition to the articles we identified based on the systematic search, we also included articles based on our iterative reading of the literature. These articles were not included in the original sample because they had either been published in journals that were not part of our systematic search or did not mention any of the keywords that we had used to generate the systematic sample. We identified 60 articles through this process (see Table 3 for an overview of the journals in which these articles were published). Our final sample was, therefore, 195 articles. In addition to the articles, our review was also informed by 25 central books on this topic.

Analyses of the Literature

After we had identified our sample, we developed a systematic coding scheme to generate an overview of the main themes in the literature and how the literature had evolved over time. We read through a random sample of the articles to develop a coding scheme that we could apply systematically to all the articles. Some of the central themes that emerged were four different perspectives on the evolution of technology, the kinds of data used, the kinds of analyses conducted, as well as the main dependent and independent variables. Together with a research assistant, we subsequently applied our coding scheme to the 195 articles while updating it iteratively. Through this process, we identified systematic differences and commonalities across the perspectives.

THE EVOLUTION OF THE LITERATURE ON THE EVOLUTION OF TECHNOLOGY

The literature on the evolution of technology began to blossom during the 1970s. Since then, there has been tremendous growth and development in our understanding of technology evolution. In the early years, the main focus of the literature was to understand the role of technological change as an antecedent of economic growth (Schumpeter, 1934). In the 1970s, the groundwork for contemporary research on technological change was laid as authors sought to understand patterns of technological change over time as well as the variation in which firms were able to successfully navigate technological change (Abernathy & Clark, 1985; Abernathy & Utterback, 1978; Clark, 1985; Rosenberg, 1982). Eventually, the literature on technology evolution branched out into different sub-streams that became increasingly heterogenous in terms of specific interests, such as underlying theoretical assumptions and what studies sought to explain.

Figure 4 shows the number of articles in our sample over time. The graph shows that the number of articles on the evolution of technology rapidly expanded from the late 1980s until the early 2000s, whereafter the number of articles per year decreased slightly. Figure 5 depicts the evolution of the literature from being dominated by a single perspective to eventually branching out into the four different perspectives. During the 1970s and 1980s, the field was dominated by articles from the economic perspective. However, since the 1990s, articles adhering to the social, cognitive, and technological perspectives have increased.

Table 5 provides an overview of the data across the perspectives fixed on a set of different variables. The tables show that about one-third of the papers in this literature were theoretical in nature, one-third were quantitative, and one-third were split among

FIGURE 4
The Number of Papers in the Technology Evolution Literature Over Time

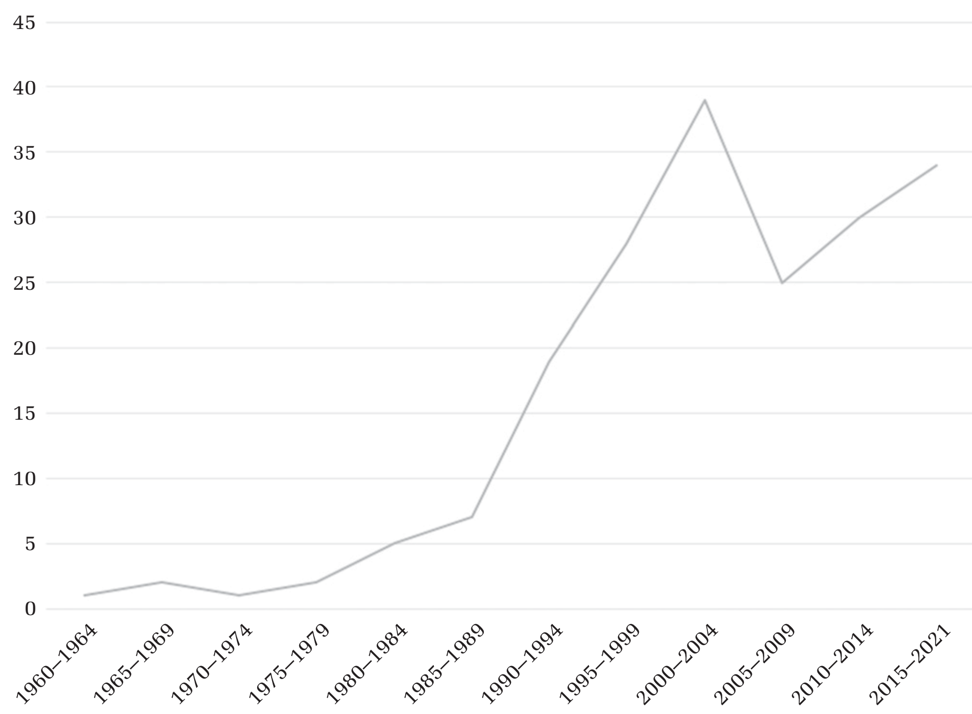
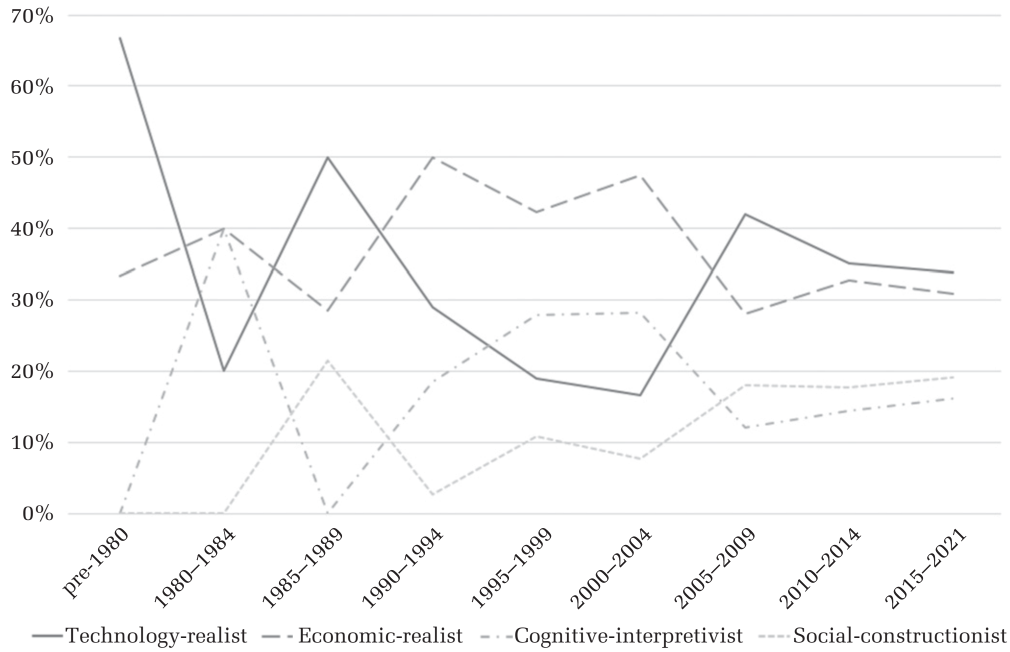


FIGURE 5
The Number of Papers in Each Perspective Over Time

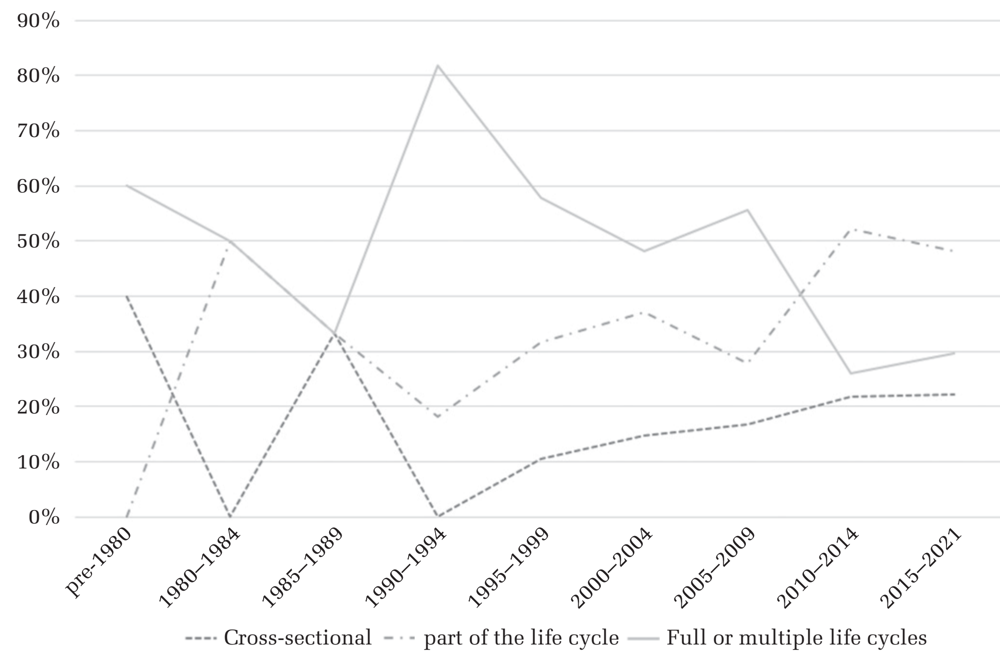


qualitative, computational, and mixed methods. The table also shows that most papers examined high-tech settings, whereas a relatively smaller volume of studies focused on low-tech settings. Furthermore, most papers examined technological discontinuity rather than incremental change, as most studies focused on studying the technological shifts that lead to new dominant designs. Early on, there was an overwhelming tendency for scholars to study one or more technology life cycles, but over time, the literature has inclined toward studies that are cross-sectional or that study only part of a technology life cycle (see Figure 6). This observation is related to another tendency in the literature, namely the overweight of studies on technology emergence and a scant examination of technology evolution during technological maturation.

Another interesting observation that emerged from our analyses was that very few papers empirically studied users, in that most papers did not include user-level or demand-side data. This is surprising given the important role that users play in scholars' theoretical frameworks of the evolution of technology literature. Importantly, the literature on user-driven innovation, which has focused on users, has examined the ones that take on the role of producers (Franke & Shah, 2003; Shah & Tripsas, 2007; Von Hippel, 1988) but not the full swath of users consuming a product.

We also found considerable variation with regard to the role of technology evolution in research designs. Although some studies treated technology evolution as a dependent variable, the majority of studies in our sample examined technology only as an exogenous shock that—as a backdrop for the research design—allowed studies to examine technology's impact on variables, such as entry and exit into an industry and organizations' ability to adapt to technological change. Studies that traced technological evolution as a dependent variable were skewed toward the technological and social constructivist perspective; those tended to focus on illuminating specific cyclical patterns or what shapes the trajectory of technology evolution. In contrast, a handful of studies that treated technology evolution as an independent variable were more likely to belong to the economic perspective. Finally, we traced each paper's unit of analysis. Across the perspectives, the firm was the dominant unit of analysis, with surprisingly few studies at the product level. Studies going beyond a single level of analysis were scarce and typically concentrated within the cognitive perspective.

FIGURE 6
The Number of Life Cycles Covered in the Papers Over Time



FOUR PERSPECTIVES ON THE EVOLUTION OF TECHNOLOGY

We now present the four perspectives on the evolution of technology. Because the others take the technological perspective as a point of departure, we present this perspective first.

The Technology-Realist Perspective

The technological perspective originated from scholarly interest in understanding technology evolution due to its impact on economies, industries, and organizations (Abernathy & Clark, 1985; Abernathy & Utterback, 1978; Henderson & Clark, 1990; Schumpeter, 1934; Utterback, 1994). Early authors adhering to the technological perspective often acknowledged the importance of cognitive and social factors (Anderson & Tushman, 1990; Clark, 1985); however, as an ideal type, the technological perspective assumes the primacy of technological factors (Anderson & Tushman, 1990; Suarez & Utterback, 1995) (e.g., selection tends to be driven by technical factors).

Another common assertion in research from this perspective is that technological entrenchment explains the path-dependent nature of technology evolution (Arthur, 2009). The technology that is ultimately retained may therefore not be superior in its performance potential but rather the consequence of previous choices in path-dependent, nonreversible ways. Rosenberg (1963: 440–441) exemplifies this perspective when he writes that:

> An explanation of many of the technological changes . . . may be fruitfully approached at the purely technological level . . . Any important improvement in the operation of a component, whether it be the currently limiting one or not, is likely to create new obstacle, in the form of limitations imposed by another component, to the achievement of a higher level of performance . . . Many aspects of technological change, in order to be adequately understood, must be examined in the terms of particular historical sequences, for in technological change . . . one thing often leads to another—but not in a strictly deterministic sense, but in the more modest sense that doing some things successfully creates a capacity for doing other things.

Inherent in the technological perspective is thus an understanding that the existing technology is the primary driver of technology evolution. Many central contributions within this perspective have echoed the sentiment that the configuration and evolutionary stages of the technology dictate the technological space within which producers can innovate (Abernathy & Utterback, 1978). Table 4a provides a few examples of studies that have primarily adhered to the technological perspective, although several of these papers also touched upon elements from the other ideal types.

Technology variation. The technological perspective holds that a technology possesses an inherent performance potential that becomes exhausted over time as performance gains are reaped through incremental innovation. Variation in designs and their associated performance is high following a technological discontinuity, as producers face high uncertainty about which technological designs are technically feasible and meet customer needs (Abernathy & Utterback, 1978; Clark, 1985; Foster, 1986; Grodal et al., 2015). These early variations are often crude, incompatible, and costly as they are often customized to specific circumstances and yet lack complementary products and services (Suarez, 2004). As technological uncertainty is reduced and the inherent performance potential of the technology eventually becomes exhausted (Foster, 1986), design variation halts as producers focus on reaping performance gains and cost decreases from minor variations on prior technological designs (Suarez & Utterback, 1995).

Technology selection. As an ideal type, the technological perspective assumes that technological variations are selected based on their inherent technological features (Rosenberg, 1963), especially functional properties (Baldwin & Clark, 2000). The ideal form of the technological perspective thus implies that selection favors the technology variation whose inherent functional features offer the best fit with users' needs. This will often be the variation with the highest performance at the time of selection, which frequently differs from the technology with the highest potential overall (Adner & Kapoor, 2016; Foster, 1986).

Technology retention. According to the technological perspective, technology lock-ins occur when a technology variation becomes favored among alternatives. Consequently, investment and learning are fed into that specific variation, enabling it to increase in performance at a greater pace than its competitors (Murmann & Frenken, 2006; Schilling, 1998). Even when inferior technologies are selected, they may be retained due to technology lock-ins (Basalla, 1988; Rosenberg, 1963). For example, Arthur (1989) showed that under the condition of increasing return, inferior technologies may lock in under random initial conditions and the accumulation of small, seemingly insignificant events. Such trajectories are very difficult to redirect (Nelson & Winter, 1982). For complex technologies, lock-ins become entrenched through design hierarchies as technology components spawn a range of sub-trajectories (Baldwin & Clark, 2000; Clark, 1985). Furthermore, markets are more prone to lock-ins if they are characterized by network externalities, namely "when a good is more valuable to a user the more users adopt the same good or compatible ones" (Suarez & Utterback, 1995: 418).

The Economic Realist Perspective

The economic perspective extends the explanations of technology evolution put forward by the technological perspective by emphasizing economic, rather than technical, factors (Klepper, 1997). The origin of the economic perspective is an attempt to explain the evolution of technology industries but with a greater emphasis on economic variables, such as scale and cost structures, rather than on inherent features of the technology (Buenstorf & Klepper, 2010; Klepper, 1997). Arguably the strongest exemplar of this perspective is the work of Klepper (1996, 2001, 2002), who argued that industry shakeouts can be explained by firm-level differences rather than the emergence of dominant designs. Klepper showed that as competition shifted from product innovation to process innovations, only firms with a high market share could invest sufficiently in process efficiency to remain competitive. Table 4b shows examples of studies that primarily adhered to the economic perspective, although several of these papers also contained elements from the other perspectives.

Technology variation. From the economic perspective, technological variation is driven by firm heterogeneity in technology and market competencies and market uncertainty, especially insufficient knowledge of demand, which spurs producers to generate different technological variations (Klepper, 2002). As ideal types, the technological and economic perspectives are distinguished in that, whereas the technological perspective posits that it is technological uncertainty in the face of the inherent potential of new technologies that generates novel technology variations, in the economic perspective, it is differences in firms' prior investments in technology competencies or heterogeneity in consumer demand that spur producers to create a variation in technological designs (Adner & Levinthal, 2001; Schilling, 1998).

Technology selection. In its ideal form, the economic perspective holds that selection occurs due to economic drivers in the market, especially consumers' preferences for selecting cheaper products

TABLE 4A
Twelve Example Studies That Primarily Draw on the Technology-Realist Perspective

Paper	Type of Study	Perspective on Variation, Selection, and Retention
Abernathy, W. J., & Utterback, J. M. 1978. Patterns of industrial innovation. *Technology Review*, 80: 40–47	Theoretical	***Variation***: Technological uncertainty ***Selection***: Uncertainty reduction ***Retention***: Cost reduction
Dosi, G. 1982. Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change. *Research Policy*, 11: 147–162	Theoretical	***Variation:*** Market demands and technological change ***Selection***: Economic and social factors ***Retention***: Path-dependency (trajectory), oligopolistic competition
Rosenberg, N. 1982. *Inside the black box: Technology and economic*s. Cambridge, U.K.: Cambridge University Press.	Theoretical; case studies	***Variation***: Market demands, technology push, government support ***Selection***: Economic and social factors ***Retention***: Learning by using, systemic complexity
Anderson, P., & Tushman, M. L. 1990. Technological discontinuities and dominant designs: A cyclical model of technological change. *Administrative Science Quarterly*, 35: 604–633.	Quantitative; various technologies	***Variation***: Technological uncertainty ***Selection***: Uncertainty reduction, social and political processes ***Retention***: Economies of scale, learning curve
Henderson, R. M., & Clark, K. B. 1990. Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms. *Administrative Science Quarterly*, 35: 9–30	Qualitative; photolithographic equipment	***Variation***: Architectural change, routine (or lack thereof) ***Selection***: Performance superiority ***Retention***: Architectural knowledge embedded in organizations
Suarez, F. F., & Utterback, J. M. 1995. Dominant designs and the survival of firms. *Strategic Management Journal*, 16: 415–430	Quantitative; various technologies	***Variation***: Competing design paths ***Selection***: Technological, economic, organizational factors ***Retention***: Standardization
Christensen, C. M. 1997. The innovator's dilemma. Cambridge, MA: *Harvard Business Review Press*	Case studies; hard disk drive	***Variation***: Managers' strategic choices ***Selection***: Shift in performance criteria ***Retention***: Lock-in with existing users
Argyres, N., Bigelow, L., & Nickerson, J. A. 2015. Dominant designs, innovation shocks, and the follower's dilemma. *Strategic Management Journal*, 36: 216–234	Quantitative; automobiles	***Variation***: Market uncertainty due to heterogenous demand ***Selection***: Surge in unknown demand ***Retention***: Past commercial success of innovation shock
Adner, R., & Kapoor, R. 2016. Innovation ecosystems and the pace of substitution: Re-examining technology S-curves. *Strategic Management Journal*, 37: 625–648	Mixed-method; semiconductor lithography equipment	***Variation***: The level of availability of complementary technology in ecosystem ***Selection***: Performance superiority ***Retention***: Extension of old technology and delay in new technology
Christensen, C. M., Suarez, F. F., & Utterback, J. M. 1998. Strategies for survival in fast-changing industries. *Management Science*, 44: S207–S220	Quantitative; rigid disk drive industry	***Variation***: Managerial decisions concerning entry ***Selection***: Technological performance and entry timing ***Retention***: Rapid performance improvement from scale and learning effects
Suarez, F. F. 2004. Battles for technological dominance: An integrative framework. *Research Policy*, 33: 271–286	Theoretical	***Variation***: N/A ***Selection***: Combination of firm-level and environmental factors. ***Retention***: Dominant product architecture spawning component niche markets.
Fleming, L., & Sorenson, O. 2001. Technology as a complex adaptive system: Evidence from patent data. *Research Policy*, 30: 1019–1039	Quantitative; multiple technologies	***Variation***: Recombination of new and existing components ***Selection***: N/A ***Retention***: N/A

TABLE 4B
Twelve Example Studies That Primarily Draw on the Economic Perspective

Paper	Type of Study	Perspective on Variation, Selection, and Retention
Klepper, S. 1996. Entry, exit, growth, and innovation over the product life cycle. *The American Economic Review*, 86: 562–583	Quantitative; automobile	***Variation***: Technological uncertainty, firm size ***Selection***: Market share and the ability to invest in process R&D ***Retention***: Economies of scale, entry barrier
Klepper, S. 1997. Industry life cycles. *Industrial and Corporate Change*, 6: 145–182	Theoretical	***Variation***: Technological uncertainty, firm size ***Selection***: Market share and the ability to invest in process R&D ***Retention***: Economies of scale, entry barrier
Schilling, M. A. 1998. Technological lockout: An integrative model of the economic and strategic factors driving technology success and failure. *Academy of Management Review*, 23: 267–284	Theoretical	***Variation***: Bets on customer expectations ***Selection***: size of customer base, complementary goods and network externalities ***Retention***: Lock-in due to superior value from the economic factors influencing selection
Wu, B., Wan, Z., & Levinthal, D. A. 2014. Complementary assets as pipes and prisms: Innovation incentives and trajectory choices. *Strategic Management Journal*, 35: 1257–1278	Formal model	***Variation***: Firm-level investment choices and complementary assets ***Selection***: N/A ***Retention***: Inherent potential of technological trajectory combined with complementary assets
Adner, R., & Levinthal, D. 2001. Demand heterogeneity and technology evolution: Implications for product and process innovation. *Management Science*, 47: 611–628	Formal model	***Variation***: N/A ***Selection***: Net utility of product performance within a specific customer niche ***Retention***: N/A
Buenstorf, G., & Klepper, S. 2010. Submarket dynamics and innovation: The case of the US tire industry. *Industrial and Corporate Change*, 19: 1563–1587	Quantitative; tires	***Variation***: Pursuit of demand in different submarkets ***Selection***: ***Retention***: Firm-level market share
Agarwal, R., & Bayus, B. L. 2002. The market evolution and sales takeoff of product innovations. *Management Science*, 48: 1024–1041	Quantitative; multiple markets	***Variation***: Firm's pursuit of differentiation ***Selection***: Actual and perceived product quality, price ***Retention***: N/A
Adner, R. 2002. When are technologies disruptive? A demand-based view of the emergence of competition. *Strategic Management Journal*, 23: 667–688	Computer simulation	***Variation***: N/A ***Selection***: Marginal utility of performance improvements, combination of objective performance and consumers' tradeoff between performance parameters ***Retention***: N/A
Malerba, F., Nelson, R., Orsenigo, L., & Winter, S. 2007. Demand, innovation, and the dynamics of market structure: The role of experimental users and diverse preferences. *Journal of Evolutionary Economics*, 17: 371–399	Simulation	***Variation***: N/A ***Selection***: Price/performance, experimental users intrinsically interested in novelty, learning effects may expand market dominance to broader segments than experimental users ***Retention***: Bandwagon effects, lacking incentives of large firms
Windrum, P. 2005. Heterogeneous preferences and new innovation cycles in mature industries: The amateur camera industry 1955–1974. *Industrial and Corporate Change*, 14: 1043–1074	Historical and quantitative; amateur photography	***Variation***: Producers specializing in requirements in different user niches ***Selection***: Utility with specific user niche ***Retention***: Niche-specific shift from product to process innovation
Cusumano, M. A., Mylonadis, Y., & Rosenbloom, R. S. 1992. Strategic maneuvering and mass-market dynamics: The triumph of VHS over β. *Business History Review*, 66: 51–94	Historical; video recording machine standards	***Variation***: Knowledge of customer needs, technological requirements, and complementary assets ***Selection***: Complementary assets and bandwagon effects ***Retention***: Standard setting through network externalities
Schilling, M. A. 2002) Technology success and failure in winner-take-all markets: The impact of learning orientation, timing, and network externalities. *Academy of Management Journal*, 45: 387–398	Quantitative; PC operating system and videogame hardware	***Variation***: N/A ***Selection***: Network externalities, entry timing, complementary assets ***Retention***: Path dependency

with maximum utility (Klepper, 1997; Murmann & Frenken, 2006). A primary mechanism that has been put forward as driving selection is the role of economies of scale in driving down technology costs for producers who are able to invest the most resources into process R&D due to their size (Klepper, 1997). Early proponents of the economic perspective often agreed with the authors of the technological perspective that technological evolution adhered to a homogenizing force. However, in opposition to technology determinism, the economic perspective holds that the selection of a dominant design is the *result* of a shakeout of producers creating a highly concentrated industry structure rather than the *effect*. In contrast, "scholars who have empirically worked with the dominant design concept share the general view that technological change has a powerful and to some extent autonomous causal impact on the development of industries and firms" (Murmann & Frenken, 2006: 932). Furthermore, representatives of the economic perspective often argued that the concept of dominant design did not apply to settings with heterogenous customer preferences (Porter, 1997; Windrum, 2005). Scholars have recently furthered both the notion that demand heterogeneity is important in understanding variation in selection (Adner & Levinthal, 2001; Rietveld & Eggers, 2018) and that selection can happen through technological exaptation, where technologies are selected to address a different user need than one for which they were originally created (Andriani, Ali, & Mastrogiorgio, 2017; Andriani & Cattani, 2016).

Technology retention. Authors adhering to the economic perspective have tended to explain technology retention through firm-level factors such as market share and investment capacity. Some firms will gain a bigger share of the market and will be able to lower prices due to economies of scale. This can become a self-reinforcing cycle wherein the competitive advantage of lower prices will further grow these firms' market share and, therefore, their R&D capacity. The economic perspective posits that this dynamic drives retention because the technologies offered by the dominant firms will be retained over time (Klepper, 1997). Another central factor in the economic perspective driving technology retention is network externalities (Katz & Shapiro, 1985), which occur when users benefit from other users adopting the same technology. In markets characterized by network externalities, technology variations that are adopted earlier have a higher probability of being selected as the users gain additional value from them due to network effects (Wade, 1995).

The Cognitive Interpretivist Perspective

The cognitive perspective challenges the technological and economic perspectives by emphasizing that it is impossible to understand the evolution of technology without taking into consideration how people understand and interpret technology (Bijker, 1997; Grodal et al., 2015; Raffaelli, Glynn, & Tushman, 2019; Tripsas & Gavetti, 2000). However, the early formulations of these ideas tended to originate from authors with strong inclinations toward the technological perspective who also occasionally acknowledged the importance of cognitive factors in shaping technology evolution (Clark, 1985; Dosi, 1982; Rosenberg, 1982). In particular, evolutionary economists such as Dosi (1982) recognized the importance of the collective cognition among engineers in shaping the direction of technological evolution. Also, Clark's (1985) work on "design hierarchies" emphasized that a wave of incremental improvements of a technology required a convergence between producers' cognitive representations of the market and users' cognitive representations of the technology. Although subsequent scholars who worked within the technological and economic perspectives abandoned the cognitive tenants, organizational scholars from different theoretical orientations later picked up on and developed what came to be the cognitive perspective. Table 4c provides a few examples of studies that primarily adhered to the cognitive perspective, although several of these papers also touched upon elements from other ideal types.

Another strong influence of the cognitive perspective was the SCOT (social construction of technology) research program within the sociology of science and technology[1] (Bijker, 1987; Bijker et al., 1987; Bijker & Law, 1994). Although some elements of these authors' work extended beyond cognitive dimensions to include power, interests, and ideological values (Bijker, 1997), a core tenet was that technologies have "interpretative flexibility"; that is, neither producers' nor consumers' understandings of a technology will be a one-to-one representation of the inherent features of the technology because technology is ambiguous and dynamic rather than transparent and fixed.

Around the mid-1990s, organizational scholars began to develop a novel stream of technology

[1] The SCOT program had several streams of thought, some that cohere highly with what we term the "social constructionist perspective" and some with what we term the "cognitive perspective."

TABLE 4C
Twelve Example Studies That Primarily Draw on the Cognitive Interpretivist Perspective

Paper	Type of Study	Perspective on Variation, Selection, and Retention
Clark, K. B. 1985. The interaction of design hierarchies and market concepts in technological evolution. *Research Policy*, 14: 235–251	Theoretical	***Variation***: Ambiguity about use ***Selection***: The merging of market and technology concepts ***Retention***: Incremental innovation and accumulated learning among users
Garud, R., & Rappa, M. A. 1994. A socio-cognitive model of technology evolution: The case of cochlear implants. *Organization Science*, 5: 344–362	Historical case study; cochlear implants	***Variation***: Cognitive ambiguity in terms of what is technologically feasible ***Selection***: Creation of routines of evaluation ***Retention***: N/A
Bijker, W. E. 1997. *Of bicycles, Bakelites, and bulbs: Toward a theory of sociotechnical change*. Cambridge, MA: MIT Press.	Multiple case study; multiple technologies	***Variation***: Interpretative flexibility ***Selection***: Different understandings ***Retention***: Cognitive and technological lock-in
Kaplan, S., & Tripsas, M. 2008. Thinking about technology: Applying a cognitive lens to technical change. *Research Policy*, 37: 790–805	Theoretical	***Variation***: Different cognitive frames among producers ***Selection***: Framing contest ***Retention***: The formation of a collective technological frame
Kennedy, M. T. 2008. Getting counted: Markets, media, and reality. *American Sociological Review*, 73: 270–295	Quantitative; workstations	***Variation***: N/A ***Selection***: Discursive construction of a category ***Retention***: Establishment of a category
Navis, C., & Glynn, M. A. 2010. How new market categories emerge: Temporal dynamics of legitimacy, identity, and entrepreneurship in satellite radio, 1990–2005. *Administrative Science Quarterly*, 55: 439–471	Mixed methods; satellite radio	***Variation***: N/A ***Selection***: Collective legitimation of category ***Retention***: Differentiation within category
Benner, M. J., & Tripsas, M. 2012. The influence of prior industry affiliation on framing in nascent industries: The evolution of digital cameras. *Strategic Management Journal*, 33: 277–302	Quantitative; digital cameras	***Variation***: Prior industry experience ***Selection***: N/A ***Retention***: N/A
Bingham, C. B., & Kahl, S. J. 2013. The process of schema emergence: Assimilation, deconstruction, unitization and the plurality of analogies. *Academy of Management Journal*, 56: 14–34	Historical case study; computers within the insurance industry	***Variation***: N/A ***Selection***: Balance of familiarity and distinctiveness ***Retention***: Formation of stable cognitive schema
Grodal, S., Gotsopoulos, A., & Suarez, F. F. 2015. The coevolution of technologies and categories during industry emergence. *Academy of Management Review*, 40: 423–445	Theoretical	***Variation***: Ambiguity spawns different designs and labels ***Selection***: Correspondence between new design and new label ***Retention***: The formation of a category
Kahl, S. J., & Grodal, S. 2016. Discursive strategies and radical technological change: Multilevel discourse analysis of the early computer (1947–1958). *Strategic Management Journal*, 37: 149–166	Multiple case study; computers within the insurance industry	***Variation***: Attempts to with cognitive schemas ***Selection***: Cognitive familiarity selected ***Retention***: N/A
Raffaelli, R. 2019. Technology reemergence: Creating new value for old technologies in Swiss mechanical watchmaking, 1970–2008. *Administrative Science Quarterly*, 64: 576–618	Historical case study; Swiss watch industry	***Variation***: Pursuit of functionality and lower price ***Selection***: Price and performance ***Retention***: Cognitively repositioning legacy technology
Zuzul, T., & Tripsas, M. 2020. Start-up inertia versus flexibility: The role of founder identity in a nascent industry. *Administrative Science Quarterly*, 65: 395–433	Qualitative; multiple-case study of the air taxi market	***Variation***: Prior industry affiliation ***Selection***: Flexibility in frame and business models ***Retention***: N/A

theorizing in which people's cognitive interpretations of technologies took center stage (Garud & Rappa, 1994; Tripsas & Gavetti, 2000). This arose as a continuation of work examining responses to technologies within organizations (Barley, 1986) but which shifted its focus toward how organizations adapt their product offerings with the commencement of a new technology life cycle (Tripsas, 2009). A foundational work for this stream was Garud and Rappa's (1994) study on the development of cochlear implants, which pointed to different understandings of the technology as central in explaining variation in technologies, because the purposes for which technologies were created differed. They found that a central driver of variation that resulted in competing technological designs was a collective dispute about the core functionality of cochlear implants—what should be the main purpose of the technology: speech recognition or the complete restoration of the user's sound experience? Another important early study was Tripsas and Gavetti's (2000) study of Polaroid's demise in the face of digital technology, which shone light on how Polaroid's understandings of camera technology and the role of photography in the user's life was an important source of inertia hindering Polaroid's transition to digital technology. This study became highly influential as it came in the wake of the scholarly attention given to the disruptive potential of technology on competition, such as Henderson and Clark's (1990) seminal article on architectural innovations and Christensen's (1997) work on why certain technological changes cause market-leading firms to fail. Although known, other works in the same period worked on developing similar insights. For example, Howells's (1997) examination of the demand pull/technology push distinction highlighted the role of cognitive imaginaries of potential markets in how producers select market niches for new technologies.

Technology variation. A central assumption of the cognitive perspective is that for technologies to gain prominence, producers and consumers must form a clear cognitive representation of what the technology is and how it should be used (Clark, 1985; Kaplan & Tripsas, 2008). In contrast to the understandings inherent in the technological perspective, the cognitive perspective holds that the actual value and potential of a technology is open to interpretation and not dictated by the inherent features of the technology (Anthony et al., 2016; Bijker, 2010; Goldfarb & Kirsch, 2019). This interpretative flexibility shapes the evolution of a technology (Bijker & Law, 1994) as the cognitive predispositions of different actors spur different interpretations of each technological variation and thus construct different possibilities of action. Interpretative flexibility shapes variation because producers bring different understandings to bear on which technologies are created (Pinch & Bijker, 1984). For example, prior industry affiliation shapes producers' technological choices because they see the opportunities of the new technology through the lens of their previous markets (Benner & Tripsas, 2012; Shane, 2000; Zuzul & Tripsas, 2020). Producers must imagine a use and demand for their technologies, although such demand is ambiguous and uncertain. Different market imaginaries shape technological variations, which is why high market ambiguity sparks a high variation in technology (Clark, 1985; Garud & Rappa, 1994; Howells, 1995, 1997). For this reason, after a technological discontinuity, producers create many cognitive representations of a technology and category understandings that spur a plethora of technological variations.

Technology selection. In its ideal form, the cognitive perspective holds that the technological variations that are selected are those that best fit customers' cognitive frame of the technology (Anthony et al., 2016; Grodal et al., 2015; Kahl & Grodal, 2016), such as consumer audiences' evaluation schemas—that is, the mental models used to evaluate a technology's value and their use routines (Garud & Rappa, 1994). A central risk for new technology products is, therefore, that they may be incongruent with audiences' evaluative schemas if they appear too novel or esoteric to consumers, which can cause products to fail commercially (Rindova & Petkova, 2007; Zunino, Suarez, & Grodal, 2019). Authors studying a range of settings have reported how technology selection ends up favoring the variation that appears most familiar to users (Kaplan & Tripsas, 2008). Predominantly, studies have reported how selected technology variations are those that appear most coherent with users' understanding of former technology generations, such as tabulating machines and early personal computers for professional use (Kahl & Grodal, 2016). However, authors have proposed in theoretical works that familiarity can be in relation to distinct categories rather than solely earlier variations (Rindova & Petkova, 2007). However, the prevailing picture from extant empirical findings suggests that the market favors the technology variations that most resemble the former technology generation (Hargadon & Douglas, 2001; Kahl & Grodal, 2016).

Technology retention. Technologies are retained because consumers and producers become inert and cognitively locked into specific understandings of the technology (Clark, 1985; Kaplan & Tripsas, 2008). Over time, as producers and users come to agree on the main use and meaning of a technology, the technological variations tend to converge and only a few different kinds of variation are left in the market (Clark, 1985; Grodal et al., 2015). In this sense, the cognitive perspective treats technology stabilization as an equilibrium between producers' cognitive frames of the market and users' cognitive frames of the technology. However, studies on technology retention from a cognitive perspective rarely traced this empirically, as most studies adhering to this perspective have focused on firms' adaptation to technological discontinuities (see Tripsas & Gavetti, 2000, for a highly influential example of such studies). However, when studies have sought to explain why firms tend to struggle with adapting to technological discontinuities, the drivers of retention have often been indicated as an aspect of the empirical investigation. As a technology becomes adapted and producers find appropriate ways of capitalizing on the technology, they may become locked into a business model afforded by the given technology. For example, Polaroid faced difficulties in transitioning to digital film because of the business model afforded by analog film (i.e., the razor and razor blade model of profiting from the sale of film rather than cameras) (Tripsas & Gavetti, 2000). In similar vein, as usage of a technology stabilizes, producers will become cognitively fixated on a certain way of using and appreciating a technology, such as Polaroid's insistence on a user preference to hold a physical picture in their hand, which led Polaroid to discredit the future significance of digital imagery, despite already being engaged in R&D on digital imaging.

The Social Constructionist Perspective

The social is the most heterogenous perspective, as it contains several scattered research traditions. Central to the social perspective is the notion that social relations—such as networks, status, or power distribution—influence technology evolution (Grodal & O'Mahony, 2017; Hargadon & Douglas, 2001; Ozcan & Santos, 2015; Podolny & Stuart, 1995). This perspective emphasizes the role of nonmarket actors—such as trade associations, professional societies, and the government—in shaping technology evolution (Rosenkopf & Tushman, 1998; Yates & Murphy, 2019). In particular, the social perspective suggests firms and nonmarket actors form a bounded structure that "is seen as co-evolving with the commercialized technology" (Lynn, Reddy, & Aram, 1996: 102). Many early scholars emphasized the importance of social structure in technology evolution (Munir & Jones, 2004). Yet, as the technological and economic perspectives rose to dominance, the importance of social factors continued to be implicitly recognized but played an ever-decreasing role, both theoretically and methodologically. However, some scholars, including industrial economists (Fagerberg, Mowery, & Verspagen, 2009), institutional theorists (Grodal, 2018), social network scholars (Owen-Smith & Powell, 2004; Powell, Koput, & Smith-Doerr, 1996; Powell, White, Koput, & Owen-Smith, 2005), scholars associated with science technology and society studies (Bijker et al., 1987; Bijker & Law, 1994; Pinch & Bijker, 1984), and actor–network theorists (Callon, 1986; Latour & Woolgar, 1986), continued to emphasize the role that social elements play in technology evolution. Table 4d provides a few examples of studies that primarily adhered to the social perspective, although several of these papers also touched upon elements from other ideal types.

The social perspective emphasizes that social relationships between market participants are essential to understand technology evolution (Lynn et al., 1996). Whereas the technological and economic perspectives tend to depict technological discontinuities as a stochastic process (Abernathy & Utterback, 1978), scholars adhering to the social perspective have held that patterns of technological discontinuity are shaped by the social structure in which firms are embedded and the influence of nonmarket actors (Lynn et al., 1996), such as social networks, communities, the cultural context of individuals and organizations (Powell et al., 1996; Saxenian, 1996; Seidel, Langner, & Sims, 2017), and the power distribution among participating actors (Bijker & Law, 1994; Grodal, 2018).

Technology variations. A premise within the social perspective is that firms' technological variations are the results of the social structures in which they are embedded. Powell et al. (1996) and Ahuja (2000), for example, showed that the structure of networks between firms is a central driver in the kinds of innovation that firms create. Seidel and colleagues (2017) theorized that different kinds of communities are most dominant in creating new variations at different points along the industry life cycle. Loosely organized communities dominate during the early part of the technology life cycle, whereas structured community–firm interactions dominate the latter part of the technology life cycle. Thus, within the

TABLE 4D
Twelve Example Studies From Primarily the Social Constructionist Perspective

Paper	Type of Study	Perspective on Variation, Selection, and Retention
Noble, D. F. 1978. Social choice in machine design: The case of automatically controlled machine tools, and a challenge for labor. *Politics & Society*, 8: 313–347	Historical case; machine tools	***Variation***: Technical education ***Selection***: Professionalization ***Retention***: Reproduction of power structures
Callon, M. 1986. The sociology of an actor-network: The case of the electric vehicle. In M. Callon, A. Rip, & J. Law (Eds.), *Mapping the dynamics of science and technology*: 19–34. New York, NY: Springer	Historical case; electric vehicle	***Variation***: Social dynamics between human and nonhuman actors ***Selection***: interests, strategies and power relationships ***Retention***: translation processes within actor-networks
Rao, H. 2004. Institutional activism in the early American automobile industry. *Journal of Business Venturing*, 19: 359–384	Historical case; automobiles	***Variation***: Different understandings and interests ***Selection***: Certification ***Retention***: Institutional forces
Ansari, S., & Phillips, N. 2011. Text me! New consumer practices and change in organizational fields. *Organization Science*, 22: 1579–1599	Qualitative; text messages	***Variation***: Interplay between users and producers ***Selection***: User needs ***Retention***: Established social norms
Kirsch, D. A. 2000. *The electric vehicle and the burden of history*. Newark, NJ: Rutgers University Press	Historical case; electric vehicle	***Variation***: Institutional embeddedness ***Selection***: Powerful market actors ***Retention***: Institutional power positions
Hargadon, A. B., & Douglas, Y. 2001. When innovations meet institutions: Edison and the design of the electric light. *Administrative Science Quarterly*, 46: 476–501	Historical case; electric light	***Variation***: Different understandings of the technology ***Selection***: Familiarity ***Retention***: Institutional fit
Akrich, M., Callon, M., Latour, B., & Monaghan, A. 2002. The key to success in innovation part I: The art of interessement. *International Journal of Innovation Management*, 6: 187–206	Theoretical	***Variation***: Social entanglement ***Selection***: Support by technical and social relations ***Retention***: Integration into social and technical structure.
Ozcan, P., & Santos, F. M. 2015. The market that never was: Turf wars and failed alliances in mobile payments. *Strategic Management Journal*, 36: 1486–1512	Multiple case study; mobile payments	***Variation***: Interactions between multiple stakeholders ***Selection***: Multi-stakeholder negotiations ***Retention***: Frequent failure due to lack of agreement
Yates, J. 2005. *Structuring the information age: Life insurance and technology in the twentieth century*. Baltimore, MD: Johns Hopkins University Press	Historical case study	***Variation***: Understanding user demands ***Selection***: Users' organizational structure ***Retention***: Users' industry structure
Dokko, G., Nigam, A., & Rosenkopf, L. 2012. Keeping steady as she goes: A negotiated order perspective on technological evolution. *Organization Studies*, 33: 681–703	Theoretical	***Variation***: Social and political factors ***Selection***: Standard setting organizations ***Retention***: Standardization
Croidieu, G., & Kim, P. H. 2018. Labor of love: Amateurs and lay-expertise legitimation in the early U.S. radio field. *Administrative Science Quarterly*, 63: 1–42	Historical case study; topic modeling	***Variation***: Diverse knowledge bases and interests ***Selection***: Professionalization ***Retention***: Professionalization and legitimation
Grodal, S. 2018. Field expansion and contraction: How communities shape social and symbolic boundaries. *Administrative Science Quarterly*, 63: 783–818	Historical case study	***Variation***: *S*elf-interest ***Selection***: Categorization ***Retention***: Power actors

social perspective, technological variation is not just the product of a stochastic recombination of existing technologies. Instead, which technologies are recombined is the product of the social structure among actors.

Technology selection. The social perspective holds that that the technological variations most likely to be selected are those that are most aligned with the interests of powerful actors (Grodal, 2018; Ozcan & Santos, 2015), such as regulators (Hargadon & Douglas, 2001; Kirsch, 2000; Yates, 2005). Anderson and Tushman (1990) suggested that technology selection was socially constructed in that they considered the selection of a dominant technological design as the outcome of a "socio-political process." However, as later noted by Suarez and Utterback (1995), this idea did not receive much empirical elaboration in papers, which primarily emphasized technological determinism. The idea was pursued in more depth when the social perspective gained greater prominence. A prominent study addressing the selection process from a social perspective is Hargadon and Douglas's (2001) work on Edison's commercialization of the light bulb. They showed that Edison designed his system to blend seamlessly with the current lighting infrastructure and thus aligned it with powerful interests in the market. As a result, centralized lighting systems came to dominate the market despite their technological inferiority.

Technology retention. In its ideal form, the social perspective holds that some technology variations are retained across time because they are aligned with powerful actors' interests or an entrenched social structure (Bijker & Law, 1994; Ozcan & Santos, 2015). Powerful social positions are especially likely to form around technology leadership. The organizations with the most influence on technological standards will thus tend to gather power and interests that will reinforce the social anchoring of the selected technological variation. An example of how a technological standard and the existing social structure are mutually reinforcing is vividly on display in Kirsch's (2000) examination of the reason why vehicles with internal combustion engines eventually rose to prominence rather than electric vehicles. Kirsch showed that the internal combustion engine was not technologically superior at first but gained dominance because it was supported by powerful actors within the market. Furthermore, once it was established, powerful path-dependent forces reinforced both the dominance of the internal combustion engine and the power of the organizations producing and supporting it, making it impossible for any competing technology to break into this sociotechnical lock-in. Rosenkopf and Tushman's (1998) paper showed that cooperative technical organizations (e.g., standard-setting organizations, technical committees, and task forces) coevolve with technology during the industry life cycle. They further showed that some technologies are retained whereas others are discarded because during the era of incremental change, memberships in the cooperative technical organizations stabilize and technical standards remain unchanged.

Across the perspectives, scholars have provided accounts for how variation, selection, and retention shape technology evolution despite pointing to different mechanisms for this evolution. Yet, while there are differences across the perspectives, there are also important similarities.

AN INTEGRATED VIEW OF TECHNOLOGY EVOLUTION

In this paper we provide an overview of the literature on technology evolution by categorizing it across four different perspectives. Below, we discuss the similarities and differences across these perspectives and propose avenues for future research.

Toward a Coevolutionary Perspective of Technology Evolution

Our review of the literature found that scholars broadly adhere to four different perspectives on technology evolution: (a) technology-realist, (b) economic realist, (c) cognitive interpretivist, and (d) social constructionist. Across the perspectives, scholars have identified three distinct ways in which technology evolves: continuous, discontinuous, and cyclical. There are three ways in which technology evolution can be cyclical: (a) cyclical through technology regimes, (b) cyclical through technology S-curves, and (c) cyclical through industry life cycles. We also find that scholars agree that the evolution of technology is driven by three mechanisms: variation, selection, and retention. At first glance, the four perspectives appear to focus on different explanations for each of these variations; however, our examination allows for a theoretical synthesis (see Figure 3). All four perspectives recognize that variation is the outcome of recombination, although they differ in terms of how this process unfolds. Likewise, all perspectives emphasize that selection is driven by environmental fit, although they vary with regard to which features of the environment influence selection. Finally, all four perspectives recognize that retention is driven by path dependence, although they disagree as to which factors reinforce this path dependence.

Variation driven by recombination. Scholars from all four perspectives have emphasized that to understand technology evolution, we first need to understand what drives technology variation (Basalla, 1988; Clark, 1985), which accounts for the constant creation of new technological variations (Utterback, 1994). All four perspectives point to the recombination of existing elements as the fundamental mechanism driving variation but offer diverse explanations for how technologies are recombined (Arthur, 2009; Eggers, 2012; Fleming, 2001; Katila & Ahuja, 2002; Schumpeter, 1942; Zuzul & Tripsas, 2020). The technological perspective emphasizes that technological variation is driven by recombination of existing scientific knowledge and technical features (Murmann & Frenken, 2006; Suarez, 2004). Such a view can be interpreted as a soft version of the technological determinism proposed by Rosenberg (1963), where prior technologies shape the trajectory of subsequent variations (Clark, 1985). The economic perspective emphasizes that technological recombination is driven by economic factors, such as capacity to invest in R&D (Klepper, 1996), and that technological competencies build on prior investments (Argyres & Silverman, 2004; Katila & Ahuja, 2002; Yayavaram & Ahuja, 2008). The cognitive perspective emphasizes that technological recombination is driven by variation in actors' cognitive frames and ideas (Anthony et al., 2016; Benner & Tripsas, 2012; Kaplan & Tripsas, 2008). The social perspective emphasizes that technological recombination is spurred by how actors are embedded in social networks and are shaped by power relationships as well as ingrained institutional structures, such as standard-setting institutions (Powell et al., 1996; Yates & Murphy, 2019).

However, although all four perspectives emphasize recombination as the driver of technological variation, papers within each of the traditions have tended to be siloed (but see Bijker et al., 1987; Clark, 1985; Grodal et al., 2015; Hargadon & Douglas, 2001; Kaplan & Tripsas, 2008). For new insights to be generated, scholars must examine how technical, economic, cognitive, and social forces together shape the recombination of technological variations. The first step to breaking down the silos is to expand our knowledge of how cross-perspective factors coevolve. Doing so would shed light on the fine-grained understanding of what drives patterns of technology variations.

A coevolutionary approach helps us to overcome the assumptions of the technological perspective that recombination is generated through random events. In contrast, the cognitive and social perspectives suggest that cognition and social structures brought by different groups of people are the source of variations (Godart & Galunic, 2019; Ravasi & Stigliani, 2012). For example, from the social perspective, when actors bridge structural holes—that is, when they are connected to people or organizations that are not connected to one another—they are able to leverage this diversity of information to create novel recombinations (Burt, 2005; Lingo & O'Mahony, 2010; Powell & Grodal, 2005). Although scholars in the social and cognitive perspectives have recognized the importance of such bricolage (Garud & Karnøe, 2003), we still lack insights into how such social and cognitive elements coevolve and how they are aligned (or not aligned) with one another.

Taking a coevolutionary perspective enables researchers to move beyond an understanding of technology evolution as an autonomous and exogenous force to instead examine how heterogeneous social, cognitive, and economic factors shape evolutionary outcomes. In future research, we must study not only how technological discontinuities alter the social world but also how the cognitive interpretations and social negotiations shape the outcomes of technological discontinuities, such as when and how technological shocks affect industries, markets, and regulatory frameworks (Andersen, Frederiksen, Knudsen, & Krabbe, 2020; Kaplan & Henderson, 2005). For example, when the transistor was invented in 1947, its disruptive shock occurred quickly in some industries but later in others (Braun, Braun, & MacDonald, 1982). Furthermore, whereas some industries tend to cycle through rapid patterns of technology change, others are remarkably stable. To understand such phenomena requires further multiple-case studies of how the same technology receives a different impact as it is adopted across multiple industries.

Another promising avenue for taking a coevolutionary perspective is to study differences in technology variation across technology life cycles. Anderson and Tushman (1990) argued that as a product class matures, it is characterized by a decrease in the number of variations. However, at times, design variation—such as architectural changes—can dramatically disrupt mature product classes. These observations raise important questions regarding how cognitive understanding shapes technological variations across technology life cycles. In new product classes, firms bring in a broad array of understandings of the technology and the market, such as familiarity with certain business models and user needs (Shane, 2000; Zuzul & Tripsas, 2020), but as product classes mature, they move toward convergence in cognitive frames, with less technological variation as the result (Kaplan & Tripsas, 2008). This raises the question of how entrants with different prior experience may break such dominant frames apart. For example, can environmental jolts or other exogenous changes break a technology frame? The answer to this question is key to better understanding technology regime patterns of change, which is a concept that has received little direct empirical attention (Pinch & Bijker, 1984) despite the fact that initial formulations of the concept included a broad array of factors spanning all four perspectives (Dosi, 1982).

Finally, a promising area of research is how expectations affect the production of technological variations. Many studies in the cognitive perspective have tended to focus on the analogy between a new technology and existing market offerings, as in tabulating machines and the computer (Kahl & Grodal, 2016) or conventional music instruments and the synthesizer (Anthony et al., 2016). However, in many emerging technologies, producers, mass media, and users often create an array of projective representations and expectations of technologies even before the actual launch of a product (Augustine, Soderstrom, & Weber, 2019; Garud, Schildt, & Lant, 2014; Granqvist & Laurila, 2011; Seidel, Hannigan, & Phillips, 2020). Considering this observation, we can ask: Do producers take such expectations into account when designing novel technological offerings? How do they shape technology evolution?

Selection driven by environmental fit. Within each of the four perspectives, scholars have held in common that selection is driven by the fit between technologies and their environments, but they have provided different explanations for what drives this fit (Basalla, 1988). Across the perspectives, scholars have acknowledged that technological superiority is rarely the sole driver of selection (Bijker et al., 1987; Clark, 1985). Even the technological perspective tends to hold that inferior technologies can win if they can climb up the maturation curve faster than competing variations (Cusumano, Mylonadis, & Rosenbloom, 1992; David, 1985). However, across the perspectives, scholars have offered different—and, at times, incompatible—explanations for how and why selection occurs.

The ideal form of the technological perspective emphasizes that selection is driven by technological lock-ins wherein one technology has managed to climb up the maturation curve faster than competing variations. In contrast, the economic perspective adheres to an explanation wherein the selected variation will be the one championed by the firm with the highest market share which therefore will be able to drive faster price decreases from higher investments in process R&D (Klepper & Simons, 1997). However, most studies have adhered to a hybrid of technological and economic realism, arguing that interactions between a technology's inherent features and heterogenous market demand drive selection (Adner & Levinthal, 2001). The cognitive perspective highlights that the technology to be selected is the one with the best fit to audiences' cognitive schemes, such as how the market offering is categorized and what evaluation criteria are being used to assess it (Kahl & Grodal, 2016). The social perspective emphasizes that the technologies selected are those that are aligned with or reinforce the existing social structure (Lynn et al., 1996).

We argue that a coevolutionary perspective is necessary to reconcile the heterogenous array of factors that the literature has found to influence selection. This is particularly the case in examining the exact mechanisms by which fit between technologies and their environment is established. Compared to studies on variation, there have been fewer empirical studies on selection mechanisms. Among those, most empirical studies have tended to adopt one perspective to interpret their data (Hargadon & Douglas, 2001; Klepper, 1997), even though many scholars theoretically have argued that technological, economic, cognitive, and social forces are all at work in technology selection. We argue that although such reductions offer methodological crispness, they limit theoretical progress. Embracing plurality opens up research opportunities. For example, despite its importance, the question of how demand heterogeneity influences fit and selection has not been abundantly studied (Adner & Levinthal, 2001; Argyres et al., 2015). We know that cognitive elements, such as products sensory and aesthetic dimensions (Baldessarelli, Stigliani, & Elsbach, 2022), play important roles in driving changes in demand and selection, yet these aspects have rarely been studied in tandem with economic and social forces (Eisenman, 2013; Rindova & Petkova, 2007). Similarly, we still have little knowledge about how social forces such as power (Hargadon & Douglas, 2001) and status shape the fit between technologies and environments (Podolny, 2010), except for a few recent works on lobbyism and the role of regulation in shaping which technological variations turn out to be favored (Andersen et al., 2020; Murmann, 2003; Ozcan & Gurses, 2018).

In this review, we reveal a surprising dearth of empirical research on the role of users in technology selection, with a few notable exceptions (see Ansari & Phillips, 2011; Eggers, Grajek, & Kretschmer, 2020). Table 5 shows that only 9% of empirical research covered in our review collected user-level data. This is problematic because users are often a main selecting audience whose aggregate choice patterns shape the ultimate trajectory of technology evolution (Abernathy & Clark, 1985; Klepper & Thompson, 2006). In their study of the evolution of the minivan, Rosa, Porac, Runser-Spanjol, and Saxon (1999), for example, showed how the dominant features of the minivan were negotiated through a sense-making process between users and producers. As early as 2008, Kaplan and Tripsas called for more research on users and their role in technology evolution. Yet in the following years, few scholars have heeded their call to action, leaving the role

TABLE 5
Descriptive Statistics of Papers in the Technology Evolution Literature

	Technology-Realist (%)	Economic-Realist (%)	Cognitive-Interpretivist (%)	Social-Constructionist (%)	Total (%)
Methods Employed					
Theoretical paper	35	21	35	28	**35**
Quantitative	33	31	22	16	**33**
Qualitative	15	15	34	23	**15**
Mixed methods	13	12	9	25	**13**
Computational & experiment	4	20	0	8	**4**
Sum	100	100	100	100	100
Timespan of the Paper					
Cross-sectional	18	10	21	31	**17**
Part of the life cycle	33	39	35	46	**38**
One or more life cycles	49	51	44	23	**46**
Sum	100	100	100	100	100
Technology in the Study					
Dependent variable	36	14	26	38	**25**
Independent variable	7	17	8	7	**11**
Context	58	69	66	55	**64**
Sum	100	100	100	100	100
Unit of Analysis					
Product & technology	32	16	12	6	**18**
Individual	0	0	8	0	**1**
Firm	37	74	42	71	**57**
Industry & field	32	10	38	23	**23**
Sum	100	100	100	100	100
Empirical Stakeholder					
Producer	89	72	63	71	**75**
Producer & user	1	8	8	19	**7**
User	0	0	12	0	**2**
Others	9	20	17	10	**15**
Sum	100	100	100	100	100
Type of Technology					
High-technology	74	68	83	94	**76**
Low-technology	14	15	17	0	**13**
Multiple technologies	12	17	0	6	**11**
Sum	100	100	100	100	100
Disruptive Technology					
Yes	80	73	65	69	**73**
No	20	27	35	31	**27**
Sum	100	100	100	100	100
Emerging Technology					
Yes	93	91	96	91	**93**
No	7	9	4	9	**7**
Sum	100	100	100	100	100

of users in technology evolution black-boxed. Scholars have tended to study users only when they act as producers by creating new technological variations (Shah & Tripsas, 2007; Von Hippel, 1988, 1998) or by modeling user preferences in formal models, rather than studying their actions empirically (Adner & Levinthal, 2001). We encourage future scholars to pull users out of the black box to unveil the social and cognitive process that underlie their preferences. Arguably, data availability and the lack of established measures may explain, in large part, why past works have omitted users from their empirical examinations. However, with the growth of online market activities, users increasingly leave online paper trails of their behaviors and preferences, which can be collected and analyzed for research purposes (Kahl & Grodal, 2015).

One way to integrate the cognitive, social, and technological perspectives is to consider how different product classes vary in their patterns of technology evolution. For example, Tushman and Rosenkopf (1992) argued that the greater the technological uncertainty, the "greater the intrusion of nontechnical factors in the product's evolution" (p. 311) because "for simple or non-assembled products, dominant designs emerge from a technological logic" (p. 321). The reasoning goes that the farther away along the value chain that a product class is from the end-user, the less interpretive flexibility there is around the product. If a product class is an intermediate good that is sold business-to-business to produce other products, such a product is more likely to serve a modular, technological function, which is in turn more susceptible to technological determinism (Baldwin & Clark, 2000). However, a large number of end-user-targeted products allow room for interpretation of a new technology (Faulkner & Runde, 2009), whereby the cognitive and social explanations override technology determinist accounts.

Future research could also benefit from a deeper gaze at the role of market intermediaries—that is, third-party organizations that function as market gatekeepers or external critics who facilitate exchange (Hirsch, 1972; Sharkey, Kovacs, & Hsu, 2022; Zuckerman, 1999). Market mediation may well explain why different technologies show different evolutionary outcomes. Although some studies have peripherally hinted at the important role of intermediaries (Hargadon & Douglas, 2001; Rosa et al., 1999), scant empirical attention has been paid to unpacking the mechanisms by which market intermediaries shape technology evolution and, in particular, technology adoption decisions and standardization (Adner & Levinthal, 2001). Market mediators might be professionalized and adhere to the professional norms and values of their profession, which might put them at odds with the norms and values of producers and users (Abbott, 2014; Hirsch, 1972). Such misalignment in values might drive professionalized market mediators to select technological variations that are aligned with their taste despite being misaligned with the tastes of users. Furthermore, some market mediators obtain their power from a particular technology and have vested interests in maintaining the status quo (Sharkey et al., 2022). The existence of powerful mediators may thus dampen technology cycles and spur continuous technology evolution rather than the dramatic cyclical patterns typically studied in the literature.

Retention driven by path dependence. The four perspectives all point to path dependence as the central mechanism driving technology retention, although they disagree on the specific drivers. The technological perspective emphasizes that path dependence occurs due to technological determinism and technological lock-ins (Murmann & Frenken, 2006; Rosenberg, 1963). The technological perspective recognizes that retention does not imply the inherent superiority of a technology but rather its performance at the time of selection. Retained technologies may either have a larger installed user base or have made leaps up the maturation curve more rapidly than competing variations (Schilling, 1998, 2002). The economic perspective highlights that path dependence occurs due to self-reinforcing mechanisms in the market where a slight (and potentially random) advantage in early adoption among users will generate economies of scale and network externalities that will reinforce the market dominance of that technology (Klepper, 1997).

The social perspective emphasizes that path dependence is generated by the surrounding social structure, which selects—through standard setting organizations, market power, or regulatory controls—technologies that optimize and support their existing positions in the market (Callon, 1986; Lynn et al., 1996). A central insight from the social perspective is that, to understand technology retention, we must to broaden our unit of analysis beyond a myopic focus on technologies and the organizations producing them to examine the larger social structures that impact those technologies (Geels, 2002; Mayntz & Hughes, 1988). This insight has both theoretical and methodological consequences. Theoretically, the social perspective breaks with the emphasis on technological and economic factors inherent in the earlier perspectives. Methodologically, the social perspective requires that we expand beyond the kinds of data that have traditionally been used to study technology evolution. In particular, analyzing technology evolution at the level of the organizational field provides a useful methodological lens for studying technology evolution (DiMaggio & Powell, 1991; Hoffman, 1999; Zietsma, Groenewegen, Logue, & Hinings, 2017).

To move beyond the existing literature, we must understand how the different drivers highlighted by the four perspectives coevolve. Future studies can investigate how the different types of path dependence interweave the complex patterns of technology life cycles, which often contain overlaps and blurred boundaries (Christensen, 1997; Suarez, 2004). Moreover, this will likely shed light on the theoretical puzzle wherein some technologies fail to be retained and thus decline, even in the absence of competitive pressure from substitute technologies (Ozcan & Santos, 2015; Rosenberg, 1982). Technological decline is thus another fruitful avenue for future research (Adner & Snow, 2010; Cusumano, Kahl, & Suarez, 2015; Dokko et al., 2012; Raffaelli, 2019).

Together the four perspectives all point to variation, selection, and retention as the drivers of technology evolution. Yet, more can be done to integrate across the perspectives. In the sections below, we discuss some themes that will benefit from such cross-pollination.

Technological Substitution and Disruption

A central focus for a large part of the literature has been the substitution of incumbent technologies with entrant technologies. Technology substitution has received great attention because it often has a disruptive impact on organizations, industries, and social fields by jolting competition and innovation patterns (Abernathy & Utterback, 1978; Anderson & Tushman, 1990). Indeed, 73% of the papers we identified on the evolution of technology examined some form of technology discontinuity that triggers a process of substitution (Adner & Kapoor, 2016; Christensen, 1997; Eggers & Park, 2018; Tushman & Anderson, 1986; Utterback, 1994). Most empirical works examined the organizational and industrial dynamics that unfold immediately after technological "disruptions" or "shocks" (Eggers & Park, 2018). However, our review indicates that this discontinuity bias is based on three underlying assumptions that must be reexamined.

The first assumption is that disruptions of the status quo in markets, industries, and societal structure occur as the result of a sudden, radical technological shock after a long period of stability (Tushman & Anderson, 1986). However, the literature on institutional change has suggested that the apparent stability of a social structure often brims with incremental changes, negotiations, and reconstructions (Lawrence & Suddaby, 2006; Lawrence, Suddaby, & Leca, 2009); these subtle adjustments can also spur dramatic realignments of value. Creative destruction (Schumpeter, 1934) occurs not only as a consequence of new technologies that swiftly disrupt the existing structure but also as a result of the changing interactive patterns that quietly shift during the period of incremental change. Thus, future research must consider temporal variation in when technology substitution occurs and how it impacts markets, industries, or societal structures. For example, some high-technology industries show an absence of cyclical patterns of discontinuity and stability (Basalla, 1988; Henderson, 1995). Despite recent research efforts to nuance the disruptive impact of technological substitution (Adner & Kapoor, 2016; Eggers & Park, 2018), many questions remain unanswered. Future studies must break with the tendency to study disruptive technologies identified ex post and instead study failed technology disruptions and contexts wherein incremental change and continuation over long time periods form the dominant pattern of technology evolution.

The second assumption is that a disruptive new technology uniformly displaces the old one by shifting the existing demand curve. Early papers on the evolution of technology tended to portray substitution by new disruptive technologies as complete, with minimal or no market share left for the technology being replaced (Christensen, 1997; Tushman & Anderson, 1986; Utterback, 1994). Subsequent studies have problematized this notion by emphasizing that users have heterogeneous preferences (Adner, 2002; Windrum, 2005) and that not all technologies will be equally palatable to all users. In particular, recent studies have shown that after a technology discontinuity, the old technology often retreats into a market niche to serve the needs of a small population of users (Adner & Snow, 2010; Raffaelli, 2019). Under certain conditions, a substituted legacy technology can even reappear and displace the technology that originally displaced it (Raffaelli, 2019). This suggests a more nuanced understanding of technological substitution in which consumer preferences are coconstructed together with the technologies. Both Clark (1985) and Kaplan and Tripsas (2008) pointed to feedback mechanisms between the evolution of demand and technology evolution; however, due to the scarcity of user-level demand-side data, there have been very few empirical examinations of these relationships.

Studies of technology evolution have also tended to focus either on how the performance of technologies evolves along overlapping S-curves (Adner & Kapoor, 2016; Foster, 1986) or on the competition among technology designs within a technology life cycle (Grodal et al., 2015; Suarez, 2004). More work is needed to integrate these two perspectives; for example, how does the continued market presence and investment into the old technology influence which technology variations are selected within the new technology? How is design competition within the new technology influenced by the dominant design of the old technology? Several works within the cognitive and social perspectives have shown that the variations of an entrant technology that are familiar to users due to their similarity to the dominant design of the incumbent technology tend to be selected over more novel designs (Hargadon & Douglas, 2001; Kahl & Grodal, 2015; Zunino et al., 2019). Future work could shed light on these puzzles through simultaneous analytical attention to both intergenerational technology change and design competition.

Furthermore, to shed light on technology substitution, we must expand our view of technological performance. Whereas early research tended to view technological performance uni-dimensionally (Anderson & Tushman, 1990), subsequent work has acknowledged that during a technological discontinuity there may be a shift in performance criteria (Christensen, 1997; Garud & Rappa, 1994; Tripsas & Gavetti, 2000). More recent work has begun to acknowledge that technological performance can be multidimensional depending on the heterogeneity of consumer preferences (Adner & Levinthal, 2001). Yet we still need a more elaborate theory of how different perceptions of technology performance and product attractiveness shape processes of technology substitution. We know that the intangible sides of products, such as their influence on consumers' emotional, sensory, and symbolic values and identity construction, are important for consumers' purchasing decisions (Eisenman, 2013; Raffaelli, 2019; Rindova & Petkova, 2007). We suggest that by expanding our view of technological performance as a multidimensional construct, we can shine light on why technological discontinuities vary in their degree of substitution and highlight how different social groups evaluate technologies by different parameters (Murphy & Medin, 1985).

The third assumption is that technology substitution automatically shifts demands and thus rapidly disrupts the existing market and industrial structures. This view overlooks the fact that changes in the socio-cognitive understandings that underlie demand typically take time and sometimes may not occur at all. An observation across the perspectives is that, at times, technological discontinuities drive change in existing industries, categories, or societal structures (Bijker et al., 1987; Hargadon & Douglas, 2001; Nelson & Irwin, 2014; Powell et al., 1996; Tushman & Anderson, 1986), and at other times, technological discontinuities give rise to new industries, markets, or categories (Klepper, 1997; Tripsas & Gavetti, 2000) or even an entirely new product class (Hargadon & Douglas, 2001; Kahl & Grodal, 2016; Rindova & Petkova, 2007). Yet, often, technological discontinuities spur no such changes in their wake (Eggers & Park, 2018).

Recently, the interplay between technological change and cognitive categories has received additional attention (Goldfarb & Kirsch, 2019; Grodal, 2018; Zuzul & Tripsas, 2020). Tushman and Anderson's (1986) seminal paper stated that some technological shifts spark a new technology generation within an existing category, whereas others catalyze new categories. For example, some changes in technological design spur the creation of new category labels to designate the product (Grodal et al., 2015; Zunino et al., 2019), which often coincides with shifts in performance criteria (Garud & Rappa, 1994). Other technological shifts unfold neatly within the existing cognitive structures of a marketplace (McKendrick & Carroll, 2001). However, research has yet to explore when a technological change gives rise to a shift in the meaning of a category and when it spurs market participants to create entirely new market categories (e.g., typewriters versus computers).

We posit that a key difference between technological discontinuities that generate new industries and those that do not is the degree of overlap in performance criteria between the old technology and the new. For example, over the last 70 years, the hearing aid industry has experienced three technological discontinuities that generated a change in the industry's dominant design (Krabbe & Grodal, 2018). However, neither the general meaning of the category nor its label (i.e., "hearing aids") were ever questioned or changed. In contrast, when televisions disrupted the radio industry, both a new technology and a new label ("televisions" vs. "radios") was created. Radios and televisions differed on a variety of performance criteria (Faulkner & Runde, 2009; Goldfarb & Kirsch,

2019) making the disruption by televisions only partial in that radio retreated into a market niche where it has survived to the present day. Further research is needed on the dynamics between technological change and their associated cognitive categories. Scholars may, for example, examine in detail how changes in the kinds of performance dimensions along which technologies are evaluated coevolve with changes in the cognitive structures surrounding the technologies (Rosa et al., 1999; Zunino et al., 2019). Future research could also investigate the conditions under which organizations strategically can exploit a technological change to recategorize or change the products' meanings (Granqvist, Grodal, & Woolley, 2013; Lee, 2001; Pontikes & Kim, 2017) or to create a new category (Kennedy, 2008; Navis & Glynn, 2010).

Finally, some studies within the sociology of technology have addressed questions regarding how power shapes technology evolution (Bijker et al., 1987; Bijker & Law, 1994), yet more work is needed in this area (Grodal & Kahl, 2017). Although power dynamics in markets may influence technology evolution, especially as powerful actors often hinder the selection of otherwise promising technologies (Hargadon & Douglas, 2001; Ozcan & Santos, 2015; Rosenkopf & Tushman, 1998), technological changes can at times also severely damage the power of certain stakeholders by undermining the dominant business model within an industry (Tripsas & Gavetti, 2000) or the expertise of a profession or occupation (Abbott, 2014; Barley, 1986; Nelson & Irwin, 2014). This raises important questions about when we should expect technological changes to challenge (versus entrench) the power distribution among market stakeholders. For example, in the wake of rising concerns about the power of technology platform providers (Parker, Van Alstyne, & Choudary, 2016), commentators and policymakers are increasingly raising questions in society about the ethics and regulation of platforms and information technology that could benefit from such insights.

Structure Versus Agency: The Strategic Role of Firms and Stakeholders in Technology Evolution

The role of structure versus agency in shaping technology evolution is a central debate in the literature (Rosenberg, 1963). These debates mirror a larger conversation within the social sciences (Giddens, 1984) and management (Barley, 1986; Battilana & D'Aunno, 2009) about the degree to which stakeholders are constrained by social structures versus having the agency to change these same social structures. A central question is whether stakeholders have agency to shape technology evolution or whether technology restricts actors to an unmanipulable structure that constrain their agency.

Within the literature on the evolution of technology, two different structures have been deemed particularly important. The first is the technological structure itself (Clark, 1985; Rosenberg, 1963), and the second is the social structure in which the firm is embedded (Powell et al., 1996). Most technologies function through their interdependence with other technologies at both the intra-product and inter-product levels (Adner & Kapoor, 2016). At the intra-product level, many technologies have subcomponents with which they have interdependencies (Baldwin & Clark, 2000; Murmann & Frenken, 2006). The automobile, for example, has subcomponents such as the engine, brakes, and audio systems. Such intra-dependencies limit the changes that can be made to a technology. Technologies also have inter-product dependencies, in that most technologies intersect with other technologies—often called complements—in the creation of larger technology ecosystems (Adner & Kapoor, 2016; Boudreau & Jeppesen, 2015). Computers, for example, need to connect to internet routers, phones, and other devices, which can limit technology evolution. Thus, the development of a technology is also a foray down one path of a design hierarchy which, once chosen, is difficult to alter (Clark, 1985; Suarez, 2004). Most articles across the four perspectives acknowledged that the existing technological structure plays a role in shaping variation, selection, and retention. The force of the existing technology in constraining technology evolution is strongest for selection and retention because the new technologies that best fit existing technological structures are those that will be selected (Hargadon & Douglas, 2001; Schilling, 2002) and, due to technological path dependence, retained. The technological structure thus limits firms' agency and their possibilities for taking strategic actions. Technologies that are incompatible with the existing technological infrastructure will be at a higher risk of becoming deselected in the market (Adner & Kapoor, 2016).

In addition to the technological structure, the social structure also constrains firms' available strategic actions. First, firms are limited in their cognitive capacity such that they will tend to recombine technologies based on their prior experiences (Benner & Tripsas, 2012). If they search outside of the social structure, they will tend to recombine technologies from organizations with which they are socially connected (Powell & Grodal, 2005; Powell et al., 1996). Second, when technologies are created, they do not enter the world in a vacuum. Instead, technologies at creation are part of an existing social structure; depending on the organizations that created them and whether a technology might help disrupt or maintain the existing power structure, different stakeholders may be more or less willing to promote them (Callon, 1987).

Yet, although both technological and social structures constrain the technological trajectory, the literature on the evolution of technology has also emphasized that various stakeholders actively shape and influence the path of technological development within these constraints. In particular, scholars have emphasized not only the strategies firms use to ensure that their technologies are selected and retained (Hargadon & Douglas, 2001; Kahl & Grodal, 2016) but also the strategies firms use to time and position their technologies within the technological landscape in order to gain a competitive advantage (Suarez, Grodal, & Gotsopoulos, 2015; Suarez & Lanzolla, 2008).

For example, although Hargadon and Douglas (2001) showed how the structure of the existing gas distribution system shaped the structure of electricity distribution, they also detailed how Edison strategically designed the electrical grid to gain a competitive advantage over other technological designs. Thus, the imprint left by the gas distribution system structure on the electrical grid was not deterministic but was rather the result of an entrepreneur's strategic efforts to increase the probability that his design would win the battle for dominance. Likewise, Garud, Jain, and Kumaraswamy (2002) showed how the emergence of Java as a technical standard was the result of a contested process in which Sun Microsystems made technological changes based on accusations that it used control of the Java standard to its own advantage. The creation of a specific technological standard was thus not based on technological determinism but was instead the result of a collective negotiation among actors within the constraints of a technological structure. Although the agentic manipulation of technological structures has received some attention in relation to technology life cycle patterns of competing technological designs, such a lens has been applied less often to understand technology regime patterns and S-curve changes, which could be fruitful avenues for future research.

The four perspectives vary in their views of how agentic organizations can influence technology evolution. In each of the perspectives, the mechanisms highlighted as the most important are also viewed as the most constraining (e.g., "managerial cognition" in the cognitive perspective and "technology" in the technological perspective). However, the perspectives differ in their view of how constraining these surrounding structures are. Whereas the cognitive and the economic perspectives see managers as having opportunities for shaping and altering the path of technology evolution, the technological and the social perspectives consider these opportunities to be more limited.

Technology platforms are another type of technology structure that has gained prominence in shaping technology evolution (Boudreau, 2010; Gawer & Cusumano, 2014). The current literature on platforms has also raised new challenges for the literature that engages all four perspectives. Platforms are two-sided markets that function due to firms (complementors) offering products or services on the platform which then attract customers and users (Parker et al., 2016). The platforms literature has thus raised two questions for the literature on technology evolution. The first question pertains to the level of analysis to which technology evolution is subjected. When considering technology evolution in the era of platforms, we can either view the focal technology as the digital platform itself or as the technologies created by complementors. Since the first proliferation of online digital platforms in the late 1990s, the technological designs of platforms have evolved to include APIs (application programming interfaces) and recommendation systems. Individual platforms—such as Apple's App Store—have undergone technological evolution, and the technologies offered on platforms—such as apps—have evolved as well (Boudreau, 2012). These multiple levels at which technology evolves on platforms mirror the levels of analysis of other technological systems where technology evolution occurs at the component, device, and systems levels (Murmann & Frenken, 2006). However, platforms also pose challenges to our understanding of technology evolution. For example, how is a dominant design defined in the platform setting? At which unit of analysis do we see dominant design emerge? And how do dominant designs coevolve at the different levels of analysis? How does the design of a platform shape the evolution of technology at the level of complementors?

Reopening the Black Box of Technology Evolution

Our review found, counterintuitively, that most studies on technology evolution were not conducted with the specific aim of studying technology evolution. First, the most important papers on technology evolution tended to be theoretical in nature. Second, the majority of empirical papers that examined technology evolution were not written with the primary goal of studying technology evolution. Lastly, the papers that did study technology evolution tended to study technology evolution only over a short period of time (see Figure 6). The focus within the literature (i.e., on how organizations and industries adapt to technological change and, in particular, incumbent firms' failures to respond to technological change) has sidestepped the process of technology evolution itself (Christensen et al., 1998; Eggers & Park, 2018; Tripsas & Gavetti, 2000; Tushman & Anderson, 1986). Empirically, the focus on the consequences of technology evolution for firm performance and survival means that the literature has often portrayed technology as an unalterable force that firms adjust, evade, or succumb to. However, we know that organizations often exert considerable influence on the technological path of their market or industry (Kahl & Grodal, 2016; Ozcan & Santos, 2015), suggesting that technology evolution should be examined as more than an exogenous force that shapes the evolution of industries and firm performance unidirectionally.

One reason that so few papers have studied technological evolution, per se, despite calls to do so (Andriani & Cattani, 2016; Basalla, 1988), is that tracing technological evolution at the artifact level is empirically challenging because discontinuities in technological features are hard to compare. For example, how do you quantitatively compare the technological features of the typewriter with the features of the computer? And even within a given technology, how can the addition of qualitatively different features be compared alongside a variable that can be used for quantitative analysis? These empirical difficulties have likely inclined scholars to push technological evolution outside the scope of their analyses. However, black-boxing technology evolution is problematic because it overlooks the coevolutionary dynamics between technology evolution and the variables of interest (for a similar observation on the literature on technology diffusion, see the diagnosis of Adner & Kapoor, 2015).

To advance our knowledge of technology evolution, we must expand on old methods and incorporate new ones. Although patents have proven useful for studying technologies at a highly aggregate level, such as that of technological regimes (O'Donoghue, Scotchmer, & Thisse, 1998) and organizations' technological capacities (Vakili, 2016), it falls short as a proxy for studying technological evolution at the artifact level, which is important for tracing other types of technological changes—especially technology life cycle changes—as well as grasping the artifact-level mechanisms. Some studies have gotten closer to the phenomenon itself, such as by studying design evolution through design rights documents (Chan, Mihm, & Sosa, 2018), but even these do not measure technological evolution directly at the artifact level. However, secondary archival sources, such as trade journals (Christensen, 1997; Hoffman & Ocacio, 2001) or product catalogs (Rosa et al., 1999), have previously proved to be fruitful data sources for studying technology evolution at the artifact level.

Developing a coevolutionary understanding of technology evolution necessitates not only theoretical syntheses but also new methodological approaches (Lewin & Volberda, 1999). For example, the cognitive and social factors shaping technology evolution are not easily observed in the quantitative data commonly used to study technology evolution (e.g., patents and data sets on product features). The relative paucity of studies on demand heterogeneity may also be attributed to the limits of current methodologies. To examine the interdependencies among economic, cognitive, and social factors, we can turn to new methodologies, such as qualitative comparative analysis, which facilitates inference even with a moderate quantity of observations (Fiss, 2011; Schneider & Wagemann, 2012; Soda & Furnari, 2012). There is also rich opportunity to create mixed-methods studies, which rely on the strength of different research methodologies. In particular, we see opportunities in combining in-depth qualitative analysis with simulation methods (Black, Carlile, & Repenning, 2004; Davis, Eisenhardt, & Bingham, 2007). These two methods complement each other as scholars will be able to use in-depth qualitative analysis to identify the mechanisms which drive technology evolution and subsequently draw on these insights to develop a simulation model which generalizes the qualitative findings beyond the studied case(s).

To advance the literature on technology evolution, future studies should also collect demand-side data beyond outcome indicators such as sales or market share. The recent digitalization of historical and textual data has granted abundant access to the documents that have been used to trace the cognitive and social factors involved in technology evolution, such as labels (Grodal et al., 2015), frames (Goldfarb & Kirsch, 2019; Kaplan & Tripsas, 2008), and discourses of evaluation (Benner & Ranganathan, 2017).

Combining this data with new tools for quantitative text analysis (Krippendorff, 2018) will allow scholars to address the coevolutionary dynamics among technological, economic, cognitive, and social factors.

CONCLUSION

Our review of the literature on the evolution of technology details a rich and continuously evolving literature. We identify four different perspectives on the evolution of technology: technology-realist, economic realist, cognitive interpretivist, and social constructionist. Across the perspectives, variation, selection, and retention have been recognized as the theoretical mechanisms that drive technology evolution. Scholars have suggested that variation is primarily driven by recombination, selection is driven by fit with the environment, and retention can be explained through path dependence. However, we also reveal systematic differences across the perspectives in their emphasis on the specific factors involved in these mechanisms. Some scholars have given precedence to technological, economic, cognitive, and social factors as driving these dynamics. To combine these insights and advance the literature, scholars must adopt a coevolutionary perspective on how factors from each perspective shape one another during technology evolution. This may necessitate breaking with existing research traditions by employing mixed-method and longitudinal research designs. While challenging, such efforts are necessary to reignite the literature on the evolution of technology.

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