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Shaping the technological landscape: the role of forward-looking cognition in the evolution of robotics

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SHAPING THE TECHNOLOGICAL LANDSCAPE: THE ROLE OF FORWARD-LOOKING COGNITION IN THE EVOLUTION OF ROBOTICS

by

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IN THE EVOLUTION OF ROBOTICS

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ABSTRACT

While there is a large amount of literature on the socio-cognitive theory of technology evolution, most has focused on the interpretations of technologies that are already in existence. The literature has barely attended to the role of forward-looking cognition—mental representations of possibilities in the future. How do innovators and entrepreneurs envision the possible, and how do they translate those abstract concepts into new material and social reality? This dissertation first synthesizes the vast literature on technology evolution, and offers a theoretical framework for understanding the role of forward-looking cognition in the evolution of technology. Using a large amount of historical archival data on the US robotics industry, my two empirical papers investigate (a) how a distant vision co-evolves with the actual technologies at the level of the organizational field (b) how entrepreneurial solutions and entrepreneurial search problems are co-constructed at the firm level.

In the first paper of my dissertation, I review the literature on the evolution of technology. 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. This essay offers 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. I 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. I integrate these perspectives by highlighting that they all emphasize recombination, environmental fit, and path dependence as central drivers of those three mechanisms. I emphasize the need for a co-evolutionary framework that cuts across the four perspectives to push the literature forward.

In the second paper of my dissertation, I examine how technological visions—mental representations of technological possibilities in the future—co-evolve with the actual technologies. This paper is set in the robotics industry. The existing literature has focused on how backward-looking interpretations of technology shape its subsequent trajectory, but has rarely examined the role of forward-looking cognition in technology evolution. To examine this, I conducted an extensive archival qualitative study covering the evolution of the field of robotics during the 100-year period from 1921 to 2020. I find that in a future-oriented field, the direction of technology evolution is largely shaped by the field participants' attempts to narrow the vision-reality gap—the perceived temporal gap between the distant vision and present reality. I identify six distinct mechanisms—linking means to the distant vision, constructing a medium-term vision, envisioning sequences, decomposing, reconstructing, and reintegrating—through which field participants strive to narrow the vision-reality gap. I also find that the vision-reality gap is

extremely volatile, and can rapidly expand and contract when salient artifacts (or reverse salients) emerge. In this study, I contribute to the socio-cognitive view of technology by highlighting the role of forward-looking cognition in technology evolution.

In the third paper of the dissertation, I study the process through which an entrepreneurial search problem is constructed. Previous studies have focused on search for solutions to a given problem. However, literature on entrepreneurship suggests that many entrepreneurs often start from formulating a very broad, abstract problem that a novel technological means is envisioned to be able to solve in the future. Forward-looking cognition, the mental representations of possibilities in the future, lies behind the process of problem formulation. In order to examine how construction of problems affects search for solutions, I conducted a qualitative analysis of archival data about 58 entrepreneurial firms founded by 42 entrepreneurs in the robotics industry. I find that most entrepreneurial firms start by linking a novel technological means to an abstract problem, and then proactively identify a core constraint in the solution space. In order to bypass the constraint, they engage in decomposing and reconstructing a core problem. In the stage of pursuing product-market fit, the issue of identifying core attributes, or core evaluation criteria weighted by users is brought to the fore. This paper contributes to our understandings of entrepreneurial search by highlighting the cognitive underpinnings of problem formulation.

TABLE OF CONTENTS

ACKNOWLEDGMENTS iv

ABSTRACT ……...vii

TABLE OF CONTENTS……………………………………………………………….x

LIST OF TABLES …..xiii

LIST OF FIGURES xiv

INTRODUCTION 1

THREE IDEAL TYPES OF FORWARD-LOOKING COGNITION…………….3

OVERVIEW OF DISSERTATION …...6

RESEARCH SETTING AND DATA …..9

CHAPTER 1: FOUR PERSPECTIVES ON TECHNOLOGY EVOLUTION …............13

INTRODUCTION 13

METHODS …..25

THE EVOLUTION OF THE LITERATURE ON THE EVOLUTION OF TECHNOLOGY 28

FOUR PERSPECTIVES ON THE EVOLUTION OF TECHNOLOGY…...........31

THE TECHNOLOGY REALIST PERSPECTIVE …...............................31

THE ECONOMIC REALIST PERSPECTIVE ….....................................34

THE COGNITIVE INTERPRETIVIST PERSPECTIVE …......................36

THE SOCIAL CONSTRUCTIONIST PERSPECTIVE …........................42

DISCUSSION...46

CHAPTER 2: VISION-REALITY GAP: THE CO-EVOLUTION OF DISTANT VISION AND TECHNOLOGY IN THE FIELD OF ROBOTICS (1921–2020) …......................71

INTRODUCTION …..71

THE CO-EVOLUTION OF VISION AND TECHNOLOGY ……......................76

METHODS 81

FINDINGS 87

PRE-PHASE: DISTANT TECHNOLOGICAL VISION…......................87

PHASE 1. LINKING NOVEL TECHNOLOGICAL MEANS TO THE DISTANT VISION 89

PHASE 2. NARROWED VISION-REALITY GAP…...........................93

PHASE 3: EXPANDED VISION-REALITY GAP AND DECONSTRUCTION OF THE VISION…... 98

PHASE 4: REINTEGRATION AND REVIVAL …...............................104

THEORETICAL MODEL: CO-EVOLUTION OF VISION AND TECHNOLOGY ……………………………………………..……………108

DISCUSSION 111

CHAPTER 3: ENTREPRENEURIAL PROBLEM-SOLUTION PAIR: HOW ENTREPRENEURS CONSTRUCT A SEARCH PROBLEM.................................... 117

INTRODUCTION 117

METHOD 120

FINDINGS 123

PHASE 1: FORMULATING A BROAD PROBLEM….........................124

PHASE 2: IDENTIFYING A CORE CONSTRAINT IN THE SOLUTION SPACE …...126

PHASE 3: ACHIEVING PRODUCT-MARKET FIT….........................129

DISCUSSION …...132

CONCLUSION…..136

LIMITATION AND FUTURE RESEARCH……………………….……….144

REFERENCES 182

CURRICULUM VITAE…………………………………………………………..206

LIST OF TABLES

Table 1. Three Ideal Types of Forward-looking Cognition 146

Table 2. Overview of the Four Perspectives on Technology Evolution 147

Table 3. The Four Perspectives' View on the Variation, Selection and Retention of Technology 149

Table 4. Research on Technology Evolution 150

Table 5a. Twelve Example Studies that Primarily Draw on the Technology Realist Perspective 152

Table 5b. Twelve Example Studies that Primarily Draw on the Economic Perspective .153

Table 5c. Twelve Example Studies that Primarily Draw upon the Cognitive Interpretivist Perspective 155

Table 5d. Twelve Example Studies from Primarily the Social Constructionist Perspective ……………………………………………………………………………......157

Table 6. Descriptive Statistics of Papers in the Technology Evolution Literature 159

Table 7. Data for Multi-method Analyses 160

Table 8: Overview of the Mechanisms 161

Table 9. Data sources 165

Table 10. Descriptive data on entrepreneurs and academics 166

Table 11. Data: Entrepreneur Descriptives ..……...167

Table 12. Contribution to Four Perspectives …..169

LIST OF FIGURES

Figure 1: Patterns of Technology Evolution: Discrete, Continuous and Cyclical Models ……………………………………………………………………………………172

Figure 2: Technological Designs during the Evolution of the Bicycle…........................173

Figure 3: Model of Technological Evolution...174

Figure 4. The Number of Papers in the Technology Evolution Literature Over Time....175

Figure 5. The Number of Papers in Each Perspective Over Time..................................176

Figure 6. The Number of Lifecycles Covered in the Papers Over Time 177

Figure 7. Process of Data Collection and Analysis…..178

Figure 8. Time trend in the frequency of the term “Robot”…..179

Figure 9. Process Model of the Co-evolution of Technological Vision and Technological Progress...180

Figure 10. Process Model of the Co-construction of Entrepreneurial Problems and Solutions …………..……………………………………………………………..181

INTRODUCTION

Technology evolution has been a central topic in organization theory and entrepreneurship (Abernathy & Clark, 1985; Garud & Rappa, 1994; Kaplan & Tripsas, 2008; Pinch & Bijker, 1984). Technology, defined as a set of knowledge embedded in artifacts used to solve problems (Basalla, 1988), often emerges in complex cognitive and social processes communicated among various stakeholders (Anthony, 2018; Rindova & Petkova, 2007). While the earlier literature on technology evolution has tended to highlight the path dependent role that prior technology structures played in determining technological trajectories (Clark, 1985; Fleming, 2001; Rosenberg & Nathan, 1982), more recent scholarship has begun to depart from this perspective by focusing on the fit between emerging technologies and existing social categories, relations, networks, and interests (Grodal, 2018; Zott & Huy, 2007). The cognitive view of technology, which typically emphasizes the convergence of producers' and users' cognitive representations of a technology, has been gaining traction (Garud & Rappa, 1994; Kaplan & Tripsas, 2008). However, this dissertation is motivated by an observation that the existing literature has predominantly focused on retrospective cognitive processes—that is, making sense of the technologies that have already come into existence (Navis & Glynn, 2010). In other words, studies in this line of research have commonly examined how the interpretation of the past and present co-evolves with technologies and markets (Grimes, 2018; Raffaelli, 2019).

In this dissertation, I explore how forward-looking cognition—mental representations of possibilities in the future (Beckert, 2016)—shapes technology evolution and entrepreneurial processes. Forward-looking cognition is concepts that are not grounded on existing realities, but on envisioned possibilities—and some possibilities are considered more desirable or feasible than others (Hannan et al., 2019). Innovative endeavors are often driven by an idiosyncratic mental representation of possibilities formed in the mind of an entrepreneur or a collective of innovators, which has often been mentioned as blueprints, sketches, or imaginaries in the recent literature (Seidel & O'Mahony, 2014; Augustine, Soderstrom, Milner, & Weber, 2019). In a way, developing a novel technology, particular one with extreme demand and market ambiguity, is a process through which an abstract mental representation of potential futures is translated into concrete artifacts that can evoke user understandings (Simon, 1990). While the existing literature on retrospective cognition mainly explains how different stakeholders interpret an emerging set of artifacts, forward-looking cognition can explicate how such novel artifacts come into existence in the first place.

Forward-looking cognition is also important because nascent markets are often constructed around prospects for potential functions and capabilities of a technology in the future, not just around its current quality (Rosenberg, 1982). Some users and corporate customers jump on the bandwagon for fear of being left behind in the future competitive landscape (Aldrich & Fiol, 1994; Pontikes & Barnett, 2017). In these dynamics, a belief about *when* a promised possibility is going to be realized is as important as a belief about *what* possibility is being promised (Granqvist and Gustafsson, 2016). Innovators and entrepreneurs do not only project imagined trajectories into the future, but also actively integrate them into their narratives (Carson, 2018) to attract resource, customers, and markets. The influence of forward-looking cognition has abundantly been alluded in organizational phenomena such as field mobilization (Grodal and O'Mahony, 2017) and entrepreneurship (Kirtley and O'Mahony, 2023), as well as in diverse technologies such as nanotechnology (Grodal, 2018), self-driving cars (Nielsen and Haustein, 2018), and quantum computing (Hilkamo and Granqvist, 2022). Yet, we still have limited knowledge on how these future-oriented beliefs shape technology evolution.

While the importance of forward-looking cognition has been alluded in many previous studies, diverse theoretical terms that carry slightly different connotations have been used across fragmented lines of literature. In this introduction, I provide a brief overview of three ideal types of forward-looking cognition that I have synthesized from varied streams of literature, and explain how each essay in the dissertation is related to different types of forward-looking cognition.

Three Ideal Types of Forward-looking Cognition

Various studies on technology evolution and entrepreneurship have alluded that such future-oriented mental models are important, but theoretical terms and definitions are scattered across varied lines of literature. In this section, I suggest that there are three distinct ideal types of forward-looking cognition: *distant vision, medium-term vision, and near-term vision*, each of which is typically related to different types of beliefs, actions, and lines of literature. In the table 1, I delineate the characteristics of and differences between the three types of forward-looking cognition.

*** Insert Table 1 about here ***

The first type of forward-looking cognition is *distant vision*. This has been less explored in the literature yet is recently gaining attention (Rindova & Martins, 2021). I define *distant vision* as a belief about the possibility of an abstract concept solving an abstract, broad-scope problem in the future. Distant visions are often radical to the extent that the concepts—manifested in multiple, interconnected classes of technologies—are envisioned to transform a large swath of the economy and society (Augustine, Soderstrom, Milner, & Weber, 2019; Beckert, 2016). For example, Grodal and O'Mahony (2017) detail how the beliefs in nanotechnology mobilized a large field of diverse actors around the vision of creating microscopic robots which would entirely transform society as we know it. Distant vision has often been referred to as visions (Carton, 2018), imaginaries (Augustine et al., 2019), or grand challenges (Ferraro, Etzion, & Gehman, 2015) in the management literature. These abstract concepts are often long-term oriented, radical, and not tightly grounded on an existing reality (Zbaracki, 1998). Actions driven by distant visions are governed by extreme uncertainty or unknown-unknowns (Knight, 1921), and are often aimed to construct an organizational field through the negotiations between heterogenous stakeholders beyond a single market. These heterogeneous stakeholders hold different interests, beliefs, and values (Grodal, 2018; Zietsma et al. 2017; Hoffman, 1999), shaping the trajectories of multiple classes of technologies that constitute an organizational field mobilized by the distant vision. The most relevant studies about this includes the cognitive and socio-constructivist view of technology evolution (Grodal, 2018; Ozcan and Santos, 2015; Hilkamo and Granqvist,

2022) and an emerging literature on shaping (Rindova and Martins, 2021).

The second type of forward-looking cognition is *medium-term vision*. I define *medium-term vision* as a belief about the possibility of a concrete, fledgling technological tool solving a less defined, abstract, mid-scope problem in the future. In many cases, an innovation and entrepreneurial process begins when an innovator or entrepreneur makes an intuitive mental connection between a new tool and its multiple potential uses in the future (Sarasvathy, 2002)—often manifested in the form of blueprints, sketches, and concept models (Simon, 1990). The potential future use is nebulous and abstractly defined (e.g., “this technology would be useful in factories”; “this material would improve the safety of electronic devices.”). In other words, the potential problem space is broadly scoped, and its realization is projected at some point in the future (Baldwin & Clark, 2000; Kilduff, Mehra, & Dunn, 2011). Although a problem space is roughly scoped, there is still a fundamental uncertainty about whether there will indeed be a market for this particular technology (Rindova & Courtney, 2020). Goals and purposes that guide business decisions are still not clear (Baldwin and Clark, 2000), and the premises are only limitedly testable (Kirtley and O’Mahony, 2023). Organizational activities guided by *medium-term vision* are typically aimed at constructing a market through both shaping and adapting mechanisms (Rindova and Courtney, 2020). The most relevant studies to this have been the literature on entrepreneurial action, effectuation, and pivoting (Sarasvathy, 2002; Berglund, Bousfiha, and Mansoori, 2020; Zuzul and Tripsas, 2020; Grimes, 2018).

The third type of forward-looking cognition, more frequently studied in management and entrepreneurship literature, is *near-term vision*. It is a belief that a concrete, emerging technology will solve a concrete problem that has a predictable market. The examples can be a biotechnology start-up developing a technology that is a potential solution for a rare disease that affects 500,000 people in the world (Cockburn & Henderson, 1998), or a platform company targeting a hypothesized, underserved niche (e.g. a dating platform for evangelical Christians). There is still a deep uncertainty around whether the developing technology will indeed be commercially viable and will attract customers within cost and institutional constraints (Ingram & Clay, 2000), but these near-term visions are relatively quickly testable (Camuffo, Cordova, Gambardella, & Spina, 2020). Methods such as minimal viable product and experimentation are increasingly being used in order to shorten the cycles of testing hypotheses. In this case, the forward-looking cognition (*near-term vision*) of innovators and entrepreneurs is more tightly linked to a cognitive representation of their immediate environment (Gavetti and Levinthal, 2001), also commonly referred to as "mental model" (Ott, Eisenhardt, & Bingham, 2017) or "small world representation" (Feduzi, Faulkner, Runde, Cabantous, & Loch, 2022).

Overview of dissertation

In this dissertation, I first provide a synthesis of the vast exiting literature on technology evolution, and present two empirical papers set in the robotics industry pertaining to how *distant vision* and *medium-term vision* shape and interact with technology evolution at field- and entrepreneurial-level.

In the first chapter, co-authored with Stine Grodal and Anders Krabbe, I review the vast literature on the evolution of technology. 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. This essay offers 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. I 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. I integrate these perspectives by highlighting that they all emphasize recombination, environmental fit, and path dependence as central drivers of those three mechanisms. I emphasize the need for a co-evolutionary framework that cuts across the four perspectives to push the literature forward.

In the second chapter, I examine how technological visions—mental representations of technological possibilities in the future—co-evolve with the actual technologies in the context of the robotics industry. The existing literature has focused on how backward-looking interpretations of technology shape its subsequent trajectory, but has rarely examined the role of forward-looking cognition in technology evolution. To examine this, I conducted an extensive archival qualitative study covering 100 years of the evolution of the field of robotics from 1921 to 2020. I find that in a future-oriented field, the direction of technology evolution is largely shaped by the field participants' attempts to narrow the vision-reality gap—the perceived temporal gap between the distant vision and present reality. I identify six distinct mechanisms—linking means to the vision, setting a medium-term vision, sequencing, decomposing, reconstructing, and reintegrating—through which field participants strive to narrow the vision-reality gap. I also find that vision-reality gap is extremely volatile, and can rapidly expand and contract when salient artifacts (or reverse salients) emerge. In this study, I contribute to the socio-cognitive view of technology by highlighting the role of forward-looking cognition in technology evolution.

In the third paper of the dissertation, I study the process through which an entrepreneurial search problem is constructed. Previous studies have focused on search for solutions to a given problem. However, literature on entrepreneurship suggests that many entrepreneurs often start from envisioning a broad problem space in which to use a novel technological means to solve an abstract problem. Forward-looking cognition, the mental representations of possibilities in the future, lies behind the process of problem formulation. In order to examine how construction of problems affects search for solutions, I conducted a qualitative analysis of archival data about 58 entrepreneurial firms founded by 42 entrepreneurs in the robotics industry. I find that most entrepreneurial firms start by linking a novel technological means to an abstract problem space, and then proactively envision a core constraint in the solution space. In order to bypass the constraint, they engage in decomposing and reconstructing a core problem. In the stage of pursuing product-market fit, the issue of identifying core attributes, or core evaluation criteria weighted by users is brought to the fore. This paper contributes to our understandings of entrepreneurial search by highlighting the cognitive underpinnings of problem formulation.

Overall, my dissertation contributes to our understanding of the role of forward-looking cognitions in the evolution of technology, and sheds light on the process through which the way visions are cognitively constructed affects the trajectories of technology evolution and entrepreneurial search.

Research setting and data

In order to investigate the overarching question of how forward-looking cognition shapes technology evolution, I conducted an in-depth longitudinal qualitative study of how the field of robotics evolved over the last 100 years (1921-2020). The concept of “robot” as mechanical men that serve human needs was first created as a distant imaginary (Augustine et al., 2019) in a science fiction play in 1921. With the advent of digital computers, the distant imaginaries have spawned more concrete *technological visions* that inspired entrepreneurs and scientists about what is technologically possible and desirable in the future. Ever since the inception of robotics as a legitimate technological field in the 1960s and 70s, the discourses about the field by producers, entrepreneurs, and stakeholders have been steeped in visionary and future-oriented language. With salient successes and failures such as the first commercially viable artifact and major bankruptcies, the collective beliefs about how fast the imagined future was approaching fluctuated to an extreme degree (Pontikes & Barnett, 2016) since the 1980s. The beliefs about the temporal gap between the vision and reality greatly affected the direction of technology evolution in the field. However, the latent visions persisted, and the field underwent a revival and resurgence phase in recent years. The constant recalibration of the forward-looking vision and its co-evolution with actual technologies over a century makes the case of robotics an extreme case of a distant vision shaping technology evolution (Eisenhardt, 1989).

I use longitudinal archival qualitative data to study the evolution of the field of robotics at three different levels of analysis: field-level, industrial-level, and entrepreneurial-level. Table 7 summarizes the data for each chapter. For the field-level analyses in the second chapter, I constructed the set of data that span four trade journals, one technology magazine and two science magazines, congressional hearings, and historically seminal academic articles in robot-adjacent fields. I also relied on four books written by prominent roboticists and science historians to understand the deeper history of underlying technologies. Three books provide a nice overview of the history of artificial intelligence and computer vision (Brooks, 1999; Crevier, 1993; Nilsson, 2009). Roland & Shiman (2002) provides an in-depth overview of the role of the military community and, particularly, an agency called DARPA (Defense Advanced Research Projects Agency).

Figure 7 delineates the data analysis process. Motivated by the initial puzzle of “how the field of robotics evolved over time,” I first created the basic timeline of robotics by collecting and analyzing the 1,354 articles that contained the term “robot” from *Popular Mechanics*, one of the longest-running popular technology magazines that has been published over the last 100 years. From the timeline, I identified initial theoretical constructs such as visionary aspirations, limitations of technologies, solvable and achievable goals, hype and disillusionment. Then I triangulated this initial understanding with early trade journals containing information on the early industrial robot (robotic arms) industry, and the history of underlying technologies (i.e. digital computer and numerical control technology). From this triangulation, I identified more refined, abstract theoretical constructs such as the directionality and temporality of technological visions, intermediary goals, and reverse salient (Hughes, 1978). In the latest data analysis step, I collected further data in order to have a finer grained understanding of what happened in the emerging robot-related industries such as mobile robot industry and self-driving car industry. This triangulation helped solidifying the mechanisms through which the distant visions and the actual technologies co-evolved, as depicted in the process model in Figure 9.

In the process of collecting and analyzing historical archival data for the second chapter, I also identified more recent archival data focusing on the accounts of individual entrepreneurs in the robotics industry. The entrepreneur-level data consists of public interviews and oral histories conducted by a flagship trade journal and IEEE History Center (Burton, Sørensen, & Beckman, 2002). Table 10 describes the data sources, and the basic characteristics of whole interviewees included in the data. From these two archives, I selected 38 entrepreneurs (42 interview scripts) to the exclusion of academics, and built the list of 58 entrepreneurial firms that these entrepreneurs had founded. Table 11 further describes each entrepreneur's name, the number of interview scripts for each, the number of firms that they had founded, types of products they build, types of target market, gender, and whether they have online social media pages (e.g., LinkedIn) with which I can triangulate the data. In the third chapter, I utilize this data to shed light on how entrepreneurs construct a search problem using forward-looking cognition.

Chapter 1

FOUR PERSPECTIVES ON TECHNOLOGY EVOLUTION

INTRODUCTION

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 (Utterback & Abernathy, 1975; Argyres, Bigelow, & Nickerson, 2015), 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 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 producers' work with a technology, such as the process from basic 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 19^{th} 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.

*** Insert Figure 1 about here ***

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 of existing technologies (Anderson & Tushman, 1990; Suarez, 2004). Authors have offered divergent definitions of discontinuous technological change. Some emphasize 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 lifecycle" (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). 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 lifecycle (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 lifecycle 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 lifecycle 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 lifecycle 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 lifecycle 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 then they differ in their explanations for how these patterns arise. In particular, they have examined these patterns of technology evolution from 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 2 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.

*** Insert Table 2 about here ***

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

*** Insert Figure 2 about here ***

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 re-creation and re-selection 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 re-created and re-selected, 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 3 for an overview). In its ideal form, the 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 (Utterback & Abernathy, 1975; Abernathy & Clark, 1985; Anderson & Tushman, 1990; Mueller & Tilton, 1969). An assumption of technological realism is that actors' cognitive representations of a technology mirror the actual technological artifact. Works adhering to the technological perspective often implies 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 focus mainly on how changes in the maturation of the technology along the s-curve or technology lifecycle shapes the variance of technological designs.

*** Insert Table 3 about here ***

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 and that 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 rarely focus on explaining long patterns of technology evolution, but instead focus more narrowly on transition periods and the competition between technological variations.

The social perspective builds on both the economical 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, but rather that 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 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 et al., 2012; Hargadon & Douglas, 2001; Pontikes & Barnett, 2015; Rao, 2004). The social perspective is heterogeneous with regards to the patterns of technology evolution that the studies explain. However, in contrast to the technological and economic perspectives, the social perspective emphasizes consistency in the social and institutional structure across technology lifecycles, which in turn creates a 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 co-evolution of these interconnected factors (Clark, 1985; Murmann, 2003), contemporary literature has largely abandoned this notion, diverging into distinct branches. As an attempt to re-ignite the co-evolutionary 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).

*** Insert Figure 3 about here ***

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 et al., 2019; Lehman, O'Connor, Kovács, & Newman, 2019; Zhang, Wang, Toubiana, & Greenwood, 2021) and included additional journals when necessary (see Table 4 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 4 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 intra-organizational innovation (Barley, 1986; Barrett, Oborn, Orlikowski, & Yates, 2012; Benner & Tushman, 2002; Carlile, 2002; Feldman, 2000; Leonard-Barton, 1992; Zbaracki, 1998; Murray & O'Mahony, 2007; Hargadon & Douglas, 2001), 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).

*** Insert Table 4 here ***

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 and/or whether it 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.

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 into the original sample because they either were 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 4 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 kind of data used, the kind of analysis 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 (Rosenberg, 1982; Abernathy & Clark, 1985; Abernathy & Utterback, 1978; Clark, 1985). 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.

*** Insert Figure 4 and Figure 5 about here ***

Table 6 provides an overview of the data across the perspectives fixed on a set of different variables. The tables show that about a third of the papers in this literature are theoretical in nature, a third are quantitative, and a third are split among qualitative, computational, and mixed methods. The table also shows that most papers examine high-tech settings whereas a relatively smaller volume of studies focus on low-tech settings. Furthermore, most papers examine technological discontinuity rather than incremental change, as most studies have focused on studying the technological shifts which lead to new dominant designs. Early on there was an overwhelming tendency for scholars to study one or more technology lifecycles, but over time the literature has inclined toward studies that are cross-sectional or that study only part of a technology lifecycle (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 emerges from our analyses is that very few papers empirically study users, in that most papers do 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 does focus on uses, examines the ones that take on the role of producers (Franke & Shah, 2003; Shah & Tripsas, 2007; Von Hippel, 1988) but not full swath of users consuming a product.

We also find considerable variation with regards to the role of technology evolution in research designs. Although some studies treat technology evolution as a dependent variable, the majority of studies in our sample examine technology only as an exogenous shock that—as a backdrop for the research design—allows 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 trace technological evolution as a dependent variable are skewed toward the technological and social constructivist perspective; these tend to focus on illuminating specific cyclical patterns or what shapes the trajectory of technology evolution. In contrast, a handful of studies that treat technology evolution as an independent variable are more likely to belong to the economic perspective. Finally, we traced each paper's unit of analysis. Across the perspectives, the firm is 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.

*** Insert Table 2 about here ***

FOUR PERSPECTIVES ON THE EVOLUTION OF TECHNOLOGY

We will now present the four perspectives. Because most of the perspectives 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; R. 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; Suárez & 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, non-reversible 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 drive of technology evolution. Many central contributions within this perspective echo the sentiment that the configuration and evolutionary stages of the technology dictates the technological space within which producers can innovate (Abernathy & Utterback, 1978). Table 5a provides a few examples of studies that primarily adhere to the technological perspective, although several of these papers also touch upon elements from the other ideal types.

Insert Table 5a about here

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 (Foster, 1986; Abernathy & Utterback, 1978; Clark, 1985; 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 and Clark, 2000). The ideal form of the technological perspective thus implies that selection favors the technology variant whose inherent functional features offer the best fit with users' needs. This will often be the variant 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 variant 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, p. 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 economical 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- to process innovations, only firms with a high market share could invest sufficiently in process efficiency to remain competitive. Table 5b shows examples of studies that primarily adhere to the economic perspective, although several of these papers also contain elements from the other perspectives.

Insert Table 5b about here

Technology variation. From the economical perspective, technological variation is driven by firm heterogeneity in technology and market competencies, market uncertainty, especially insufficient knowledge of demand, which spurs producers to generate different technological variations (Klepper, 2002). As ideal types, the technological and economical 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 economical 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 economical perspective holds that selection occurs due to economic drivers in the market, especially consumers' preferences for selecting cheaper products 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 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, "[s]cholars 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). 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 the notion that demand heterogeneity is an important element of technological change (Adner & Levinthal, 2001).

Technology retention. Authors adhering to the economic perspective tend 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 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, 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 economical perspectives by emphasizing that it is impossible to understand the evolution of technology without taking into consideration how people understand and interpret technology. 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 amongst 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 economical 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 5c provides a few examples of studies that primarily adhere to the cognitive perspective, although several of these papers also touch upon elements from other ideal types.

Insert Table 5c about here

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

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[1] The SCOT program had several streams of thought, some that cohere highly with what we term

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 1:1 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 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 lifecycle (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

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the "social constructionist perspective" and some with what we term the "cognitive perspective."

transition to digital technology. This study became highly influential, as it came in the wake of the scholarly attention given to disruptive potential of technology on competition, such as Clark and Henderson's (1990) seminal article on architectural innovations and Christensen's (1997) work on why certain technological changes cause market-leading firms to fail. Although (regrettably) less-often cited, other works in the same period worked on developing similar insights. For example, Howells's (1997) examination of the demand pull/technology push distinction highlights the role 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). 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 (Shane, 2000; Benner & Tripsas, 2012; 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 et al., 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 report 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 variants 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 trace this empirically, as most studies adhering to this perspective focus on firms' adaptation to technological discontinuities (see Tripsas & Gavetti, 2000, for a highly influential example of such studies). However, when studies seek to explain why firms tend to struggle with adapting to technological discontinuities, the drivers of retention are often 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 analogue 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 users 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 into 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 (Hargadon & Douglas, 2001; Ozcan & Santos, 2015; Podolny & Stuart, 1995). This perspective emphasizes the role of non-market 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 non-market actors form a bounded structure that "is seen as co-evolving with the commercialized technology" (Lynn et al., 1996, p. 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 et al., 2009), institutional theorists (Grodal, 2018), social-network scholars (Owen-Smith & Powell, 2004; Powell et al., 1996, 2005), scholars associated with science technology and society (STS) 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 5d provides a few examples of studies that primarily adhere to the social perspective, although several of these papers also touch upon elements from other ideal types.

Insert Table 5d about here

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

Technology variations. A premise within the social perspective is that the technological variations created are the results of the social structures in which firms are embedded. Powell et al. (1996) and Ahuja (2000), for example, show that the structure of networks between firms is a central driver in the kinds of innovation that firms create. Seidel, Langner and Sims (2017) theorize that different kinds of communities are most dominant in creating new variations at different points along the industry lifecycle: Loosely organized communities dominate during the early part of the technology lifecycle, whereas and structured community-firm interactions dominate the latter part of the technology lifecycle. Within the social perspective, technological variation is, thus, 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 (Ozcan & Santos, 2015; Grodal, 2018), such as regulators (Hargadon & Douglas, 2001; Kirsch, 2000; Yates, 2005). The idea of technology selection as socially constructed was hinted at already in Anderson and Tushman (1990), who argued that the selection of a dominant technological design is often the outcome of a "socio-political process." However, as later noted by Utterback and Suarez (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 show 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 and 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 dominance instead of electric vehicles. Kirsch shows that the internal combustion engine was not technologically superior at first, but instead rose to 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 socio-technical lock-in. Rosenkopf and Tushman's (1998) paper shows that cooperative technical organizations (e.g., standard-setting organizations, technical committees and task forces) co-evolve with technology during the industry lifecycle. They further show that 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.

DISCUSSION

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.

Towards a Co-Evolutionary Perspective of the Mechanisms Driving Technology Evolution

Our review of the literature found that scholars broadly adhere to four different perspectives on technology evolution: 1) technology realist, 2) economic realist, 3) cognitive interpretivist and 4) social constructionist. Across the perspectives, scholars have identified five distinct ways in which technology evolves: 1) continuous, 2) discontinuous, 3) cyclical through technology regimes, 4) cyclical through technology S-curves, and 5) cyclical through industry lifecycles. We also find that scholars agree that the evolution of technology is driven by three mechanisms: 1) variation, 2) selection, and 3) 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 differ with regards to which features of the environment that 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 emphasize 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 (Eggers, 2012; 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), wherein prior technologies shape the trajectory of subsequent variations (Clark, 1985). The economical 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. The cognitive perspective emphasizes that technological recombination is driven by variation in actors' cognitive frames and ideas (Benner & Tripsas, 2012). 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 tend 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 co-evolve. Doing so would shed light on the fine-grained understanding of what drives the patterns of technology variations.

A co-evolutionary 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 recombination (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 co-evolve and how they are aligned (or not aligned) with one another.

Taking a co-evolutionary 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 technological discontinuities. In particular, we must better understand the temporality of when technological shocks affect industries (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 et al., 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 co-evolutionary perspective is to study differences in technology variation across technology lifecycles. Anderson and Tushman (1990) argued that as a product class matures, it will be 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 lifecycles. 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 et al., 2019; Garud et al., 2014; Granqvist & Laurila, 2011; Seidel et al., 2020). In light of this observation, we can ask: Do producers take such expectations into account when designing novel technological offerings? How does it shape technology evolution?

Selection driven by environmental fit. Within each of the four perspectives, scholars hold in common that selection is driven by the fit between technologies and their environments, but they provide different explanations for what drives this fit (Basalla, 1988). Across the perspectives, scholars acknowledge 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 variants (Cusumano et al., 1992;

David, 1985). However, across the perspectives, scholars offer different—and, at times, incompatible—explanations for how 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 variants. In contrast, the economical perspective adheres to an explanation wherein the selected variant 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 adhere 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 co-evolutionary 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 ample 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 the sensory dimensions of products and aesthetics (Baldessarelli et al., 2022), play important roles in driving changes in demand and ultimately selection, yet these aspects are barely studied in tandem with economic and social forces (Eisenman, 2013; Rindova & Petkova, 2007). Similarly, we still have little knowledge about how social constructs such as power 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 et al., 2020). Table 6 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 mini-van, Rosa et al. (1999), for example, show how the dominant features of the mini-van 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 taken heeded their call to action, leaving the role of users in technology evolution black-boxed. Existing research tended to study users only when they also partake in the production of technological variations (Shah & Tripsas, 2007; Von Hippel, 1988, 1998), or to model user preferences in formal—rather than empirical—ways (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 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 in their behaviors and preferences, which could 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 non-technical 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 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 gate-keepers or external critics who facilitate exchange (Hirsch, 1972; Sharkey et al., 2022; Zuckerman, 1999). Market mediation may well explain why different technologies show different evolutionary outcomes. Although some studies peripherally hint 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). 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 et al., 2017).

To move beyond the existing literature, we must understand how the different drivers highlighted by the four perspectives co-evolve. Future studies can investigate how the different types of path dependence interweave the complex patterns of technology lifecycles, 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 (Rosenberg, 1982; Ozcan & Santos, 2015). Technological decline is thus another fruitful avenue for future research (Adner & Snow, 2010; Cusumano et al., 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 is 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 examine some form of technology discontinuity that triggers a process of substitution (Christensen, 1997; Eggers & Park, 2018; Utterback, 1994; Adner & Kapoor, 2016; Tushman & Anderson, 1986). Most empirical works examine 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 re-examined.

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 social changes suggests that the apparent stability of a social structure often brims with a series of incremental changes, negotiations, and reconstructions (Lawrence & Suddaby, 2006); these subtle adjustments can also lead to 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 changes. 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 (Henderson, 1995). Despite recent research efforts to nuance the disruptive impact of technological substitution (Adner & Kapoor, 2016), 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 are 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; Utterback, 1994; Tushman & Anderson, 1986). 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 smaller 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 if producers are able to redefine its value beyond solely functional and utilitarian properties (Raffaelli, 2019). This suggests a more nuanced understanding of technological substitution in which consumer preferences are co-constructed together with the technologies that are being offered. First Clark (1985) and, later, Kaplan and Tripsas (2008) pointed to feedback mechanisms between the evolution of demand and technology evolution; however, due to technology scholars' reluctance to draw on user-level demand side data, there are very few empirical examinations of these relationships.

Studies of technology evolution also tend to focus either on how the performance of technologies evolves along overlapping S-curves (Foster, 1986; Adner & Kapoor, 2016), or on the competition among technology designs within a technology lifecycle

(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 show that the variants 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 acknowledges 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 multi-dimensional depending on the heterogeneity of consumer preferences (Adner & Levinthal, 2001); other works are increasingly recognizing intangible sides of products' attractiveness, emphasizing consumers' emotional, sensory and symbolic needs related to values and identity construction, which have further complicated the picture (Eisenman, 2013; Raffaelli, 2019; Rindova & Petkova, 2007). Yet we still need a more elaborate theory of how different perceptions of technology performance and product attractiveness shape processes of technology substitution. By viewing technological performance as a multi-dimensional 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 disrupts the existing market and industrial structures, without considering the fact that changes in the socio-cognitive understandings that underlie demand typically take time, and sometimes may not occur at all. Each of the perspectives has pointed to different kinds of shifts in the social structures surrounding technologies, such as society, industries and categories (Bijker et al., 1987; Hargadon & Douglas, 2001; Nelson & Irwin, 2014; Powell et al., 1996). A broad observation is that, at times, technological discontinuities drive change in existing industries, categories or societal structures (Tushman & Anderson, 1986) and, at other times, give rise to new industries, markets or categories (Klepper, 1997; Tripsas & Gavetti, 2000), or even an entirely new product class (Kahl & Grodal, 2016; Rindova & Petkova, 2007; Hargadon & Douglas, 2001). Yet, at other times, 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 (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 spark 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 vs. computers).

We posit that a key difference between technological discontinuities that generate new industries and those that unfold within existing industries is the degree of overlap in performance criteria. For example, during 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 to hearing aids, when televisions disrupted the radio industry, there was the creation of both a new technology and a new label (televisions vs. radios). Radios and televisions differed on a variety of performance criteria (Faulkner & Runde, 2009); the consequence was that televisions only partly disrupted the radio industry, making it possible for radio to retreat into a market niche where it has survived to the present day. Further research is needed on the dynamics between technological change on the one hand and, on the other, the emergence and change in the cognitive categories that provide structure to these technologies. Scholars may, for example, examine in detail how changes in the multiple performance dimensions along which technologies are evaluated co-evolve with changes in the cognitive structures that are used to give meanings to these technologies (Rosa et al., 1999; Zunino et al., 2019). Furthermore, future research could investigate the conditions under which organizations strategically can exploit a technological change to recategorize or change the products' meanings (Granqvist et al., 2013; Lee, 2001; Pontikes & Kim, 2017) or to create a new category (Kennedy, 2008; Navis & Glynn, 2010).

Finally, many 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 can often hinder the selection of otherwise promising technologies (Hargadon & Douglas, 2001; Rosenkopf & Tushman, 1998; Ozcan & Santos, 2015), 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 (Abbott, 2014; Barley, 1986; Nelson & Irwin, 2014). This raises important questions about when we should expect technological changes to challenge (vs. entrench) the power distribution among market stakeholders. For example, in the wake of rising concerns about the power of technology platform providers (Parker et al., 2016), commentators and policy makers are increasingly raising questions in society about the ethics and regulation of platforms and information technology that could benefit from such insights.

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

The role of structure vs. 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 vs. 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 social structures have been deemed particularly important. The first is the technological structure itself (Clark, 1985; Rosenberg, 1963); 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 sub-components with which they have interdependencies (Baldwin & Clark, 2000; Murmann & Frenken, 2006). The automobile, for example, has sub-components 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 acknowledge 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 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 et al., 1996; Powell & Grodal, 2005). 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 also emphasizes 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 et al., 2015; Suarez & Lanzolla, 2008).

For example, although Hargadon and Douglas (2001) show how the structure of the existing gas distribution system shaped the structure of electricity distribution, they also detail 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 et al. (2002) show 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 amongst actors within the constraints of a technological structure. Although the agentic manipulation of technological structures has received some attention in relation to technology lifecycle 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 economical 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 (Gawer & Cusumano, 2014; Boudreau, 2010). The current literature on platforms also raises 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 thus raises 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 technology being examined across digital platform 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. 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 co-evolve at the different levels of analysis? How does the design of a platform shape the evolution of technology at the level of complementors?

Re-opening the Black Box of Technology Evolution

Our review found, counterintuitively, that most papers on technology evolution are not written with the specific aim of studying technology evolution. First, the most important papers on technology evolution tend to be theoretical in nature. Second, the majority of empirical papers that examine technology evolution are not written with the primary goal of studying technology evolution. Lastly, the papers that do study technology evolution tend 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 often portrays 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 study technological evolution, per se, 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 co-evolutionary dynamics between technology evolution and the variables of interest (see also Adner and Kapoor's (2015) diagnosis of the literature on technology diffusion for a similar observation).

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 et al., 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 lifecycle 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 et al., 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 catalogues (Rosa et al., 1999), have previously proved to be fruitful data sources for studying technology evolution at the artifact level.

Developing a co-evolutionary 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 (QCA), which facilitates inference, even with a moderate quantity of observations (Fiss, 2011). Future studies should 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

(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 co-evolutionary dynamics among technological, economic, cognitive and social factors.

In 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: technological 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 suggest that variation is primarily driven by recombination, selection is driven by fit with the environment, and that 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 give precedence to technological, economic, cognitive and social factors as driving these dynamics. To combine these insights and advance the literature, scholars must adopt a co-evolutionary 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, yet such efforts are necessary to reignite the literature on the evolution of technology.

Chapter 2

VISION-REALITY GAP: THE CO-EVOLUTION OF DISTANT VISION AND TECHNOLOGY IN THE FIELD OF ROBOTICS (1921–2020)

INTRODUCTION

Recently, scholars have highlighted how the socio-cognitive understandings of a technology affect industry dynamics, particularly focusing on frames, schemas, or categories used to make sense of an emerging technology (Bingham & Kahl, 2013; Grodal, Gotsopoulos, & Suarez, 2015; Kaplan & Tripsas, 2008; Navis & Glynn, 2010). This literature has largely attended to the understandings of a technology that already came into existence—for example, how stakeholders developed the schema for understanding the product class *computer* when it was already out in the market (Bingham & Kahl, 2013). However, cognitive understandings and discourses about technologies are not confined to technologies at present—in fact, entrepreneurs, researchers, investors, and other stakeholders in a technological field often have a conception of what is desirable and possible in the future, even though it is not tightly grounded on an existing reality. For example, entrepreneurs engage in storytelling about future expectations (Garud, Schildt, & Lant, 2014), build prototypes and concepts for future products (Seidel & O'Mahony, 2014), and envision radical and even revolutionary changes in the society and economy (Grimes, 2018; Zuzul & Tripsas, 2020). Although the literature has touched some elements of the forward-looking social cognition, few empirical studies systematically examined the role of what I term "technological vision”—mental representation of what is technologically desirable and feasible in the future—in the course of technology evolution.

The dearth of studies on this topic is surprising given that many new technologies are steeped in discourses about their potential future (Goldfarb & Kirsch, 2020), and the time lag between the initial conception of a technology and its industrial manifestation can often be decades (Kaplan & Murray, 2010; Moeen & Agarwal, 2017). As a class of technologies develops over a long period of time, the technological vision that shapes its direction co-evolves. In other words, the changing socio-cognitive understandings of what is desirable and feasible, how distant the vision is from the present state of the world, and how fast the envisioned future is approaching emerge (Crilly, 2017). The importance of forward-looking temporal understanding of a technology was mentioned in the canons in the literature—for instance, Rosenberg (1983) stated that “expectations concerning the future course of technological innovation are a significant and neglected component” (Rosenberg, 1983: 104). These expectations and visions of a technology shape and are shaped by the unfolding pathways of the actual technologies. Thus, I ask: how do technological visions co-evolve with the actual technologies?

Studying the role of technology visions in technology evolution is important because it sheds light on the several puzzles that are less explained in the existing literature. First, significant scholarly attention has been devoted to how product innovation happens at the organizational level or industry level (Garud, Tuertscher, & Van de Ven, 2013; Seidel & O’Mahony, 2014). However, in many cases, transformational technologies often emerge from large-scale innovation projects that aim to create a new class of product that would bring a discontinuous change (Bresnahan, Greenstein, & Henderson, 2011). An abstract cognitive representation of future often guides the collective efforts of field participants, and helps them coordinate (Bechky, 2003; Gavetti & Levinthal, 2000). When innovation is driven at the field level which involves diverse groups of stakeholders and costs a significant amount of resources, the anticipated technologies must be desirable and feasible in a reasonably near future, though not necessarily immediate. This type of distant forward-looking cognition, which I term "technological vision," can be broad and abstract without a concrete mental map of how to realize the conceived ideal (Grodal & O'Mahony, 2017). A technological vision is a guiding principle, rather than a concrete plan or blueprint, that is broad enough to mobilize people from diverse backgrounds. This can also explain the persistence of field participants in long-term innovation projects when such an endeavor often comes to fruition in no less than decades (Moeen & Agarwal, 2017). Without understanding the role of technological visions, one cannot fully apprehend how an organizational field centered around a technology evolves in the long-term (Zietsma, Groenewegen, Logue, & Hinings, 2017).

Second, extant studies on the evolution of technology have devoted less attention to how the temporal expectation of envisioned technologies—the rate at which the promised future is approaching the present—interacts with the actual technological progress. While several scholars suggested that innovation occurs based on the cumulation of incremental changes (Allen, 1983), more recent literature has begun to point out that the overall rate of innovation in a particular field can be accelerated or slowed down by a variety of factors (Furman & Teodoridis, 2020). Simultaneously, Rosenberg (1982) emphasized that field participants including producers and potential users often form a perception of what would be the potential future improvements. Explicating the co-evolution of field participants' subjective perception of potential future and the actual technological progress might provide a hint on an empirical puzzle: Why is the amount of investment and attention towards a certain technology so volatile while the actual rate of technological progress tends to gradual and cumulative? In the history of many technologies, we observe a period of time in which investors and stakeholders are extremely excited about a nascent technology, only to be followed by a period of disillusionment and disengagement (Goldfarb & Kirsch, 2020; Pontikes & Barnett, 2016). Both the over-excitement and ensuing cynicism bring challenges to the pursuit of a technological vision in a linear and constant way (Moeen & Agarwal, 2017; Vincenti, 1990). Thus, how field participants resolve the tension between volatile expectations and the more gradual, actual rate of technological progress remains an important puzzle in studying the evolution of technology.

Third, it is difficult to account for large changes in the direction of technological progress without considering the role of technological visions. If field participants are just driven by their understanding of the existing technologies and their immediate implications, why do we often experience the emergence of an entirely new field? In particular, we need an explanation of how heterogeneous actors are brought together to spur the emergence of a field, because it is unlikely that they engage in a coordinated action without a shared understanding of the direction (Grodal & O'Mahony, 2017). If people search for new technological solutions only based on their existing expertise and mental representation of the existing landscape (Feduzi et al., 2022), why triggers people from distant domains with very little existing common ground to interact and collaborate with one another? Complex patterns of recombination that span across a field would be enabled by this type of coalescence, and such coalescence would not happen if each participant focuses only on their own local innovation goals (Beckert, 2016; Jasanoff & Kim, 2015). Technological visions propose how heterogenous people across different sectors with different incentives coalesce to propel a new technological direction.

In order to examine the overarching question of how technological visions co-evolve with the actual technological progress, I conducted an in-depth longitudinal qualitative study on the evolution of the field of robotics over the last 100 years. This paper primarily suggests that in a future-oriented field, the direction of technology evolution is largely shaped by the field participants' attempts to narrow the vision-reality gap—the perceived temporal gap between the distant vision and present reality. I identify six distinct mechanisms—linking means to the vision, setting a medium-term vision, sequencing, decomposing, reconstructing, and reintegrating—through which field participants strive to narrow the vision-reality gap. I also find that vision-reality gap is extremely volatile, and can rapidly expand and contract when salient artifacts (or reverse salients) emerge. In this study, I contribute to the socio-cognitive view of technology by highlighting the role of forward-looking cognition in technology evolution.

CO-EVOLUTION OF TECHNOLOGICAL VISIONS AND PROGRESS

Technological Visions as a Driver. Developing a new class of technological products often requires interactions and collaborations among distinct communities (e.g. different industries, academia, non-profit organizations, or government agencies). The extant research has demonstrated the complex patterns of collaborations and coalescence that occur at a broad field level in different classes of technologies (Rosenkopf & Tushman, 1998). For example, product developments in nanotechnology require a large degree of integration and convergence of research disciplines that span start-ups, regional initiatives, and research facilities (Robinson, Rip, & Mangematin, 2007). However, a fundamental question—how do these diverse participants begin collaborating on developing a new class of technology in the first place?—has often been left unexamined. It is difficult to explicate what exactly initiated the conversations between actors as heterogenous as chip manufacturers and pharmaceutical researchers without examining how the vision of creating "nanotechnology" itself emerged (Grodal, 2018). While much research on recombination between knowledge from distant and heterogeneous groups emphasizes that such recombination contributes to the advent of a new class of technology (Fleming, 2001), those studies often overlook the cognitive underpinning that enables the recombination of distant knowledge. A visionary preconception of non-existent products and technologies often precedes the actual field mobilization and collaborations between diverse disciplines (Augustine et al., 2019). Recombination does not occur in a vacuum of visions, but it often takes place when participants in distinct communities share a technological vision of what would be technologically desirable and feasible in a reasonably near future (Kneeland, Schilling, & Aharonson, 2020). Without such a shared cognitive understanding, those communities would often not be in a conversation with one another.

Understanding how technological visions can help cohesion and convergence across an emerging field is particularly important as more and more research and development efforts go into complex large-scale technological projects such as robotics, gene editing, or the creation of quantum computers (Cusumano, 2018). Previous research on technology evolution has often been focused on a particular industry in which industry members are relatively homogeneous, or a firm-level analysis. While an industry might be an appropriate unit of analysis for many relatively small-scale technologies such as hard disk drive (Christensen, 2015) or digital camera (Tripsas, 1997), the development of complex, large-scale technologies such as robotics or large biomolecular drugs cannot be fully understood without investigating what is the driver of their development at a field level, and how that driver interacts with the actual technological progress. While many studies on fields have underscored the importance of a shared cognitive underpinning that helps a field coalesce and converge (Fligstein & McAdam, 2012), the field-level pursuit of technological visions can be complicated by a number of reasons, which necessitates a careful examination of the process of how technological visions and the actual technological progress unfold in an evolutionary manner.

Technological Visions and the Actual Technological Progress. While technological visions are important in mobilizing an early field, many scholarly works imply that the question of how the visions could actually be implemented in the process of technology evolution is also, if not more, important. For example, in a study of how NASA leaders motivated their employees with the organization's ultimate aspirations, Carton (2018) argued that leaders' visions for an organization can be a double-edged sword which can both help motivate organizational members, and dispirit members with the spread of skepticism and loss of a direction (Langeler, 1992). Many studies on organizational fields allude that similar dynamics could occur at the field level. Grodal and O'Mahony (2017) suggest that while an overarching field-level goal helps mobilize an organizational field, the goal's sheer breadth and ambition can also posit the problem of how to identify concrete goals against which field participants can measure their actual efforts. In high-technology fields, three assumptions need to be questioned in order to further our understanding of how technological visions co-evolve with the actual technological progress. First, technological visions can motivate participants to connect to one another's knowledge and advance towards the shared goal together, but what if the technological visions do not unfold as they were envisioned? For instance, Carton (2018) pointed out that leaders offered their organizational members a structural map of how their everyday work would connect to the ultimate aspirations that were broad and visionary. At the field level, field participants might also discuss a blueprint about how the ultimate visions would be materialized in the future (Garud et al., 2014). However, a large portion of the research is left undone with regards to what would happen when the technology does not progress as it was promised in the cognitive map or blueprint of the future. It is well known that the evolution of technology is fraught with uncertainty, unexpected obstacles, and alterations (Rindova & Courtney, 2020). In order to understand the process of the unfolding of technological visions in an emerging field, we first need to understand what will happen when the blueprint goes amiss.

Second, scholars have tended to overlook the fact that in the evolution of a large technological field, the development of different components or sub-fields does not necessarily advance at the same rate. Questioning the assumption of a uniform rate of sub-field developments is important, particularly in a technological field in which a large degree of integration is required between sub-fields to advance the ultimate technological vision. For example, in the evolution of a digital computer, the early field had been stalled for a long time in the early 20th century although they had the basic design of logic circuit, because the development of sub-components such as vacuum tubes did not catch up with the development of underlying mathematics (Rosenberg, 1983). In other words, the stall of progress in one sub-field can deter the development of the whole field. In his study of the proliferation of electric networks, Hughes (1978) aptly pointed out that, and referred to a stalled sub-component or sub-field as a “reverse salient” in that if a whole technological field is likened to an advancing battle line or military front, the reverse salient is a section that has fallen behind the front line. This reverse salient can play a role as an important design constraint, and deter the realization of technological visions as it was promised. There have been few scholarly examinations on how the uneven progress in different sub-fields influence the perception and actualization of technological visions in a field.

Third, while the extant research has often assumed linearity in the development of a field (Meyer, Gaba, & Colwell, 2005), it has not provided sufficient explanations for a high level of volatility that prevails in many technological fields. The vast majority of studies in the evolution of technology have focused on the linear understanding of evolution—for instance, the era of ferment triggered by early technological variations, followed by the rise of a dominant design and retention (Anderson & Tushman, 1990). Recently, more studies have begun to point out that the evolution of technology is not as linear as previously assumed, and to illustrate more non-linear and complex processes of technology evolution (Adner & Kapoor, 2016; Anthony, Nelson, & Tripsas, 2016; Raffaelli, 2019). These studies, however, still did not pay enough attention to the phenomenon in which a technological field often receives highly volatile attention, expectations, and resources—in other words, a class of technology is often exposed to over-expectations and hypes at one point in time, only to be followed by disappointments and divestments at another time (Goldfarb & Kirsch, 2020; Pontikes & Barnett, 2016). Often, the perceived gap between the promise of a technological vision and the actual progress in reality is highly volatile, particularly in comparison to the actual technological progress, which seems to be more gradual in many cases (Fenn & Raskino, 2008). The high degree of variance in expectations across time is under-examined in the literature, and merits both theoretical and empirical explanations.

This study suggests that when a distant vision is linked to an emerging technological means, it narrows the perceived temporal gap between the distant vision and reality, and thus catalyzes interests, enthusiasm, and the initial mobilization of a field. A salient success can easily contract the vision-reality gap to an extreme extent, leading to overcommitment of resources. However, when such unrealistic expectations collapse and the audiences are disillusioned, the subjective vision-reality gap can be expanded to a level that delegitimizes the field. In order to maintain legitimacy, the field participants deploy various mechanisms through which to narrow the vision-reality gap again—including decomposing and restructuring the features of the vision.

METHODS: Setting and Data

In order to examine how technological vision is constructed and changed over the course of the technology evolution, I conducted an in-depth qualitative historical case study of robotics using longitudinal, archival data spanning from 1921 to 2020. Robot is an extreme case of technological vision (Eisenhardt, 1989) in the sense that it began as an extremely distant fictional imaginaries (Beckert, 2016) and slowly became the distant, yet tangible technological vision pursued by researchers, entrepreneurs, and government agencies. The term *robot* was first created in a science fiction play titled R.U.R. ("Rossum's Universal Robots") in 1921, which inspired inventors around the world to build machine artifacts that mimicked and imitated human features and functions. I focus on the evolution of the collective technological vision that the field participants pursued in the broad field of robotics, rather than a specific type of products such as robotic arms (Barrett, Oborn, Orlikowski, & Yates, 2012; Kaplan & Tripsas, 2008; Roy & Sarkar, 2016).

For the study of the evolution of robotics, I collected (a) 1,354 articles that include the term "robot" in the magazine Popular Mechanics between 1921–2020, (b) 54 early academic and technical papers written by AI researchers between 1962–1972 (to cover the period in which the term "robot" traversed from science fiction to the parlance of academic science), (c) 2,278 articles from the oldest trade journal *Industrial Robot* between 1973–2019, and (d) further articles from other short-lived trade journals such as *Military Robotics*, and *Robotics World.* For triangulation and a richer understanding of the social and scientific contexts, I also relied on four books written by prominent roboticists and science historians. Table 7 demonstrates the list of archival data.

In order to investigate the overarching question of how technological visions shape technology evolution, I conducted an in-depth longitudinal qualitative study of how the field of robotics evolved over the last 100 years (1921–2020). The concept of "robot" was first created as a distant imaginary (Augustine et al., 2019) in a science fiction play titled *R.U.R. (Rossum's Universal Robot)* in 1921. Since the 1960s, with the advent of digital computers and numerical control technologies, the distant imaginaries have spawned more concrete *technological visions* that inspired entrepreneurs and scientists about what is technologically possible and desirable in the future. Despite the growth of the field of robotics as a solid industrial and scientific field, the primary imaginary associated with the concept "robot" as "mechanical men" in the public mind proved to be strikingly persistent over time.[2] The persistence of this imaginaries also influences the repeating revival and resurgence of technological visions over the course of the field evolution. The persistence of such perceptions make the case of robotics an extreme case

[2] In an analysis that is not fully reported in this proposal summary, I constructed the list of movies that contain the term "robot" in their titles or synopses. I found out that over 90 percent of robots depicted in those movies have been consistently shown as humanoid robots over the last 100 years.

of technological visions (Eisenhardt, 1989).

I use longitudinal archival qualitative data to study the evolution of the field and associated industries of robotics. Table 7 summarizes the data. For the field-level analyses, I constructed the set of data that span four trade journals, one technology magazine and two science magazines, congressional hearings, and historically seminal academic articles in robot-adjacent fields. I also relied on four books written by prominent roboticists and science historians to understand the deeper history of underlying technologies. Three books provide a nice overview of the history of artificial intelligence and computer vision (Brooks, 1999; Crevier, 1993; Nilsson, 2009). Roland & Shiman (2002) provides an in-depth overview of the role of the military community and, particularly, an agency called DARPA (Defense Advanced Research Projects Agency).

Figure 7 delineates the data analysis process. Motivated by the initial puzzle of “how the field of robotics evolved over time,” I first created the basic timeline of robotics by collecting and analyzing the 1,354 articles that contained the term “robot” from *Popular Mechanics*, one of the longest-running popular technology magazines over the last 100 years. From the timeline, I identified initial theoretical constructs such as visionary aspirations, limitations of technologies, solvable and achievable goals, hype and disillusionment. Then I triangulated this initial historical understanding with early trade journals reporting on the industrial robot (robotic arms) industry, and the deeper history of how underlying technologies came into being. The knowledge about the underlying technologies came mostly from carefully selected books. From this triangulation, I identified more refined, abstract theoretical constructs such as the directionality and temporality of technological visions, intermediary goals, and reverse salient. In the latest data analysis step, I collected further data in order to have a finer grained understanding of what happened in the emerging robot-related industries such as mobile robot industry and self-driving car industry. This triangulation helped solidifying the mechanisms by which technological visions and technology in reality co-evolve, as depicted in the process model in Figure 9. I aim to iterate further between data analyses and theory building until I reach a level of theoretical saturation.

Insert Table 7 about here

Data Analysis

I analyzed the data drawing on inductive methods to develop a process theory (Grodal, Anteby, & Holm, 2020; Langley, 1999). Figure 7 provides an overview of our data analysis process.

Insert Figure 7 about here

Stage 1: Puzzle and first-round coding. I began my initial analysis of the data with a puzzle focused on how the concept of a robot and the field of robotics evolved. To begin to shed light on this puzzle, I first identified and collected a technology magazine named *Popular Mechanics* because of its span of 100 years and its focus on mechanic technologies. I identified 1,354 articles that included the term robot or robotics, and constructed the basic timeline of the types of featured robots, and conducted a first-round open coding of data. I particularly focused on the earliest robot artifacts and how they drew on the archetypical image of robots based on the original science fiction concept of a robot. From the data, I also observed the sudden rise of interests in industrial robots in the 1980s, the decline of the interests, and the gradual rise of interests in alternative types of robots which were extremely diverse in their forms and applications.

Stage 2: Identifying initial theoretical themes. After the first-round coding, I focused on grouping codes that were relevant to the evolution of the concept of a robot and the field of robotics, and identified initial theoretical themes (see Figure 7). I found that the original science fiction concept and public fascination associated was influential to a varying degree throughout the period of the data, and I theorized it as what could be called aspirations or visions. I also found out that the concept of a robot fluctuated over time, and it seemed to be related to the changes in the field of robotics such as hype and disillusionment. I began to consider a theoretical framework in which the concept of a future technology and the actual development of a field co-evolves over time.

Stage 3: Identifying underlying technologies and sectors. Realizing that the initial *Popular Mechanics* magazine did not offer sufficient explanations of how certain types of robots emerged and why, I engaged in a systematic examination of underlying technologies of robotics, mainly relying on four books I collected written by prominent roboticists. From this process, I found three sectors that had distinct visions and contributions to the field of robotics—namely industry, academia, and government (or military) sectors. Based on the new in-depth knowledge, I identified core data that would allow me to track changes in discourses in each of the three sectors.

Stage 4: Identifying phases. From the analysis of the data identified in Stage 3, I have gotten to a deeper understanding of technological visions and the evolution of sub-fields. The analysis of trade journals, internal technical memos, and scientific papers provided me with a detailed understanding of how technological visions changed over time in each of the sectors. I obtained a concrete understanding of technological visions and the field of robotics for each phase, what were the events that triggered each phase.

Stage 5: Identifying refined theoretical constructs. The concretization of phases, trigger events, and each sector's role in the co-evolution of visions and field development allowed me to refine the theoretical constructs. From the reiterative data analysis process, I refined the construct of technological vision, and identified what constituted the technological progress—rate and direction. I further elaborated that there were two modes of rate throughout the research period, which was *modest* and *accelerated*, and three modes of direction which was *integration*, *fragmentation*, and *reintegration*.

Stage 6: Final mechanisms. By integrating the initial mechanisms identified in stage 2 with the new refined theoretical constructs *technological vision* and *technological progress*, I identified and elaborated nine mechanisms that explain how technological visions co-evolve with the actual technological progress. Each phase comprises two mechanisms, the first of which is about how field participants envisioned the future of the technology, and the second about how the field of robotics changed accordingly. Table 8 provides an overview of the phases.

Insert Table 8 about here

FINDINGS

The findings delineate how the technological visions of creating robots co-evolved with the actual technological progress in the field of robotics between 1921 and 2020. Figure 8 delineates the time trend of the relative frequency of the term "robot" reflected in Google n-gram and *Popular Mechanics* during the time period. I detail the temporal development below.

Insert Figure 8 about here

Pre-phase: Distant Technological Vision (1921 – 1944)

The idea of creating an automaton has long existed in the imagination of humankind (Mayor, 2018). However, the first popular conceptualization of mechanical men as a technological device that serves human needs, rather than a mystical imagined creature, came out in 1921 in a science fiction play called "Rossum's Universal Robot (R.U.R)." Karel Čapek, a Czech playwright, derived the term "robot" from a Czech word "robota" which meant serf labor. In his play, he envisioned robots as mechanical servants that assisted their human masters (and ultimately revolted and annihilated humans). The play was widely successful in both Europe and the United States, and the concept of robot disseminated into other types of science fiction media such as novels and motion pictures in the following decades.

While the science fiction play tapped into the deep anxiety about machines replacing human labor experienced during the industrial revolution, the concept also fascinated many inventors on both sides of the Atlantic. Since the 1920s, many inventors built large-sized mechanical men that were electrically controlled, designed to imitate human movements and functions such as "answering the telephone, starting and stopping machinery, and reading the water gauges at reservoirs" (*Popular Mechanics*, Jan 1928). These expensive electric dolls, to which inventors often devoted several years of their lives, were mostly used for entertainment and advertisement purposes. For example, in 1938, engineers at the Westinghouse Electric Corporation built a seven-foot-tall robot named Elektro, which toured many American fairs and conventions in the next decade as an advertisement device for the company.

Although the robot artifacts were able to imitate human movements to a limited extent for the audience's amusement, there was no underlying technology that would enable those artifacts to operate without direct human control. The robot artifacts had very limited real-world applications, and the technological vision of creating mechanical men that have practical use was considered extremely distant from the reality. For example, a *Popular Mechanics* article in 1933 quoted an engineer saying: "[the senior management] want us to make an automatic charger. Might as well ask us to build a robot able to play the piano by ear." In this blunt statement, robot was summoned as a metaphor of unrealistic technological expectations.

In this pre-phase, the perceived temporal gap between the technological vision of creating mechanical men and the present state of technology was vastly distant. Engineers and the public projected the technological vision to an extremely distant future. The vision was perceived as a fictional imaginary.

Phase 1. Linking Novel Technological Means to the Distant Vision (1945 – 1978)

Novel technological means. There were two major technological triggers that narrowed the perceived gap between the distant vision of creating robots and the present state of technologies. The first technological trigger was the advent of numerical control, a technology for precisely controlling the movement of large metallic machines using three-dimensional coordinates. This technology inspired inventors and entrepreneurs to build potentially useful machines. The second one was the emergence of digital computers after World War II. Despite being bulky, costly, and only available to a few labs around the world, this technology inspired a small group of scientists to investigate the parallel between machine and human intelligence. The two lines of technologies would be cross-pollinated soon.

Linking the Novels Means to the Distant Vision. In 1954, an inventor named George Devol patented a machine that was designed to move an object with a hand-like manipulator using the novel numerical control technology. The inventor met a young engineer named Joseph Engelberger and told him about his invention at a cocktail party. The young engineer immediately linked the idea of a seemingly mundane machine to the concept of "robot." Envisioning the future of manufacturing transformed by these "robotic arm" machines, Engelberger quit his job, co-founded a company named Unimation with the inventor, and took on an early "uphill battle to persuade skeptical U.S. manufacturers to employ his programmable arms" (Bloomberg, 1997). He linked the novel technological means to the distant vision, and in so doing, narrowed the perceived gap between the vision and present reality.

The emergence of this experimental market coincided with similar projects by emerging computer scientists. In pursuit of finding the parallel between machine and human intelligence, in 1962, a PhD student at the MIT Artificial Intelligence lab created the first programmable hand-like machine. In his dissertation, he linked his novel technological means to the distant vision of creating an automaton. He stated that:

> The idea of building a mechanical hand to be operated by a digital computer was originally presented by Shannon and Minsky during a seminar at the Massachusetts Institute of Technology in the fall of 1958. … The first mechanical arms that we know of were built by the ancient Egyptians … which does point out the existence of some kind of primordial interest in machines resembling human beings and imitating human actions. I can testify to the fact that this interest still exists, at least in most of the people who have met my mechanical hand. (Ernst, 1962)

The invention of the programmable machines was considered one of the most unexpected successful side projects of the artificial intelligence research. In 1964, two researchers at the Stanford Research Institute began to think about the possibility of building a wheeled mobile automaton[3], and wrote a proposal to the Department of Defense. Ivan Sutherland, the then-director of the Advanced Research Projects Agency (ARPA) and a central figure in computer science, soon approved the plan to develop "intelligent automata" for potential military reconnaissance applications. Over half a decade, the SRI team developed the first mobile robot Shakey, which could move around a floor and perform rudimentary reasoning about the environment. Although the immediate application was not clear, the development of Shakey excited a great deal of

[3] The use of the word "robot" in academia was not settled yet at this point in time. The use of the term in academia began to be stabilized around the late 1960s.

interest from academic researchers, and laid the foundation of the academic community in the field of robotics. While the early industrial and academic communities in the field of robotics were forming, the government did not exhibit a great interest at this stage. There was a funding cut for the mobile robot Shakey in 1972 due to a negative assessment of its prospect in practical applications, although there were still fringe interests about its space applications from NASA.

Different Communities Converging on the Distant Vision. The technological visions of the industrial and scientific communities soon began to coalesce and cross-pollinate. On one hand, scientists recognized that their computer-programmed moving machines had a promising industrial application (Pieper, 1969) such as the industrial robot Unimate. More scientists started developing robotic arms (McCarthy & Hayes, 1981). For example, a Stanford team developed a promising hand-eye system that used a TV camera and primitive computer vision (Nilsson, 2009). On the other hand, the fledgling industrial robot industry also became aware of the research going on in artificial intelligence laboratories. Victor Scheinman, one of the important early inventors from Stanford, remembered that the industrial community was searching for academics who would work on robotic arms:

> In 1968 or maybe ’67, there were a couple of guys. One was named Joe Engelberger and another one was named George Devol [the founders of Unimate]. … He wanted to give some money to somebody at Stanford as a fellowship to work in robotics and Stanford picked me. … I got to travel with George and with Joe to Unimation in Connecticut and around the county looking at early robot installations in factories and finding out what was available.

Unimation and the other emerging competitors kept trying to attract manufacturers. In the mid-1960s, they began to sell early industrial robots to both domestic and international manufacturers. A few manufacturers in Japan and Europe began to experiment with the idea. In 1969, General Motors rebuilt a plant in Lordstown, Ohio to experiment with the idea of having Unimate arms perform spot-welding. With the slow and gradual growth, in 1973, the first trade journal *Industrial Robot* was launched. The first article of the first issue of the journal announced that:

> (Contemporary) machines are generally blind, deaf, dumb and moronic. … With modern techniques of information processing and machine control the emancipation of man from mental as well as physical drudgery is within our grasp. … the search for 'versatility' is the 'new' challenge to technology in the field of industrial automation. (Industrial Robot, 1973)

While achieving "emancipation of man from mental and physical drudgery" and "versatility" was still an extremely abstract and distant technological vision, many scientists and entrepreneurs converged on building and improving robotic arms as a medium-term goal, or medium-term vision. During the 1970s, the number of academic articles about programmable arms gradually increased, although the subject did not have its own journal.

Overall, triggered by the novel technological means, the early industrial and academic communities converged on the shared distant vision of creating robots. Particularly, they converged on the medium-term vision of creating and improving robotic arms that held more concrete promises for potential markets. The link between the novel technological means and distant vision, and the creation of medium-term vision narrowed the perceived temporal gap between the distant vision and reality. This helped mobilize the initial field.

Phase 2. Narrowed Vision-Reality Gap (1978–1986)

The First Commercially Viable Artifact. The collaborations between industrial robot entrepreneurs and artificial intelligence researchers culminated in the creation of the PUMA Arm in 1978, which was considered a major commercial milestone. The arm was first designed by a Stanford researcher, and further developed by Unimation and GM. While previous industrial robots were bulky, heavy and "took up a great deal of space," the "pint-sized PUMA, on the other hand, comes in models weighing as little as 75 pounds, and can fit in the space once occupied by a human worker" (Popular Mechanics, 1982 Sep). The reduction in size made the artifact much more commercially viable than previous ones. While the application of the robot was still confined to spot-welding, the sales increased rapidly. While there were only 200 industrial robots in service in 1970, as of 1980, 3,800 industrial robots were in operation in the US (Roy and Sarkar, 2016). The first commercially viable industrial robot served as a salient success that would draw a great deal of attention from the media, and as a consequence, vastly narrowing the perceived vision-reality gap.

Envisioning Sequences leading up to the Distant Vision. Though commercially viable, the application of the salient artifact was extremely limited—spot welding in automotive manufacturing. However, the industry and media showed frantic reactions to the coming of the technology. For example, a 1983 trade journal article stated that "robotics finally has achieved a self-nurturing momentum" and "by 1993 … work-a-day world will be the robot's oyster." (Industrial Robot, 1983). The expectation was built that the future of "robots autonomously working in factories and replacing human workers" will come in an extremely near future. For instance, a 1982 *Popular Mechanics* article proclaimed that:

> Real robots don't look like us. … The term *robot* has [now] come to refer to any programmable machine that performs some type of work. While US industrialists originally shied away from investing in anything as "sci-fi" sounding as a robot, they are now clamoring for … the automatons. … The age of seeing, feeling robots is coming. Finally, we're entering the first stages of a robot revolution.

The industry was also brimming with optimism. Although the initial market for spot welding was tiny, the industrialists held a belief that the initial market will serve as a steppingstone towards the realization of more glorious technological visions—e.g., robots working on assembly lines, or service robots penetrating home environments.

This mental connection between the initial salient success and the future realization of greater technological visions was enhanced by forecasting, or envisioning sequences of the future progress. To be fair, the industrialists were aware that the initial market for spot welding was a niche one and would be saturated in the coming few years. The industrial community, however, shared a vision that robots would be able to take up more complicated jobs in the factory settings such as picking up items, assembling components, and other tasks that would require more "intelligence." For example, the president of a robotic firm attending a conference in Detroit stated that "while the current ratio of activity is 80/20 in favor of welding, this will change to 80/20 in favor of assembly in the next three to five years." (Industrial Robot, 1980).

Second, the industrial community believed that improving computer vision would be the next core step in order to narrow the vision-reality gap. They were also optimistic about this envisioned step. For example, Joseph F. Engelberger, the founder of Unimation, attended a workshop for "leading representatives of USA robot researchers, manufacturers and users" in 1979. A forecast was made in the workshop:

> One of the exercises was a Delphi forecast and some of the conclusions that emerged from this workshop were:
>
> 1. The most desirable sensory capabilities are simple vision and tactile sensing. …
>
> 2. There is a strong consensus among all participants that simple vision is the number one priority for research and development efforts. …
>
> 3. Sensory capabilities, including complex vision, are seen to reach commercial availability before 1985.
>
> (*Industrial Robot*, Dec 1979)

General optimism was pervasive that computer vision and more general-purpose robots would be achieved within a few years. The industrial community envisioned the impending automation in factories, and even discussed the potential social ramifications. The success of the initial niche market was generalized into the future success of hypothetical technological visions, and this further narrowed the perceived temporal gap between the future vision and present state to a great extent. Predictions abounded that the robot revolution would arrive in the coming decade. An article in *Industrial Robot* claimed:

> The first and second generations of robots in use today, … incapable of seeing, feeling, or recognizing, will be relieved in the foreseeable future by the next generation of robots. And this could happen in even less than ten years.

The government also came to pay more attention to robotics, envisioning their own technological visions and potential future sequences. DARPA (Defense Advanced Research Projects Agency), a defense organization that is normally responsible for "carrying [distant ideas] to proof of concept" (Roland and Shiman, 2002), was the first government agency to fund robotics projects. Prompted by a few robot enthusiasts within the agency who envisioned the potential of mobile robots to transform warfare, DARPA set a small (relative to the scale of defense research spending) funding to support wheeled robot projects. The visionaries at DARPA, similar to their industrial counterpart, were optimistic about the future sequences of the robotics revolution. In fact, the computer vision experts at DARPA tended to be much more conservative about what computer vision and mobile robots can achieve in a near future, and considered the goal of the robotics program as "a real stretch." (Roland and Shiman, 2002). Despite the warning sign, the robotics visionaries remained optimistic and pursued the ambitious goal of creating autonomous land vehicles.

Catering to the intense interests from the industry and government communities, academia started promoting robotics as a legitimate scientific discipline. In 1982, the *International Journal of Robotics Research*—the first high-profile peer-reviewed journal dedicated to robotics—was founded. Its first editorial note stated that "the media, industry, and research sponsors are assured that the time for a surge in robotics has arrived." Overall, the technological visions from the industrial, government, and academic communities contributed to narrowing the perceived temporal gap between the technological vision and reality.

Overcommitment of resources. The optimistic projection of the future about the next stages of the technological development led to a surge of interest and (retrospectively) overinvestment into the robotics industry, to the extent that it was considered a “frenzy” (Industrial Robot, 1982). Robot exhibitions and industry conferences were overcrowded, and industrial communities often felt that they “totally underestimated the interest” from the public (Industrial Robot, 1980; 1982). Automotive manufacturers were often the primary driver of investment in the nascent robotics technology. During this period, General Motors was the largest customer of industrial robots and corporate funder of robot research, purchasing more than half of robot products in the early 1980s (Industrial Robot, 1988). The automotive executives considered robotics as a potential savior that would rescue the US automotive manufacturing from decline. Outside the automotive industry, electronics and engineering companies also invested in industrial robots in order not to miss out on the potentially promising technology.

In a similar vein, in 1983, DARPA allocated massive $30 million to the development of mobile robots and autonomous vehicles. A great deal of this investment went to academic institutions such as robotics programs at Carnegie Mellon University, MIT, and Stanford.

In Phase 2, overall, the salient success rapidly narrowed the perceived gap between the technological visions and the present state of technologies. The industry, government, and academic communities envisioned the future sequences of the robotics technology that would follow the salient success. High expectation was built up within the field of robotics and among the public.

Phase 3. Expanded Vision-Reality Gap and Deconstruction of the Vision (1987 - 2006)

Salient Failures. The initial market for spot welding in the automotive factories continued to grow until 1986, as the industrial community predicted or perhaps longer than that. However, as opposed to the prophecy about the arrival of next stage technologies, the robotics technologies did not progress fast enough to perform tasks such as assembly, detection of the environment, or navigation over terrains. The markets did not emerge for the next stage technologies that had struggled to advance, particularly due to the stall in computer vision. Around 1986 and 1987, there were economic signals that the spot welding market reached the point of saturation, and the industrial robot industry entered the stage of shakeout. The Japanese and European robotics companies rapidly caught up with the US pioneers (Roy & Sarkar, 2016), and in 1987, there was a major decline in profits and sales across the industry.

Disillusionment. The shakeout in the initial market immediately dampened the development of the field of robotics. In 1987, a trade journal article reported that:

> Robot growth rate falter[ed] in 1986. … Certainly there has been a lot of hype and possibly an overreaction to their capabilities. … This trend was predicted some time ago but it was expected that some of the newer applications would take over, in particularly assembly. This has not happened as quickly as expected. (Industrial Robot, 1987)

This hard reality crashed the inflated expectations about the future of robotics.

What drastically changed was the public perception of robots, and the interests of potential buyers and investors. In a New York Times article titled “Brave new world seen for robots appears stalled by quirks and costs,” the writer stated that “robots’ best year was 1987, when 6,219 were sold, for $443 million. Shipments have not exceeded 4,000 a year since then … General Electric and Westinghouse have gotten out of the business entirely, and more than half the 50-some companies that were making them five years ago have disappeared” (Kilborn, 1990). Major funders such as GM and Ford began to divest and decreased their purchase of industrial robots, when GM still made up almost half of the industrial robot sales in the US. Corporate research labs were closed down, and many corporate researchers migrated to academia. While robotic companies were still making progress in finding new market applications and small niches, the public focused on the issue that big corporations ceased investment in robotics, and the big promise in the robotics technology became shattered.

The government community, or DARPA, was also disillusioned from the grand promises of robotics. In 1987, Jacob Schwartz, the new chair of DARPA, made a judgment that robotics and AI was not as promising as they were hyped, and decided to cut funding. According to Roland and Shipman (2002), while AI might be possible and promising, it was “nowhere near ripe.” Schwartz also likened the quest of robotics to rowing to the moon. “No matter how many galley slaves you put on the galley and no matter how hard you beat them, you are not going to row to the moon. You have to have a different approach” (pp. 274). However, what would be the next approach was unclear, and the DARPA simply cut funding for robotics. Government funding in large part “dried up.” A 1987 *New York Times* article stated:

> A major source of that challenge has been the failure of robotics to live up to its advance notices in the early 1980's, when it was touted as the industry of the future and the best hope for reviving America's manufacturing sector. Many of the robots … turned out to be less accurate, less flexible, weaker or slower than promised. (Feder, 1987)

The sense of crisis and disillusionment also spread into academia. Rodney Brooks, a prominent roboticist at MIT, recounted that in the mid-80s, scientists were already anxious that there was too much excitement out there. Computer vision, which turned out to be a core component for the advancement of most robotics technologies, was still primitive—despite the initial development in computer graphics. He said that “there were no vision systems around doing anything even remotely as sophisticated. The progress in computer vision was questioned. … SRI held a weekly seminar series [in 1984] to try to uncover the sources of the seeming stall in computer vision.” (Brooks, 1999). The vision of creating industrial robotic arms, which initially mobilized the field of robotics, lost its attraction as a guiding technological vision. In other words, the perceived gap between the technological vision and the present state became distant again.

Decomposing the vision. The disillusionment and subsequent divestments fragmented the fledgling field of robotics. First, the industrial community mostly shifted its attention to solving more concrete, narrower, and less visionary problems. They began to avoid mentioning grand technological visions altogether. Around 1988, robotics companies started adopting a different narrative. For example, the head of an engineering group at DeViliss said that “our approach is that the customer does not want to buy a robot—he wants a solution to a painting or a spraying problem" (Hollingum, 1988). Another company called Crocus was praised to have "a philosophy of meeting practical needs rather than displaying impressive but unnecessary technology" (Rooks, 1988a). The same year, the founder of Precision Robotics reverberated the sentiment by explaining that "the basic philosophy was that the company should be application-orientated, rather than robot-orientated. So we limited the performance of the robot to the needs of those applications, rather than try to make a universal robot that can do many things, but probably poorly" (Rooks, 1988b). The industrial community began focusing much more on incremental improvements of robotic arms, hands, and grippers, and gradually the industrial robot was accepted as a mundane and mature market, rather than something mesmerizing and visionary (Kilborn, 1990). The industry as a whole began to focus on local, incremental innovation goals.

Second, the government agency DARPA cut funding to the field of robotics, and retained only a limited amount of attention to the wheeled mobile robots (Roland & Shiman, 2002). They narrowed their focus on gradually improving the speed and navigation capability of autonomous land vehicles, without grand initiatives or blueprints.[4] DARPA established a small office dedicated to land vehicle, and granted a limited amount of funding to institutions that still held on to autonomous robot projects. They consistently invested around a few million dollars a year into the land vehicle technology, which was not a great amount relative to the standard of defense budgets.

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[4] Well-known companies such as iRobot and Boston Dynamics were founded around 1990 in order to pursue this direction.

While the DARPA took on a pragmatic approach, in response to the changing defense requirements, the US Congress started paying more attention to automation in the military. In 2001, along with the discussion that the US needs to avoid soldiers' casualties in combat zones, Congress demanded that a third of the military's ground combat vehicles be automated by 2015. Knowing that this was an unrealistic goal with the current rate of progress, the DARPA planned an event to facilitate the progress of this broad goal. This would culminate in the DARPA grand challenge in 2004 and 2005, which would be discussed as a triggering event that initiated the Phase 4.

Removing a reverse salient and reconstructing a new intermediate vision.

While the industry and government were pursuing narrower local goals compatible with existing technologies without resorting to a grand vision, academics were seeking their own near-term goals. First, a new approach called behavior-based architecture became popularized in the 1990s (Brooks, 1999) which aimed to build primitive intelligence, instead of human-level intelligence. There was an agreement that imitating human-level intelligence was an unobtainable goal in the near future, while the artificial intelligence and robotics research was stalled for years. The new approach characteristically aimed to have robots imitate the movement of primitive living organisms (e.g., insects), which was perceived as a nearer-term goal. Accordingly, the new class of mobile robots was designed to follow a few simple rules without sophisticated cognitive and control function that would require an impossible amount of computing power. Defining nearer-term, more solvable, and achievable goals, the new approach was successful in reigniting excitement among otherwise distraught roboticists.

The simplified goals also helped mobilize amateur roboticists, hobbyists, and engineering students, who were enthusiastic about tinkering with simpler forms of robots that could play table soccer or fly around. A magazine article stated that “across Europe, Japan, and the United States, roboticists are junking traditional control systems in favor of biology-inspired behavior” (Popular Mechanics, 1995 Jul). Robot competitions such as RoboCup and Battle Bot emerged as a way of boosting morale and building a community around these simpler and primitive robots. In addition to that, some academics began to explore more narrowed scoped, fringe applications such as having the robotic arm to assist surgery.

Describing these new approaches, a newspaper article in 1988 stated that:

> A diverse group of scientists, some with romantic inclinations shaped by the science fiction of the 1940's and 50's, is working toward a different sort of robot: the general-purpose robot. They are looking for a robot with true flexibility, true adaptability, a robot that knows where it is and even (this may be necessary) who it is. These researchers still hope to create the generalist, liberal-arts, renaissance robot. (Gleick, 1988)

Overall, the industry and government avoided discussing distant and broad technological visions altogether, while academia was the only community that still retained, to some extent, the flame of enthusiasm about the original technological vision of creating robots. All three communities focused on their own specific goals that did not cross paths with each other—the field was fragmented. For example, a trade journal article in 2002 lamented about the lack of conversations between academia and industry. They did not attend each other’s conferences anymore, and the two communities were widely segregated. The grand technological vision that used to bind different communities in the field was void at this stage, and each community was achieving a modest level of progress in the highly fragmented field.

Phase 4. Reintegration and Revival (2006–2020)

Trigger: A field-configuring event. As mentioned in the previous phase, Congress demanded one-third of the ground military units be automated, but the DARPA knew that it was an impossible goal with the current rate of progress. In February 2003, as an attempt to encourage new ideas about the mobile robot technologies, the DARPA announced a 142-mile race for autonomous land vehicles with a $1 million prize for those who finished its course the fastest. Jose Negron at DARPA recounted:

> The defense contractors that DARPA had been working with, they got stuck in a mind meld. They were thinking step by step, evolutionary, and they weren't progressing. So we needed a revolutionary approach, a leap forward, and I kept telling Tony there would be hundreds of people interested in joining us, people who do not do DOD business. People who work late at night, in their garages and bedrooms, because they love what they do.

In the first 2004 competition, no participant succeeded to travel more than 8 miles. In 2005, however, five vehicles covered the complete distance of 142 miles. This surprising and unexpected rate of progress caught the attention of the media, and the interest of many investors from high-tech industries. This government-driven event served as a field-configuring event in the field of robotics that reignited interests.

Reviving the latent vision. The concrete material reality of autonomous vehicles traversing the 142-mile desert path inspired excitement across the media, public, and perhaps most importantly, the leaders in other technology industries. Before 2006, there were only 15 robotics firms in the US that received venture capitalists' funding. However, the success of the Grand Challenge event caught the attention of some of the leading figures in Silicon Valley. First, a Silicon Valley billionaire investor Scott Hasan was greatly intrigued by what he observed from the DARPA Grand Challenge, and he went on to found an important robotics incubator named Willow Garage. Second, Bill Gates, the founder of Microsoft, also took particular interests in robotics after the event, and built a robotics unit named Microsoft Robotics Developer Studio. In 2006, he wrote an enthusiastic robot-related article at Scientific American:

> In 2005 five vehicles covered the complete distance [at DARPA Grand Challenge]. … Despite the difficulties, when I talk to people involved in robotics … the level of excitement and expectation reminds me so much of that time when Paul Allen and I looked at the convergence of new technologies and dreamed of the day when a computer would be on every desk and in every home. … The robotics industry could make the same kind of quantum leap that the PC industry made 30 years ago. (Gates, 2007)

Third, Sergey Brin and Larry Page, the founders of Google, were also inspired by the event, and they approached the winners of the 2005 DARPA Grand Challenge at Stanford to join a Google skunkwork unit to develop autonomous land vehicles. This move was part of the broader trend of the formation of the self-driving car community, which emerged as an important spin-off from the field of robotics after the Grand Challenge event. Whether it was Bill Gates' vision of "robots in every home" or Brin and Page's vision of developing self-driving cars, the field-configuring event helped revive the technological vision of developing robots that had been latent and often avoided.

While the new sources of money were flooding in, existing manufacturers of industrial robots (or robotic arms) became increasingly excited about the idea. In 2008, an *Industrial Insight* article claimed that: “What’s next for robotics? … don’t be surprised if convoys of robotic military vehicles eventually travel supply routes too “hot” for human operators, and commercial delivery fleets send robot assisted trucks on civilian roads providing relief and safer conditions for long haul drivers. … In the future, factory robots will not only set on pedestals bolted to the floor, but move around on booms, cranes, slides and wheels.” Although the mature industry tended to avoid overly promising and futuristic rhetorics, the number of articles discussing the future of the industry and robotics technologies started increasing since 2008.

The government reacted to the trend. Up until 1990s, the military was the only sector in the government that took particular interest in developing robotics technologies—the US Congress rarely discussed the topic. In 2010, Congress held hearings on “the Future of War” and “the Future of Manufacturing” to discuss the advance of the robotics and the future visions. In 2010, the President Obama announced the National Robotics Initiative, which would become the epitome of the contribution from the government community to the field of robotics.

Academia reacted to the wave sensitively. For example, in 2007, IEEE Robotics & Automation Magazine—a prestigious and more public-oriented scientific journal that has wide readership—issued a special issue on “the Grand Challenge of Robotics.” The editorial of the issue stated that “inspired by the hugely successful DARPA Grand Challenge … each workshop was charged with defining the grand challenges for their research areas. This involved identifying the main problems that were still to be resolved, discussing which challenges held the most promise for moving the field forward, and selecting representative challenge tasks or demonstrations that could be used to serve as tests for progress being made toward solving these challenges. Grand challenges such as these can serve as concrete targets for which multiple groups can focus their research efforts in order to make tangible, and measurable, progress." In 2012, reacting to the National Robotics Initiative announced by President Obama, the same journal issued an enthusiastic statement about "U.S. National Strategy for Robotics," which detailed the initiative about robotics (Christensen, 2012).

Reintegration. The revival of the technological visions throughout the field of robotics energized the field again. First, the new money flowing into robotics focused on mobile robots rather than conventional industrial robots (or robotic arms), and they focused on developing a standardized system that can further facilitate the field-wide technological progress. The most notable success was Robotics Operating System, which was evaluated as highly successful in standardizing robot software that would further accelerate robot developments across different institutions and companies.

The number of start-ups based on the mobile robot technologies also increased in this period. Before 2005, it was generally said that venture capitalists and investors shuddered at the mention of "robot" or anything that resonated the futuristic technological vision. There were only 15 venture-backed robotics start-ups at the time of 2003 according to a trade journal article (Industrial Robot, 2005). In 2006, a dedicated robotics start-up incubator Willow Garage emerged in association with the Stanford AI and Robotics program. Around 2013, robotic start-ups started receiving backup and investment from large software technology companies such as Google and Amazon.

The number of mobile robots began rising around 2006 across all types of journals (major trade journals, scientific journals, popular technology magazine) that I collected and analyzed Figure 8 shows that the frequency of the term "robot" starts rebounding in the late-2000s. It also shows that in 2008, for the first time, the frequency of the appearance of mobile robots starts outnumbering that of industrial robots.

Overall, the revival of the technological visions and the reintegration of the previously fragmented field began to accelerate the rate of progress in the field, and redirected investments and innovation efforts.

Theoretical Model: Co-evolution of Technological Visions and Technological Progress

I set out to study the process through which technological visions co-evolved with the technological progress by examining how technological visions associated with robots and the field of robotics co-evolved in the last 100 years. Figure 9 provides an overview of the theoretical model that emerged from the study.

** Insert Figure 9 about here **

I identified a pre-phase and four phases through which technological visions of robots co-evolved with the actual technological progress. During the pre-phase, a technological vision only exists in the form of distant imaginaries due to the utter lack of enabling technologies. While it inspires inventors to create idiosyncratic artifacts, they do not induce any market demand or industrial expectations.

During the first phase, more feasible futures are envisioned when a few inventors and entrepreneurs observe *technological triggers* and create salient artifacts. The entrepreneurs link the salient artifacts to the distant imaginaries or distant visions, and further envision more near-term technological visions that can be translated into markets and industries. More medium-term visions are formulated to narrow the gap between vision and reality, to help mobilize talents and resources, and to bring about collaborations between diverse communities. This ultimately leads to a first commercially viable prototype that has limited market applications yet symbolically ushers in the impending realization of the original technological visions.

The second phase is triggered by a *salient success*. Although the initial market application is limited and predicted to take up only a small fraction, the field participants in different communities envision the future sequences of the technological progress that would enable many more market applications, or promise a larger market. The initial small-scale success of the technological field becomes generalized into the promise of future successes of much larger scale applications. Hype occurs, stakeholders overcommit their resources, and the field is inundated with investment and attention.

The third phase is triggered when field participants face salient failures without realizing the promise of the next technological sequences. Often, what Hughes (1983) termed "reverse salient"—a core component that shows slower progress than other components that stalls the advancement of an entire technological field—turns out to be an obstacle to the promise in the last phase. The realization that the actual rate of technological progress did not match with the previous expectations leads many field participants to be disillusioned with the original technological visions, and to abandon the distant vision. This leads to the fragmentation of the field, in which field participants start pursuing more achievable and solvable local goals, instead of a grand technological vision. The visions and goals are decomposed, deconstructed, and reconstructed to narrow the vision-reality gap again. The field participants pursuing different types of goals do not communicate or collaborate with each other anymore.

In the last phase, some field participants realize that gradual and substantial progress has been made in a fragmented way in the pursuit of narrower local goals, yet there is a lack of integration of those fragmented progress. This realization leads to the revival of the latent technological visions that have been avoided in the previous phase. With the revival of the latent vision and salient exemplars that symbolize its return, excitement builds up across industries and technological fields again, and this boosts the reintegration of the field. The redirection and reintegration of the field help accelerating the rate of technological progress towards the goal of the ultimate technological vision.

Overall, technological vision guides the direction and rate of technology by mobilizing, identifying sequences, and reintegrating. Narrowing the vision-reality gap is a core mechanism through which field participants mobilize, legitimize, and revitalize the technological field. The directionality and temporality of the technological vision co-evolves with the actual direction and rate of the technology evolution in a complex way.

DISCUSSION

Technological progress often unfolds in fields, rather than in organizations, where participants are more diverse in their interests and more difficult to track. Technological visions are complex and often require long-term sustained focus, making progress uncertain (Ferraro 2015). While field scholars have shown how fields mobilize around common issues of concern (Hoffman, 1999) and create shared field-level goals (Lounsbury et al., 2003; Weber et al., 2008; Wry et al., 2011; Zietsma et al., 2016), how such shared goals, or visions in a technological field co-evolve with the actual technological progress is not well understood. In this paper, I examined how a technological vision co-evolves with the actual technologies over an extremely long period of time with the following theoretical contributions.

Distant Vision and Technology Evolution: Narrowing the Vision-reality gap

In this paper, I examined how a distant vision shapes and is shaped by the actual development of technologies in the context of the field of robotics. One of the primary findings is that the subjective perception of temporal gap between the technological vision and the present state of technologies—referred to as vision-reality gap—serves as a key driver of organizational activities such as field mobilization, commitment of resources, and constructing sub-goals. Particularly, narrowing the vision-reality gap is a core mechanism through which field participants construct and legitimize a future-oriented organizational field. I identified six mechanisms through which field participants strived to narrow the vision-reality gap—linking means to the distant vision, constructing a medium-term vision, envisioning sequences, decomposing, reconstructing, and reintegrating.

The first three mechanisms—linking means to the distant vision, constructing a medium-term vision, and envisioning sequences are crucial in the initial mobilization phase of a future-oriented organizational field. When there is the temporal delay between action and outcome, individuals and field participants tend to focus more on near-term consequences (Kahneman & Tversky, 1979). Time calibration is a crucial element in mobilizing a future-oriented technological field, and I show how field participants constructed a medium-term vision and expected sequences of events in order to impose a structure on uncertain future (Wood, Bakker, & Fisher, 2021). The following two mechanisms—decomposing and reconstructing the vision—happens in the disillusionment phase after intense anticipations and overcommitment of resources (Pontikes & Barnett, 2016). When the expectation heightened by a salient success is falsified and the existence of reverse salient—a component that stalls the advancement of a technological system (Hughes, 1978)—becomes clear, the vision-reality gap rapidly expands to the extent that delegitimizes the field. In this phase, field participants actively engage in decomposing the original vision into smaller subsets of achievable and solvable (thus more near-term) goals, and reconstructing a medium-term or even distant vision in a way that bypasses the constraints highlighted by reverse salient (Baldwin & Clark, 2000). This is a way they strive to recalibrate the vision-reality gap and revitalize the field. The last mechanism, reintegration, can be consciously driven by institutional actors when they perceive sufficient advancements in decomposed sub-visions and sub-goals. When successfully implemented, this can lead to a revival phase of a future-oriented field.

A noticeable finding is that the vision-reality gap is profoundly volatile, sometimes getting out of control expanding and contracting in the minds of the broader audiences (Goldfarb & Kirsch, 2020). Salient successes and failures often trigger the rapid contraction and expansion of the gap without the intention of producers and core members of the field. For example, when the first commercially viable robot artifact was released, it triggered an uncontrollable upsurge in expectations about how fast the distant vision was approaching the present. The theoretical possibility of the importance of maintaining the vision-reality gap, beyond just narrowing it, can be contemplated in the future research.

Overall, this paper identifies the vision-reality gap as an important cognitive construct that shapes the direction of technology evolution and future-oriented organizational field, and the mechanisms through which field participants actively engage in recalibrating it. This is an important contribution to the literature on the socio-cognitive view of technology evolution, and an emerging literature on forward-looking cognition and shaping (Rindova & Martins, 2021).

Temporality and Directionality of Technological Visions

Overall, the findings show that technological visions can have two dimensions: first, technological visions have the dimension of directionality, particularly indicating the level of integration or fragmentation. The breadth of the technological vision can fluctuate over time, from the pursuit of a grand overarching vision to the focusing on narrower, numerous special-purpose applications. The other dimension that constitutes technological visions is temporality—in other words, the temporal perception of how distant the technological vision is from the present state of the world. The perception often dictates what would be achievable and solvable in either near-term or distant future (Garud et al., 2014; Kaplan & Orlikowski, 2013). The paper also suggests that the subjective perception of temporal gap between the technological vision and the present state of technologies—whether the gap is narrow or too distant—serves as a key driver of the maintenance or change in technological vision, and the field-wide direction of technical change.

This paper shows that the technological visions can mobilize a nascent field, and reintegrate a mature field when it is fragmented. This is particularly important to understand the emergence of a technological field, because fields often lack centralized control over their participants. Scholars tended to assume that grand goals can direct the efforts of field participants to advance the technology (Wry, Lounsbury, & Glynn, 2011). However, there has been little attention to how the fluctuations in such grand goals, or more overarching technological visions, co-evolve and interact with the actual rate and direction of technological progresses. In addition, while previous literature has examined how organizations' ambitious goals could become displaced over time (Grodal & O'Mahony, 2017; Selznick, 1949), there were few studied which examined how technological visions can revive and reintegrate a fragmented field. This paper suggests the inherent tension between the breadth of technological visions and the need for integration.

The paper also shows that the co-evolutionary process between technological visions and the actual progresses is important because it directly affects the rate and direction of technological advancements. When it comes to the reintegration of a fragmented field, it particularly affects the rate of technological progresses. While much research has focused on the influence of institutional factors (e.g., patent regime, state laws) on the rate of progress in certain technological fields, it has rarely mentioned the role of socio-cognitive constructs such as a vision in affecting the rate of progress. This paper also suggests that while technological progress tends to be linear, the market growth is not; because market growth is often the function of adoption, and adoption is the function of how people perceive and evaluate the given technology, which can be highly volatile compared to the actual progresses of cumulative innovation. This research helps explain how complexity emerges from distributed demands within the field through participants' own interests and interactions pressures, and how it interacts with the actual rate and direction of a technology.

The Role of Constrains in Technology Evolution

This paper also suggests various mechanisms to narrow the perceived gap between the technological aspiration and the present state—such as envisioning future sequences, creating nearer-term goals, and reviving visions. Creating nearer-term goals is a particularly relevant mechanism when the field runs into unexpected obstacles that delay the development of the whole field (Hughes, 1978). Interestingly, psychology literature has suggested that creativity can often be enhanced by constraints (Mehta &

Zhu, 2016). In the findings of the study, when the nascent field of robotics faced constraints such as the stall in the development of core components, field participants shifted their focus to smaller, more solvable problems in order to detour the obstacle. This tended to lead to more experimentations in the design form of robotics products, which would have a future implication on innovations and creativity.

Lastly, by studying the integrating role of a technological vision and fluctuations in the vision, this study also contributes to the theory of socio-cognitive meaning construction and shift in meanings. Category scholars have recently theorized the changes in category meanings (Lo, Fiss, Rhee, & Kennedy, 2020), but they have not focused on the generative role of future-oriented categories, or categorical visions. Similarly, scholars studied the process of category emergence (Navis & Glynn, 2010; Jones, Maoret, Massa, & Svejenova, 2012) but they have focused on observation and clustering of objects that already exist. This paper has contributions to our understanding of how an imagined category plays a role as a guiding vision, and how that guiding vision is translated into the creation of concrete material artifacts.

Chapter 3

ENTREPRENEURIAL PROBLEM-SOLUTION PAIR: HOW ENTREPRENEURS CONSTRUCT A SEARCH PROBLEM

INTRODUCTION

Search literature has often focused on the search for solutions to a given problem, in other words, the search for solutions triggered by identifying a problem (Maggitti, Smith, & Katila, 2013; Posen, Keil, Kim, & Meissner, 2018). However, literature on entrepreneurship has long alluded that entrepreneurs often start their search processes from discovering a novel technological means, paired with only abstract and broad ideas about which problems could be potentially solved by the new means (Gans & Stern, 2003; Sarasvathy, 2001). While the search processes modeled in the behavioral theory of the firm have often assumed a low-cognition model in which firms engage in adaptive behaviors to find a local peak given a fixed problem (Cyert & March, 1963; Levinthal, 1997), entrepreneurial search must be theorized as a high-cognition process guided by actors' mental representations of possibilities in the problem and solution space that undergo constant redefinition and reformulation (Karp, 2022; Kirtley & O'Mahony, 2023; Pontikes & Barnett, 2016).

A few recent studies have begun to suggest that firms might engage in the search process under the guidance of forward-looking cognitive representations of the problem landscape and solution landscape (Gavetti & Levinthal, 2000; von Hippel & von Krogh, 2016). Several studies have suggested that forward-looking cognitive constructs such as future expectations, visions, or goals can influence and guide the search behaviors

(Bhardwaj, Camillus, & Hounshell, 2006; Sitkin, See, Miller, Lawless, & Carton, 2011; Winter, Cattani, & Dorsch, 2007). For example, the initial opportunities that entrepreneurs envisioned can serve as a motivating goal that guides their search paths (Shane, 2000). Yet, these studies have paid scant attention to how "problems" that guide the search for solutions are constructed, taking for granted that problems are given or simply identified at the starting point of search. This posits the question: How are entrepreneurial search problems constructed?

The overall absence of studies on problem formulation leaves three following characteristics of search problems unexamined. First, problems have depth and nested structures. Some problems are broader, and more loosely defined which allows a larger space to reformulate. For example, problem formulation such as "applying nanotechnology to meet industrial needs" is extremely broad and allows plenty of interpretations (Grodal, 2018; Wry, Lounsbury, & Jennings, 2014). This broadly formulated problem also leaves profound ambiguity about how the vision will be achieved or what would be the concrete search paths (Knight, 1921). For instance, innovators at Corning pursued the vision of developing optical communications, although researchers in the company "didn't really know a thing about telecommunications." (Cattani, 2006). As opposed to this, some problems are more narrowly defined, or serve as an intermediary step to solve a higher-order problem (Baldwin & Clark, 2000; Clark, 1985). Some problems are well-structured and have well-defined subordinate, intermediate problems nested within them, while others are not. For example, what recent literature calls "long jump"—wherein innovators make a leap in the landscape to attain distant combinations (Kauffman, 1993; Kneeland et al., 2020)—seem to lack a well-defined problem structure. We still know little about what guides this type of long-jump search that often underlies the most dramatic and outlier types of innovations (Lerner & Stern, 2012; Nelson, 1962).

Second, some innovators and firms look for problems that their solution can potentially solve—in other words, problem formulation can be driven by the discovery of solutions (Agarwal & Shah, 2014; Shane, 2000). Innovators might have a very vague idea about what kind of "problem" their potential solutions can be applied to. For example, Bhardwaj et al. (2006) showed that corporations actively look for new problems that they can solve with their means in which they expect high future growth. This is particularly the case in entrepreneurial firms; what entrepreneurship literature commonly refers to as "opportunity" is in practice a pair of problem and solution that has a potential to have a market and profit (Shane & Eckhardt, 2003). The initially formulated problem can be extremely abstract. For instance, Wry et al. (2014) show that some entrepreneurial firms focus on solving a scientific "why" question, without having clear ideas about real world problems that they need to solve for commercialization.

The lack of empirical studies on problem definitions in the process of search can partially be attributed to the limitation on data; most empirical works in search literature have used patent data, by which they can measure the breadth and scope of recombination (Fleming, 2001), but not the intention and motivation behind such a recombinatory effort, or the underlying paths that led to the innovation. In order to examine how problems are defined and constructed in line with solutions in the process of search, I draw on the qualitative analyses of archival data that provides the accounts of 58 entrepreneurial firms founded by 42 first-time or serial entrepreneurs in the field of robotics. In this study, I find that most entrepreneurs set their initial starting point in a broadly defined problem-solution space (the combination of a broadly defined problem and a broadly defined solution), and in the process of achieving the concrete commercialization route, (a) forward-looking problem identification ("what will prevent this from finding applications in the industrial settings in general)" and (b) identifying relevant market features and configuring them to achieve a fit are important.

Method

Data collection. In order to investigate the question of how problems are defined and constructed in line with solutions, I conducted a qualitative analysis of 58 firms created by 42 first-time or serial entrepreneurs in the field of robotics. The data provides a detailed description of the career trajectories of each roboticist, the solutions that they created and the problems that they searched, and their problem identification and decisions in the process of commercializing the technologies (Burton et al., 2002).

The field of robotics is an extreme case of the search for problem definitions (Eisenhardt, 1989) because robotics is well-known for creating abundant solutions waiting for problems they can solve (Cromwell, 2018). On top of that, while robotic technologies share broad scientific principles and vocabularies, their market applications are extremely diverse, and the field of robotics has not seen the rise of a dominant design despite the long history of the field (Nilsson, 2009). This helps control the potential industry evolution effect.

Table 9 delineates the list of archival data I used for this study. The 37 public interviews of founders and executives of prominent robotics start-ups were conducted between 2013 and 2019 by Joanne Pransky, the associate editor of a flagship trade journal *Industrial Robot*. The robotics start-ups covered by this interview series are mostly high-profiled companies that aim to commercialize cutting-edge robotics technologies such as mobile robots, medical robots, or collaborative robots. The 89 oral histories were collected by the IEEE (Institute of Electrical and Electronics Engineers) History Center in 2011. The interviews describe the career history of roboticists who have engaged in the field of robotics since its formative days; the interviews are mostly high-profiled academics and entrepreneurs in the field. From the two archives, I selected 42 entrepreneurs to the exclusion of academics, and constructed the list of 58 entrepreneurial firms that they had founded. In order to triangulate with the accounts of robotics entrepreneurs, I am currently collecting patents, academic publications, and other public interviews produced by the entrepreneurs or their firms. Because most of the entrepreneurs are holders of doctoral degrees and left an ample corpus of paper trails of their innovation, the additional data is promising to provide more detailed information about the process of constructing problems and solutions.

*** Insert Table 9 about here***

The two main archives are supplemented by trade journals and other sources of field-level data that were used in the other parts of my dissertation. The trade journal *Industrial Robot* (1973-2020), from which I derived the public interview data, and the online trade journal *Industry Insight* from the Associations for Advancing Automation are an excellent source of information that has helped me to understand the overall history and recent trend of robotics industries. I also relied on four books written by prominent roboticists and science historians to understand the deeper history of underlying technologies. Three books provide a nice overview of the history of artificial intelligence and computer vision (Brooks, 1999; Crevier, 1993; Nilsson, 2009). Roland & Shiman (2002) provides an in-depth overview of the role of the military community and, particularly, an agency called DARPA (Defense Advanced Research Projects Agency).

Table 10 provides the overview of the data sources, demographic descriptions of interviewees included in the two main data archives.

*** Insert Table 10 about here***

From the original data sources, I selected 38 entrepreneurs (42 interview scripts) and 58 entrepreneurial firms that they had founded. Table 11 further describes each entrepreneur's name, the number of interview scripts for each, the number of firms that they had founded, types of products they build, types of target market, gender, and whether they have online social media pages (e.g., LinkedIn) with which I can triangulate the data.

*** Insert Table 11 about here***

Data Analyses. Using qualitative analysis techniques outlined by Strauss and Corbin (1998), I coded 42 interviews and oral histories, and I aim to engage in iterations between my data and my emerging framework. I started by open coding the public interviews and oral histories to identify emerging, common themes, and from the first-order codes (e.g. goal: alignment, goal: near-term, persistence: passion, shift of direction, start-up: government funding, user understanding, etc.) I identified second-order themes such as goal and shift of direction (Gioia, Corley, & Hamilton, 2013). Noticing that the themes of goal and shift of direction are important and common across the accounts of entrepreneurs, I began a literature review of mental models, cognitive representations, and problem-solving, and found out that the search for the problem definitions is one of the major missing links in search literature (Gavetti & Levinthal, 2000; Posen et al., 2018). Motivated by these theoretical constructs, I re-coded the data to center my analysis around the definition and discovery of problems and solutions. Thus far, I identified mechanisms and central themes related to the definition of problems and solutions out of the analysis of 19 firms founded by 14 entrepreneurs. I aim to iterate further between data analyses and theory building until I reach a level of theoretical saturation.

Findings

From the data analysis, I identified three broad phases that can be generalizable to most entrepreneurial firms I studied—*formulating a broad problem, identifying a core constraint in the solution space, and achieving product-market fit*. I describe the three phases and sub-mechanisms under each phase.

Phase 1: Formulating a Broad Problem

Pairing a broad entrepreneurial problem and broad entrepreneurial solution. Most entrepreneurs described their initial definition of an entrepreneurial problem-solution pair—in other words, the coupling of a broadly defined problem and broadly defined solution. For example, Paolo Pirjanian, the CTO of iRobot Corporation, said that when he started Evolution Robotics (now merged with iRobot Corporation) in 2001, "we realized that one of the first key building blocks for robotics was autonomous navigation" and "were focused on going after the consumer market." In other words, he set his starting point in the space of a broad entrepreneurial problem-solution pair of "applying autonomous navigation to any potential problems in the consumer market" (as opposed to military or industrial market). In another example, Esben Ostergaard, who founded Universal Robots in 2005 whose revenue is now around $220 million, stated that he "saw a lot of value in making a new kind of robot that was more like a tool for the people to use," and decided to "apply the transformer robot technology from my PhD project." In other words, he chose an abstract problem-solution pair of applying his transformer robot technology to the problem of making robots more usable for ordinary people and workers in industrial sites.

Defining a broad entrepreneurial solution first. While most entrepreneurs mentioned a broad problem-solution pair that they identified as an initial starting point, they differed in whether they emphasized a solution or a broadly defined problem. In many cases, they discovered a solution first, as many academic entrepreneurs would (Agarwal & Shah, 2014; Wry et al., 2014). In the field of robotics, which is dominated by high-skilled, highly educated entrepreneurs who mostly hold PhD degrees in engineering or computer science, many of the initial discoveries were made as a solution to academic research questions. For instance, William Townsend, the founder of Barrett Technology, worked to "put out the idea of robots that should work collaboratively and safely with people" in his PhD years around 1985, and realized that the core problem in achieving robot safety was chains hanging from the robot joints. He invented the cable drive technology as a solution to his research question of robot safety, and this new technological means soon became coupled with a broadly formulated market problem.

The discovery of a unique, broadly applicable solution (often triggered by solving an academic research question or workplace problems) often became the center of the entrepreneurial problem-solution pair. In other words, in some cases, solutions are the core element of an entrepreneurial vision, harder to pivot from than problems are (Grimes, 2018). For example, Ralph Hollis, who was a roboticist employed at IBM in the 1970s, obtained an idea of levitating motors in magnetic fields in a "flash of genius" moment when he was trying to solve a workplace problem. "And then one evening it occurred to me that: why not just levitate the fine motion device in magnetic fields? And then you could move it in any direction you want and there would be no suspension. So I sat down and I did the calculations and thought of a few geometric configurations. … We started putting together a system that could levitate." He became a serial entrepreneur, and dedicated his career to applying this solution to multiple problems in different industries—which became the *preferred direction* that guided his action throughout his search paths (Winter et al., 2007). He persisted in searching for various ways of commercializing the core solution, with less constraints in problem formulation.

Defining a broad entrepreneurial problem first. In some cases, robotics entrepreneurs first formulated a broad problem that needs to be (and they believe can be) fixed. For example, when Rodney Brooks—one of the founders of iRobot—was in China, he recognized that "I saw early signs that we were not going to have an infinite supply of labour in China in the way that we all thought earlier. … This is what was happening with Chinese manufacturers and led to labour shortages. How could we provide robots to make up that difference?" To solve this very abstract problem, he started a new start-up named Rethink Robotics, experimenting with solutions. In this case, the problem was a core, less flexible element in the entrepreneurial problem-solution pair, while solutions were treated as more exchangeable.

Phase 2. Identifying a Core Constraint in the Entrepreneurial Solution Space

Although the entrepreneur defines a broad entrepreneurial problem-solution pair, it often serves as a mere starting point from which a rugged journey for search begins. Here, I suggest that identifying a core constraint in the solution space can be central to problem construction. I also show how temporal aspects of problem statement can be an important mechanism by which entrepreneurs shift their direction.

Identifying a potential core constraint in the entrepreneurial solution space. Entrepreneurial firms often proactively defined what would be a potential core constraint in the solution space that might be deterrent. When Helen Greiner, one of the founders of iRobot Corporation, shifted her attention to small-sized unmanned aerial vehicles (drones), she realized that one of the core constraints that was holding back the industrial use of drones was a short time of flight. She said: “The big issues is the time of flight. It’s fine if you’re flying your Phantom (drone) for 25 minutes. But for a real industrial operation, that’s probably not enough time.” Then instead of trying to push against the core constraint (trying to extend the time of flight) head-on, she focused on deconstructing the solution so that it can be usable—she ultimately decided to develop a drone that could be tethered. This became a core design choice from which she narrowed search for solutions (she ultimately developed “microfilament technology” that enabled her to tether drones). The identification of core constraints and subsequent design choices occurred before her new firm engaged in market search or user feedbacks.

Similarly, when Paolo Pirjanian chose his broad entrepreneurial problem-solution pair of using autonomous navigation to meet consumer market demands, he and his team realized that the existing autonomous navigation systems were too costly to have industrial applications. “$10,000 was not a deployable solution. … We needed to find a much more cost-effective approach to solving this navigation problem.” This identification of a core constraint also led him to deconstruct the solution in a heuristic way; “my intuition for this solution was the use of cameras. Cameras, which were just getting embedded into cell phones, cost less than a dollar in high volume.”

Also, Ostergaard recounted that when he put his laboratory robot into food production lines, he noticed that “we ended up with a 500-kilogram, half-ton machine, for placing strawberries on cakes or for putting pepperonis on pizzas. It was simply way over dimension for the task. Additionally, reprogramming or redeployment of the machine wasn't feasible at the time because it was impossible for the production workers to learn to use this technology and there wasn't enough work to justify the hiring of robot programmers." In other words, he realized that his robot was bulky and difficult to use in real-world, industrial settings.

By defining a potential core constraint that would hinder the successful industrial application of their product-solution pair, entrepreneurial firms also defined what would be the most important feature—be it cost, size, or duration—in their process of commercialization. In other words, entrepreneurs proactively identified what Hughes (1983) called the reverse salient, a component or attribute that would stall the advancement of the whole system.

Temporal (mis)judgment. Temporal assessment of a problem seems to play an important role in making the decision to shift the direction (Lawrence, Winn, & Jennings, 2001). For example, Rodney Brooks, one of the founders of iRobot, recalled that the robotics and computer vision encountered "seeming stalls" and "predicates" already in 1983-84 (Brooks, 1999). Expecting that the computer vision problem will not be solved for a very long time, he made a temporal judgment that the problem (goal) of creating a human-like robot would be too distant from the present. Instead, he posited a new research problem of creating smaller robots that imitate simpler life forms such as mosquitos or snakes. This shift of direction and identification of a new problem revolutionized the field of robotics in the late 1980s.

Meanwhile, for many entrepreneurs, it seems to be very difficult to make an accurate temporal judgment. Some entrepreneurs tend to be overly optimistic about how fast their solutions to the problems can be commercialized. For example, the CTO of iRobot Corporation stated in an interview:

> You have to ground your research and development into reality, which is a contrast to what I used to do in academia. … In 2001 when I started the company, I had an advisory board of the most prominent robotic researchers. I remember we were talking about navigation, localization and mapping and they said, "Solved. It's a solved problem." But until today, 12 years later, it is only now that we consider it mature enough to be integrated into products.

Similarly, Helen Greiner, one of the founders of iRobot, recounted that one of her previous companies received around $5 million worth of venture capital funding, but their initial problem formulation turned out to be too ahead of the time. The idea was creating Internet-connected robot, around 2000, it turned out to be a pipe dream when the Internet infrastructure was not as solid and ubiquitous. Realizing that there is a significant temporal gap between the present and the envisioned future in which their solutions to the problem will be commercialized (Kahneman & Tversky, 1979; Wood et al., 2021), she and her firm decided to pivot to focus on other applications.

Phase 3. Achieving product-market fit

Rapid prototyping Once the entrepreneurs settled on a broad entrepreneurial problem-solution pair, identified a core constraint in the solution space, and successfully deconstructed and reconstructed a solution to bypass the constraint, they typically started working on prototyping through lean iterations. Buehler, the executive of Imagineering, said that "we all learned a lot about the value of making things real—validating ideas quickly in a realistic environment, and iterating many times. This seems like a simple insight, but it's really important to get stuff out of the lab." Ostegaard added that "our goal was to have a fully completed working prototype. We took a very quick, iterative approach." Creating a proof of concept was crucial to get validation for the idea. Ostegaard continued: "After two years, we had a prototype that could do work in a greenhouse. That was the first time I believed we could actually do this, because we managed to have our prototype robot in the back of a car ... In four hours, we managed to set up the robot and program it, and it did its job. If you compare this to traditional robots, there's no way to transport traditional robots in the back of the car … We could see that our whole concept would work."

Simplifying entrepreneurial solutions. In the rapid prototyping and iteration process, it was also important to define what is the feature that is necessary for commercialization, and what is the feature that is not. When Steve Cousins founded Savioke, the original solution he had was a bulky multi-purpose robot that could both navigate physical spaces and use manipulators (robotic arm and hand) to pick items up. However, when he and his team went through use-cases, they found out that "when somebody's around the robot (the person can) load and unload items, and therefore an item doesn't need to be picked up automatically. That means that you don't have to even have that manipulation." This realization led them to discard the manipulation feature from their original solution. Similarly, Ostegaard said: "the mistake … was putting too many features into a single implant. … The take-home message from this experience is that incorporating many features that the user will never use is a result of a bad design process. I learned this lesson the hard way."

Fitting features. After the initial conceptualization and attainment of the working prototype and early users, companies that are in a similar problem-solution space become competitors to each other. At this stage, the configuration of product features seems to be what determines the success and failure of the competitors. For example, Rethink Robotics and Universal Robots were competitors in a very similar problem-solution space. Rethink Robotics was founded by serial entrepreneurs from more privileged backgrounds, but it lost the competition. A trade journal article points out that: “Rethink suffered because they prioritized safety and cost over speed and precision and baked those decisions into the hardware itself. Those design choices limited the type of applications where the robots could be used as well as the company’s ability to reengineer the robots to improve their performance. … Universal succeeded because its robots were accurate and repeatable, yet safe enough to work next to people” (The American Society of Mechanical Engineers, 2019). Even in a very similar problem-solution space, slight differences in the configurations of features led to dramatically different outcomes. For instance, in an interview, the founder of Rethink Robotics said that “If you’re going to use the safety strategy we use in Baxter (product), which we’re totally happy with, it’s not going to work if you’ve got a 50-kilogram payload, going at meters per second. In a certain niche, the strategy works, and that’s where we’re exploiting it.” In retrospect, this emphasis on prioritizing safety features turned out to limit the scope of problems and users that the solution could be used for, thus limiting the product’s marketability and ultimate fitness. Further data analyses and triangulation from archival data (patents, press releases or further interviews) will help identify how and why the configurations of features of products that are aimed for the very same problem-solution pair begin to diverge.

Figure 10 is the process model that delineates the flow of mechanisms that connect the construction of entrepreneurial solution space and entrepreneurial problem space.

** Insert Figure 10 about here **

DISCUSSION

The importance of defining a problem that an entrepreneur can solve to add value to the world is profound in entrepreneurship (Shane, 2000). One of the fundamental traits that characterizes entrepreneurship is that entrepreneurs often begin their search processes from discovering a novel, concrete means that is envisioned to be potentially useful in the future (Gans & Stern, 2003; Sarasvathy, 2001). This is a fundamentally different process from what is assumed in the existing search literature—search for solutions to a given problem (Maggitti et al., 2013; Posen et al., 2018). However, studies on the entrepreneurial search or market search processes have only begun to arise (Karp, 2022; Pontikes & Barnett, 2016). In order to understand the entrepreneurial search processes, it is crucial to shed light on how entrepreneurs construct their search problem (Kirtley & O'Mahony, 2023). This paper examines how entrepreneurs in the context of the robotics industry envision a problem to be solved, and thus attempts to uncover the cognitive underpinnings of problem formulation.

From the emergent framework from my preliminary analysis, I propose "entrepreneurial problem-solution pair" as an important form of entrepreneurial vision (von Hippel & von Krogh, 2016). My findings suggest that a broadly formulated entrepreneurial problem-solution pair is often the first cognitive construct that entrepreneurs conceive before crafting a concrete business idea. In other words, a prospective entrepreneur sees a novel technological means (often coming out of laboratories), and makes an mental connection between the concrete means and a broadly-defined, abstract problem that the technological means could potentially solve in the future (e.g. "This new technology will be able to improve the safety issues in human-robot collaborations.") There is a profound uncertainty around whether the entrepreneurial problem-solution pair is indeed a promising one, or whether the problem-solution pair will be a true entrepreneurial opportunity that can lead to profit (Shane & Eckhardt, 2003). However, this is often the very first cognitive step that an entrepreneur takes before engaging in actions. This empirical finding is supported by von Hippel & von Krogh (2016)'s theoretical intuition that search might be triggered by formulating a very broad problem statement.

My empirical findings further suggest that the initial formulation of a broad problem-solution pair is often followed by identifying a core constraint in the solution space (Berglund, Bousfiha, & Mansoori, 2020). A fledgling technological means might lack an important capacity that is needed for actualizing the envisioned problem-solution pair (e.g. "this drone might be useful in factories, but it can actually fly for only 30 minutes.") The solution (and often also a problem) is decomposed and deconstructed to bypass such a constraint. The level at which this pivot (i.e. deconstruction and reconstruction of a solution or problem) occurs can be an interesting unit of analyses (Kirtley & O'Mahony, 2023). While entrepreneurs might rapidly iterate details of design or user need statements, the initial broadly formulated problem or solution, or the entrepreneurial problem-solution pair might not easily change over time (Zuzul & Tripsas, 2020). This necessitates theorizing a search problem as having depth and nested structure, in which a broadly defined problem can be interpreted as some type of superordinate goal or guiding vision, while smaller sub-problems can be considered as subordinate goals. The level at which the problems are deconstructed and reconstructed must be an important observation point for future research.

This paper also suggests that the entrepreneurial problem-solution pair is essentially a type of forward-looking cognition—particularly, a medium-term vision in which a concrete means is envisioned to solve an abstract, broadly formulated problem. Examining how such a medium-term vision guides the evolution of innovation and design choices at the entrepreneurial firm level would be an important contribution to the socio-cognitive view of technology evolution and entrepreneurship.

While the problem space-solution space pair and garbage can model might be seemingly similar, the garbage can model (Cohen, March, & Olsen, 1972) is based on the assumption that pre-formulated problems and solutions are put into the "garbage can," merely linked to each other rather than co-constructed in a complex interaction pattern. This is partially due to the limitation of simulation models based upon which the garbage can model was theorized. In this paper, the entrepreneurial problem-solution pair is not simply a random pair of a pre-formulated problem and solution. In the earliest phase of commercializing a technology, both entrepreneurial problem space and solution space are broadly construed, with a high level of ambiguity and flexibility with regards to how to readjust the original entrepreneurial problem-solution space. In this complex cognitive process, the entrepreneurial solutions and problems are co-constructed in search of market viability (von Hippel & von Krogh, 2016). Figure 10 delineates the process.

A boundary condition of this paper is that this type of "solutions looking for a problem" is most relevant to technology entrepreneurship in which highly educated entrepreneurs seek ways to commercialize novel technological means coming out of scientific research laboratories. This type of entrepreneurship is often referred to as technology entrepreneurship (Gans & Stern, 2003) or academic entrepreneurship (Agarwal & Shah, 2014), which is a subset of entrepreneurs. The research context, robotics industry, is also a particular case in which the solutions can be applied to many different types of real world problems—what Teece (2018) termed "enabling technologies" or "general purpose technologies" (Bresnahan & Trajtenberg, 1995). Future research will shed light on how the theory of forward-looking cognition can be applied to non-technology intensive settings such as art or social entrepreneurship.

CONCLUSION

Overall, this dissertation synthesizes four main perspectives of technology evolution, and investigates the role of forward-looking cognition in shaping the evolution of robotics technology at the field- and entrepreneurial-level. In the empirical chapters, this dissertation particularly explores how a distant vision (technological vision) and medium-term vision (entrepreneurial problem-solution pair) co-evolves with the actual innovation trajectories. Table 12 highlights the contribution of two empirical papers to each theoretical perspective discussed in the first chapter. Broadly, this dissertation contributes to the socio-cognitive view of technology evolution and entrepreneurship by theorizing and highlighting the role of forward-looking cognition.

*** Insert Table 12 about here ***

Co-evolution of cognitive constructs and technology

In the first paper, I highlight the importance of a co-evolutionary approach to overcome the assumptions that technology evolution is triggered by random discontinuities. In particular, the cognitive and social perspectives emphasize that technologies co-evolve with socio-cognitive understandings of and social structures embedding the emerging technologies (Burt, 2005; Lingo & O'Mahony, 2010; Powell & Grodal, 2005). Technological superiority is rarely the sole driver of selection, but the fit between emerging technologies and existing social categories, relations, networks, and interests shape the pattern of selection (Clark, 1985; Pinch & Bijker, 1984). The way the new market offerings are categorized and evaluated affects the pathways of technology evolution (Garud & Rappa, 1994; Rosa, Porac, Runser-Spanjol, & Saxon, 1999). The alignment with the existing social structures, or the attempts to achieve it, also (Hargadon & Douglas, 2001) influences the evolution of technology. The demand heterogeneity and institutional factors such as market intermediaries are also important elements to consider in the co-evolutionary model of technology (Karp, 2022; Rosenkopf & Tushman, 1998).

From the synthesis of literature, I also point out that a promising area of research is how expectations, an underexamined cognitive construct, 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 prototypes or artifacts emerge (Augustine et al., 2019; Garud et al., 2014; Granqvist & Laurila, 2011; Seidel et al., 2020). In such an early stage, the technological and economic determinist view loses even more explanatory power because of the profound uncertainty shrouding the new field (Knight, 1921), giving way to the analysis of subjective cognitive constructs and social construction of technology. Not only the retrospective understandings of the past and present co-evolve with technologies, but also do the future-oriented expectations—even though they are more elusive and volatile. The synthesis of literature suggests that this is one of the promising future research areas that has been undertheorized and understudied in the existing literature on the co-evolutionary view of technology.

The types and role of forward-looking cognition

In the introduction of the dissertation, I define forward-looking cognition as the mental representations of possibilities in the future (Gavetti & Levinthal, 2000). Some possibilities are considered as more desirable and feasible than others (Hannan et al., 2019), thus the cognitive map of possibilities is infused with value and affect. Forward-looking cognition can play a vital role in technology evolution, and the development of relevant organizational fields or entrepreneurial activities.

For clarifying the terms scattered across a diverse set of research streams, in this dissertation, I lay out three ideal types of forward-looking cognition: *Distant vision, medium-term vision, and near-term vision*. The classification is mainly along the dimension of temporal horizon, and the three types of forward-looking cognition vary in the abstractness and testability of the belief, associated organizational activities, relevant literature, and potential consequences for the evolution of technology (see Table 1). First, distant vision is a belief about the possibility of an abstract concept solving an abstract, broad-scope problem in the future. Distant visions are often radical, and are envisioned to transform a large swath of the economy and society. Long-term oriented and broadly scoped, this type of cognition is commonly engaged in constructing an organizational field through the negotiations between heterogenous stakeholders beyond a single market. The second type of cognition is *medium-term vision*. Medium-term vision is a belief about the possibility of a concrete, fledgling technological tool solving a less defined, abstract, mid-scope problem in the future. Often manifested in the form of blueprints, sketches, and concept models (Simon, 1990) that are imagined to multiple have potential uses in the future (Sarasvathy, 2003), the medium-term vision is typically aimed at constructing a market through entrepreneurial actions, both shaping and adapting (Rindova and Courtney, 2020). The third type of forward-looking cognition is *near-term vision*. It is defined as a belief about a possibility of a concrete, emerging technology solving a concrete problem that has a predictable market. It is more tightly grounded on a cognitive representation of the present (Gavetti and Levinthal, 2001), and takes the form of hypotheses or assumptions that are relatively easily testable through market experimentations and systematic measures (Camuffo et al., 2020).

Overall, this theoretical framework contributes to our understanding of forward-looking cognition that has been only sparsely studied across fragmented lines of literature with divergent terminology (Garud et al., 2014; Kirtley & O'Mahony, 2023) The framework clarifies the differences between the three types of forward-looking cognition, and how diverging lines of literature that sometimes use the same terminology (e.g. "vision," "future-oriented," "mental model") actually engage in different phenomena.

Distant vision and technology evolution: Narrowing the vision-reality gap

In the second paper, I examine how a distant vision shapes and is shaped by the actual development of technologies in the context of the field of robotics. One of the primary findings is that the subjective perception of temporal gap between the technological vision and the present state of technologies—referred to as vision-reality gap—serves as a key driver of organizational activities such as field mobilization, commitment of resources, and constructing sub-goals. Particularly, narrowing the vision-reality gap is a core mechanism through which field participants construct and legitimize a future-oriented organizational field. I identified six mechanisms through which field participants strived to narrow the vision-reality gap—linking means to the distant vision, constructing a medium-term vision, envisioning sequences, decomposing, reconstructing, and reintegrating.

The first three mechanisms—linking means to the distant vision, constructing a medium-term vision, and envisioning sequences are crucial in the initial mobilization phase of a future-oriented organizational field. When there is the temporal delay between action and outcome, individuals and field participants tend to focus more on near-term consequences (Kahneman & Tversky, 1979). Time calibration is a crucial element in mobilizing a future-oriented technological field, and I show how field participants constructed a medium-term vision and expected sequences of events in order to impose a structure on uncertain future (Wood et al., 2021). The following two mechanisms—decomposing and reconstructing the vision—happens in the disillusionment phase after intense anticipations and overcommitment of resources (Pontikes & Barnett, 2016). When the expectation heightened by a salient success is falsified and the existence of reverse salient—a component that stalls the advancement of a technological system (Hughes, 1978)—becomes clear, the vision-reality gap rapidly expands to the extent that delegitimizes the field. In this phase, field participants actively engage in decomposing the original vision into smaller subsets of achievable and solvable (thus more near-term) goals, and reconstructing a medium-term or even distant vision in a way that bypasses the constraints highlighted by reverse salient (Baldwin & Clark, 2000). This is a way they strive to recalibrate the vision-reality gap and revitalize the field. The last mechanism, reintegration, can be consciously driven by institutional actors when they perceive sufficient advancements in decomposed sub-visions and sub-goals. When successfully implemented, this can lead to a revival phase of a future-oriented field.

A noticeable finding is that the vision-reality gap is profoundly volatile, sometimes getting out of control expanding and contracting in the minds of the broader audiences (Goldfarb & Kirsch, 2020). Salient successes and failures often trigger the rapid contraction and expansion of the gap without the intention of producers and core members of the field. For example, when the first commercially viable robot artifact was released, it triggered an uncontrollable upsurge in expectations about how fast the distant vision was approaching the present. The theoretical possibility of the importance of maintaining the vision-reality gap, beyond just narrowing it, can be contemplated in the future research.

Overall, this paper identifies the vision-reality gap as an important cognitive construct that shapes the direction of technology evolution and future-oriented organizational field, and the mechanisms through which field participants actively engage in recalibrating it. This is an important contribution to the literature on the socio-cognitive view of technology evolution, and an emerging literature on forward-looking cognition and shaping (Rindova & Martins, 2021).

Entrepreneurial problem-solution pair as a form of medium-term vision

The importance of defining a problem that an entrepreneur can solve to add value to the world is profound in entrepreneurship (Shane, 2000). One of the fundamental traits that characterizes entrepreneurship is that entrepreneurs often begin their search processes from discovering a novel, concrete means that is envisioned to be potentially useful in the future (Gans & Stern, 2003; Sarasvathy, 2001). This is a fundamentally different process from what is assumed in the existing search literature—search for solutions to a given problem (Maggitti et al., 2013; Posen et al., 2018). However, studies on the entrepreneurial search or market search processes have only begun to arise (Karp, 2022; Pontikes & Barnett, 2016). In order to understand the entrepreneurial search processes, it is crucial to shed light on how entrepreneurs construct their search problem (Kirtley & O'Mahony, 2023). In the third paper of the dissertation, I examined how entrepreneurs in the context of the robotics industry envision a problem to be solved, and thus attempts to uncover the cognitive underpinnings of problem formulation.

From the emergent framework from my preliminary analysis, I propose "entrepreneurial problem-solution pair" as an important form of entrepreneurial vision (von Hippel & von Krogh, 2016). My findings suggest that a broadly formulated problem-solution pair is often the first cognitive construct that entrepreneurs conceive before crafting a concrete business idea. In other words, a prospective entrepreneur sees a novel technological means (often coming out of laboratories), and makes an mental connection between the concrete means and a broadly-defined, abstract problem that the technological means could potentially solve in the future (e.g. "This new technology will be able to improve the safety issues in human-robot collaborations.") There is a profound uncertainty around whether the problem-solution pair is indeed a promising one, or whether the problem-solution pair will be a true entrepreneurial opportunity that can lead to profit (Shane & Eckhardt, 2003). However, this is often the very first cognitive step that an entrepreneur takes before engaging in actions. This empirical finding is supported by von Hippel & von Krogh (2016)'s theoretical intuition that search might be triggered by formulating a very broad problem statement.

My empirical findings further suggest that the initial formulation of a broad problem-solution pair is often followed by identifying a core constraint in the solution space (Berglund et al., 2020). A fledgling technological means might lack an important capacity that is needed for actualizing the envisioned problem-solution pair (e.g., "this drone might be useful in factories, but it can actually fly for only 30 minutes.") The solution (and often also a problem) is decomposed and deconstructed to bypass such a constraint. The level at which this pivot (i.e. deconstruction and reconstruction of a solution or problem) occurs can be an interesting unit of analyses (Kirtley & O'Mahony, 2023). While entrepreneurs might rapidly iterate details of design or user need statements, the initial broadly formulated problem or solution, or the entrepreneurial problem-solution pair might not easily change over time (Zuzul & Tripsas, 2020). This necessitates theorizing a search problem as having depth and nested structure, in which a broadly defined problem can be interpreted as some type of superordinate goal or guiding vision, while smaller sub-problems can be considered as subordinate goals. The level at which the problems are deconstructed and reconstructed must be an important observation point for future research.

This paper also suggests that the entrepreneurial problem-solution pair is essentially a type of forward-looking cognition—particularly, a medium-term vision in which a concrete means is envisioned to solve an abstract, broadly formulated problem. Examining how such a medium-term vision guides the evolution of innovation and design choices at the entrepreneurial firm level would be an important contribution to the socio-cognitive view of technology evolution and entrepreneurship.

Another important contribution of this paper is that it tracks how abstract concepts are instantiated into concrete artifacts. While many seminal works emphasized the importance of artifacts as the material manifestations of problem-solving knowledge (Rindova & Petkova, 2007), there are still not enough studies that systematically tracked the evolution of innovation embedded in artifacts. Understanding how concepts are translated into concrete material realities is essential to understand design processes. For example, in his account of design, Herbert Simon emphasized: "[designs are determined in] a relation among three terms: the purpose or goal, the character of the artifact, and the environment in which the artifact performs" (Simon, 1996: 5) This paper can potentially contribute to the emergent theories on design by attending to all three elements that are specified by Simon (1996).

LIMITATION AND FUTURE RESEARCH

A boundary condition of this paper is that this type of "solutions looking for a problem" is most relevant to technology entrepreneurship in which highly educated entrepreneurs seek ways to commercialize novel technological means coming out of scientific research laboratories. This type of entrepreneurship is often referred to as technology entrepreneurship (Gans & Stern, 2003) or academic entrepreneurship (Agarwal & Shah, 2014), which is a subset of entrepreneurs. The research context, robotics industry, is also a particular case in which the solutions can be applied to many different types of real world problems—what Teece (2018) termed “enabling technologies” or “general purpose technologies” (Bresnahan & Trajtenberg, 1995).

While robotics is an extreme case of the importance of forward-looking cognition in technology evolution and entrepreneurship, the theories of forward-looking cognition is not limited to high technology industries. For example, Sarasvathy (2003) uses the example of chefs in explaining her adjacent concept of effectuation, and a recent paper discussed the role of future-oriented thinking in impact investing (Logue & Grimes, 2022). The theories of forward-looking cognition can also have ample implications for the recent literature on grand challenge (Ferraro et al., 2015) or social entrepreneurship. Future research will shed light on how the theories of forward-looking cognition can be applied to, or show variations in, non-technology intensive settings such as art or social entrepreneurship.

Table 1. Three Ideal Types of Forward-looking Cognition

	Distant vision	**Medium-term vision**	**Near-term vision**
Temporal horizon	Distant	Medium-term	Near-term
Belief about possible futures	This abstract concept will solve an abstract problem.	This concrete means will solve an abstract problem.	This concrete means will solve a concrete problem that has a market.
Solution	Abstract concept	Concrete means	Concrete means
Problem	Abstract, broad-scope problem	Abstract, mid-scope problem	Concrete problem
Testability of the belief	Untestable	Limited testability	Testable
Organizational activities	Constructing a field	Constructing a market	Testing a market
Action towards the environment	Shaping	Shaping/adapting	Adapting
Primary mode of action	Social construction	Effectuation	Experimentation
Stakeholders	Engaging with numerous stakeholders	Engaging with limited stakeholders	Engaging with capital and consumers
Consequences for the evolution of technology	The trajectories of multiple classes of technologies (field-level)	The trajectories of core technologies (firm-level)	Market development (No changes in core technology)
Examples	Robotics Nanotechnology Geoengineering	Air taxi Satellite radio	Dropbox
Relevant studies	Grodal (2018) Rindova and Martins (2021) Augustine et al. (2017)	Sarasvathy (2003) Kirtley and O'Mahony (2023) Zuzul and Tripsas (2020)	Gavetti & Levinthal (2001) Camuffo et al. (2020) Karp and O'Mahony

Table 2. 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	Abernethy and Clark, 1985; Tushman and Anderson, 1986; Schilling, 2002; Suarez, 2004	Technological evolution is driven by technological factors. *Includes:* S-curve theory, industry lifecycle theory, technology lifecycle 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 entre-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 effect industries and organizations	Macro-cycles of economic growth; Industry lifecycles; Technology lifecycles
Economic realist	Gort and Klepper, 1982; Klepper, 1997	Technological evolution is driven by economic factors. *Includes:* Evolutionary economics, industrial economics, industry lifecycle 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 lifecycles;
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 theory, categorization theory	Technology as the interplay between knowledge, artifacts and ways of evaluating	Firm adaptation to technological change, the commerciali-zation of new technology, arbitrariness of the path of technological change. Focus is on categories and frames.	Qualitative archival studies, cases studies, interviews, textual linguistic analysis to capture beliefs and "frames." Focuses on firms and users.	*Technological Interpretivism*: Actors' cognitive representations do not directly represent the technology in itself due to 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	From emergence to taken-for-grantedness; Organizational adaptation processes; Convergence between diverse cognitive represent-tations

Social construc-tionist	Yates, 1993; Hargadon and Douglas, 2001; Akrich, Callon and Latour, 2012; 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, co-evolution 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

Table 3. The Four Perspectives' View 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 amongst 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 ques of technological variation's tangible features and discoursive 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 which sold in bulk in prior years will be cheaper to produce and they will therefore be re-selected by consumers.	Taken-for-grantedness amongst 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

Table 4. 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** (1059)	**129** (418)	**96** (130)	**12** (210)	**6** (16)	**0** (12)	**3** (54)	**4** (92)	**7** (128)

Search words: "techn* evolution" OR "techn* emergence" OR "innov* evolution" OR "innov* emergence" OR "evolution of techn*" OR "techn* change"

* The reason that a lower percentage of papers were included from outside of core management is that 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 studies we found in sociology addressed inequality-related subjects. Other studies we found in the economics 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, Social Studies of Science*

Table 5a. 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*(7), 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(3): 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 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*, 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*, 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*(6), 415-430	Quantitative; various technologies	***Variation****:* Competing design paths ***Selection****:* Technological, economic, organizational factors ***Retention****:* Standardization
Christensen, C. M. (1997). The innovator's dilemma. *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*(2), 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*(4), 625-648	Mixed-method; semiconductor lithography equipment	***Variation****:* The level of availability of complimentary 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*(12-part-2), 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*(2), 271-286.	Theoretical	***Variation:*** NA ***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*(7), 1019-1039.	Quantitative, multiple technologies	***Variation:*** Recombination of new and existing components ***Selection****:* NA ***Retention:*** NA

Table 5b. Twelve Example Studies that Primarily Draw on the Economic Perspective

Paper	Type of Study	Perspective on Variation, Selection and Retention
Klepper, S. "Entry, exit, growth, and innovation over the product life cycle." *The American Economic Review* (1996): 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(1), 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. "Technological lockout: An integrative model of the economic and strategic factors driving technology success and failure." *Academy of Management Review* 23.2 (1998): 267-284.	Theoretical	**Variation:** Bets on customer expectations **Selection:** size of customer base, complimentary 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*(9), 1257-1278.	Formal model	**Variation:** Firm-level investment choices and complimentary assets **Selection:** NA **Retention:** Inherent potential of technological trajectory combined with complimentary assets
Adner, R., and D. Levinthal. "Demand heterogeneity and technology evolution: implications for product and process innovation." *Management Science* 47.5 (2001): 611-628.	Formal model	**Variation: NA Selection:** Net utility of product performance within a specific customer niche **Retention: NA**
Buenstorf, G., and Steven K. "Submarket dynamics and innovation: the case of the US tire industry." *Industrial and Corporate Change* 19.5 (2010): 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*(8), 1024-1041.	Quantitative, multiple markets	**Variation:** Firm's pursuit of differentiation **Selection:** Actual and perceived product quality, price **Retention:** NA
Adner, R. (2002). When are technologies disruptive? A demand-based view of the emergence of competition. *Strategic management journal*, *23*(8), 667-688.	Computer simulation	**Variation:** NA **Selection:** marginal utility of performance improvements, combination of objective performance and consumers' tradeoff between performance parameters **Retention:** NA
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*(4), 371-399.	Simulation	**Variation:** NA **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*(6), 1043-1074.	Historical and quantitative; Amateur photography	***Variation****:* Producers specializing on 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 Beta. *Business history review*, *66*(1), 51-94.	Historical, Video recording machine standards	**Variation:** Knowledge of customer needs, technological requirements, and complimentary assets **Selection:** Complimentary 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(2): 387-398	Quantitative; PC operating system & videogame hardware	***Variation****:* [Not addressed] ***Selection****:* Network externalities, entry timing, complementary assets ***Retention****:* Path dependency

Table 5c. Twelve Example Studies that Primarily Draw upon 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(5), 235-251	Theoretical	***Variation***: Ambiguity about use ***Selectio***n: The merging of market and technology concepts ***Retention***: Incremental innovation and accumulated learning amongst users
Garud, R., & Rappa, M. A. (1994). A socio-cognitive model of technology evolution: The case of cochlear implants. *Organization Science*, 5(3), 344-362.	Historical case study; cochlear implants	***Variation***: Cognitive ambiguity in terms of what is technologically feasible ***Selection***: Creation of routines of evaluation ***Retention***: Not addressed
Bijker, Wiebe E. (1997) *Of bicycles, bakelites, and bulbs: Toward a theory of sociotechnical change*. MIT press, 1997.	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(5), 790-805.	Theoretical	***Variation***: Different cognitive frames amongst 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(2), 270-295.	Quantitative; workstations	***Variation***: Not addressed, ***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(3), 439-471.	Mixed methods; satellite radio	***Variation***: Not addressed ***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(3), 277-302.	Quantitative; digital cameras	***Variation:*** Prior industry experience ***Selection***: Not addressed ***Retention:*** Not addressed
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(1), 14-34.	Historical case study; computers within the insurance industry	***Variation:*** Not addressed ***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(3), 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(1), 149-166.	Multiple case study; computers within the insurance industry	***Variation:*** Attempts to with cognitive schemas, ***Selection:*** Cognitive familiarity selected, ***Retention:*** Not addressed
Raffaelli, R. (2019). Technology reemergence: Creating new value for old technologies in Swiss mechanical watchmaking, 1970–2008. *Administrative Science Quarterly*, 64(3), 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(2), 395-433.	Qualitative, multiple-case study of the air taxi market	***Variation:*** Prior industry affiliation ***Selection:*** Flexibility in frame and business models ***Retention:*** Not addressed

Table 5d. 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*(3–4), 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 *Mapping the dynamics of science and technology* (pp. 19–34). Springer.	Historical case; electric vehicle	***Variation***: Social dynamics between human and non-human 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(3), 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*(6), 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,* 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(3), 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(02), 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(10), 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*. JHU 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*(5–6), 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 US radio field. *Administrative Science Quarterly*, *63*(1), 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*(4), 783–818.	Historical case study	***Variation:*** *S*elf-interest ***Selection:*** Categorization ***Retention:*** Power actors

Table 6. Descriptive Statistics of Papers in the Technology Evolution Literature

	Technological-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%
The Time Span of the Paper					
Cross-sectional	18%	10%	21%	31%	**17%**
Part of the lifecycle	33%	39%	35%	46%	**38%**
One or more lifecycles	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%

Table 7
Data for Multi-method Analyses

Type	Source	Number of articles
Industrial robot industry	Trade Journals *Industrial Robot* (1973-2020) *Robotics World* (1993-2006)	 723 (2,278) 223
Industrial/ Mobile robot industry	Associations for Advancing Automation *"Industry Insight"* articles (2000-2020)	1,062
Public	Technology Magazine *Popular Mechanics* (1921-2020)	 1,354
Academia	Technical notes and seminal articles in related fields • MIT AI lab, Stanford AI lab, DoD, et cetera. (1962-2016) International Journal of Robotics Research (1982-) General academic journal *Science* (1962-) *Science Robotics* (2016-)	81 526 49
Defense/ Government	Trade Journals *Military Robotics* (1991-1998) Congressional hearings (1996-2020)	 403 (1,058) 784
Overall historical context (books)	AI (Crevier, 1990) Cambrian Intelligence (Brooks, 1995) Strategic Computing: DARPA and the Quest for Machine Intelligence, 1983-1993 (Alex & Philip, 2002) The Quest for Artificial Intelligence: A History of Ideas and Achievements (Nilsson, 2010)	4

Table 8: Overview of the Mechanisms

Phase	Mechanism	Quotes
Pre-phase: Distant Technological Vision	Inspiration	"Robot that moves and talks opens a London exposition: "Eric," a man of tin who moves and talks, stood up, when asked to, on a platform in London recently and formally declared open the annual exhibition of the Model Engineer society. Looking like a suit of ancient armor borrowed from the London Tower, the mechanical man, … made a whirring noise and slowly arose until he stood more than six feet tall." (Popular Mechanics, Dec 1928)
Phase 1: Field Linking the Novel Technological Means to Distant Vision	*Trigger*	*Technological triggers: Digital computer and numerical control*
	Linking the novel means to distant vision	"Reporting a robot for industry, and this is it, Unimate—a machine that can reach out to seven feet and perform a multitude of tasks in factory or laboratory as skillfully as a man, but without getting tired. It's controlled by a built-in memory system. You just lead it once through the required motions and it can then repeat them 24 hours a day, week after week. It can position objects to within 50 thousandths of an inch, completely unaffected by heat, cold, fumes, or dust. It could take over a lot of unpleasant jobs." (British Movietone newsreel, 1967) "This report describes the results of research during the past nine months on the project, 'Application of Intelligent Automata to Reconnaissance.' The primary goal of this project is to investigate techniques in artificial intelligence applied to the control of a mobile automaton in a realistic environment." (Rosen & Nilsson, 1967) "Many tasks done by human hands cannot yet be taken up by automatic machines. Machines can, however, extend the capacities of the hand, and they suggest ways in which manipulation can be made automatic. … There are now manipulators for handling explosive chemicals, for working underwater and for certain industrial operations. I shall discuss … a general type of manipulator that is capable of doing various kinds of jobs seems to open the way … for amplifying man's powers and performances." (Mosher, 1964)
	Communities converging on the vision	The publication of the first trade journal *Industrial Robot* (1973) The foundation of the Robotics Industries Association in Ann Arbor, Michigan (1974) "Machines are generally blind, deaf, dumb and moronic. … [But] With modern techniques of information processing and machine control the emancipation of man from mental as well as physical drudgery is within our grasp." (Heginbotham, 1973) "In 1968 or maybe '67, there were a couple of guys. One was named Joe Engelberger and another one was named George Devol [the founders of Unimate]. … He wanted to give some money to somebody at Stanford as a fellowship to work in robotics and Stanford picked me." (IEEE interview with Victor Scheinman)

Phase 2: The Narrowed Vision-Reality Gap	*Salient Success*	*Economic trigger: the first commercially viable product for the initial market*
	Envisioning sequences	"One of the exercises was a Delphi forecast and some of the conclusions that emerged from this workshop were … There is a strong consensus among all participants that simple vision is the number one priority for research and development efforts. … Sensory capabilities, including complex vision, are seen to reach commercial availability before 1985." (Engelberger, 1979) "Jerry Kirsch, president of Auto-Place said vision will 'play a major role in assembly systems', especially in batch production. He also believes that while the current ratio of activity is 80/20 in favour of arc and spot welding this will change to 80/20 in favour of assembly in the next three - five years." (Industiral Robot, 1980) "This report identifies potential military applications of robotic-artificial intelligence technology and considers near-, mid-, and far-term technological projections. … Current efforts to refine this technology are constrained in time and focus primarily on near-term applications. As the field of robotics develops, wider applications can be expected. By 1990, the development of other sensory techniques will enable robots to approximate human capabilities in assembly tasks." (Crumley, 1982) "At present, research papers in robotics are distributed across a number of journals, … or, more likely, they are never published in refereed journals at all. Most often, papers are circulated as laboratory reports or appear in conference proceedings. … The media, industry, and research sponsors are assured that the time for a surge in robotics has arrived. There is plenty of work to be done, involving challenging applications, innovative designs, and a fresh insight into motor control and perception." (Brady & Paul, 1982)
	Over-commitment of resources	"It is inevitable that there will be a big shake out of companies in future. At the present time it is relatively easy to get venture capital, in fact you have only to put the name of robot in the company and the dollars come pouring in! But eventually this money is going to run out. It is to be hoped that when this happens the potential of robots will not be lost through bad experiences due to over commitment and over optimism on behalf of budding roboticists." (Industrial Robot, 1982)
Phase 3: The Expanded Vision-Reality Gap and Deconstruction of Vision	*Salient Failure*	*Economic trigger: a stall in the initial market*
	Disillusion-ment	Robot growth rate falter[ed] in 1986. … Certainly there has been a lot of hype and possibly an overreaction to their capabilities. … This trend was predicted some time ago but it was expected that some of the newer applications would take over, in particularly assembly. This has not happened as quickly as expected. (Rooks, 1987) No matter how many galley slaves you put on the galley and no matter how hard you beat them, you are not going to row to the moon. You have to have a different approach. (quoted in Roland & Shiman, 2002)

		There were no vision systems around doing anything even remotely as sophisticated. The progress in computer vision was questioned. … SRI held a weekly seminar series [in 1984] to try to uncover the sources of the seeming stall in computer vision. (Brooks, 1999)
	Deconstructing and reconstructing visions and goals	The basic philosophy was that the company should be application-orientated, rather than robot-orientated. So we limited the performance of the robot to the needs of those applications, rather than try to make a universal robot that can do many things, but probably poorly. (Rooks, 1988b) Recent Pentagon decisions bringing down the youthful Defense Airborne Reconnaissance Office and the JPO implement Congressional direction in the fiscal 1998 budget, even though Congress itself created the JPO 10 years ago. Aquila became a powerful symbol of a formula for failure. The last we heard then- Aquilas left over from the doomed project were put in storage. Given the Air Force's traditional disdain of robot planes, the so-called hubristic "silk- scarf" syndrome, the battlelab has a daunting challenge: to forge air battle plans mixing manned and unmanned systems. (Military Robotics, Apr 1998) As I see it, the Robotic Industries Association is finding it hard to locate research worthy of being honored. Worthy, that is, in promising some utilitarian benefit. Somehow giving robots facial expressions, the ability to walk, or yet another navigation algorithm does not measure up. No, and gladiatorial skill at mangling other robots is not helping the robotics industry. Paper after paper has no more utility than a place in the bibliography of a subsequent paper. … Some of the blame can be laid upon the leading robot manufacturers. They should know where the research opportunities lie; but, in the face of market softness, longer range R&D is abrogated. They battle mightily for conventional applications when future leadership will be borne of current R&D. Meanwhile professors, unfettered by reality, create projects for students who have no goals other than Master's and Ph.D. theses. (Industrial Robot, 2002)
Phase 4: Revival and Reintegration	*Trigger*	*Field-configuring event intended for reintegration*
	Reviving the latent vision	Inspired by the hugely successful DARPA Grand Challenge, … the workshop was charged with defining the grand challenges for their research areas. This involved identifying the main problems that were still to be resolved, discussing which challenges held the most promise for moving the field forward, and selecting representative challenge tasks or demonstrations that could be used to serve as tests for progress being made toward solving these challenges. Grand challenges such as these can serve as concrete targets for which multiple groups can focus their research efforts in order to make tangible, and measurable, progress. (Ostrowski, Tapus, & Yim, 2007) Robots will become just as ubiquitous, all-purpose and adaptable. Automation will do what it has always done. Make things faster, easier, better. Industrial, meets Collaborative, meets Service Robotics. The differences will become inconsequential, indistinguishable. The best technologies from each will converge to create robots that just get the job done. Collaboration will transcend species, from human-robot, to robot-robot and robot-machine. It will seamlessly integrate advanced technologies that give robots their intelligence – sensing, perception, learning, communication, grasping. (Industry Insights, Jan 2015)

		While more capable than ever, robotic bin picking still has its limitations. We haven't quite grasped that Holy Grail – random bin picking with robots. But there have been tremendous strides. Empowered by advanced vision technology, software, and gripping solutions, robots are finding their way in unchartered territory. (Industrial Insights, Mar 2016)
	Reintegration of the Field	There is so much that has happened in the last 10 years in terms of developing an ecosystem for start-ups. We're seeing more accelerators open with a focus on hardware and even specifically on robotics. Qualcomm and Techstars have just opened a robotics accelerator and it's not the first one to focus on robotics. Back in 2012, there were only two hardware accelerators, and in two years approximately 15 others have opened. That's huge! (Industry Insights, Jan 2015) DARPA is offering US$2 million to creators of a robot that can drive an open-frame utility vehicle to a building in need of repairs, find a leaking pipe, and fix it. This is not a pipe dream. Even under supervised autonomy, it illustrates the incredible progress of robotics since the first Grand Challenge was announced a decade ago. (Dietsch, 2012) Tomorrow's robotics are taking shape in today's labs. From package delivery robots and self-driving cars, to surgical snakes and search and rescue robots, the innovations have profound implications. A year, 3 years, or maybe 5 to 10 years down the road, they could be at our door, in our home, or at our side when we need them most. As we've said before, robotics is a multidisciplinary sport. The traditional areas of study, mechanical engineering, electrical engineering and computer science, have broadened into biological systems and cognitive science. Many of the top university robotics programs are attacking robotics challenges from all angles and making fascinating discoveries along the way. (Industrial Insights, Oct 2018)

Table 9. Data sources

	Type	Source	Number of articles	Years
Main data	Public interviews	***Industrial Robot*** Public Interviews (“***Pransky Interview***”) • Conducted by Joanne Pransky, the associate editor of *Industrial Robot*	37	2013-2019
	Oral histories	***IEEE Robotics History: Narratives and Networks*** • Conducted by The IEEE History Center	89	2005-2010
	Patents, publications, and further public interviews	Patents, publications, and further public interviews of 46 founders and 58 entrepreneurial firms identified in the interviews and oral histories	collecting	1970s-now
Supplementary data	Trade journals and magazines	*Industrial Robot* Associations for Advancing Automation *“Industry Insight”* articles (2000-2020)	1,289 1,062	1973-2020 2000-2020
	Books	AI (Crevier, 1990) Cambrian Intelligence (Brooks, 1995) Strategic Computing: DARPA and the Quest for Machine Intelligence, 1983-1993 (Alex & Philip, 2002) The Quest for Artificial Intelligence: A History of Ideas and Achievements (Nilsson, 2010)	4	1990-2010

Table 10. Descriptive data on entrepreneurs and academics

Industrial Robot public interviews ("Pransky interview") 2013-2019	**Number of firms**: Number of interviews: 37 **Entrepreneurs**: **27** Government lab: 5 Percent female: 13.5%
IEEE oral histories Robotics History: Narratives and Network 2005-2010	**Number of firms**: Number of interviews: 89 **Entrepreneurs**: **15** Government lab: 17 Academia: 54 Percent female: 13.6%
Smithsonian Archive Group Interviews 1989-1990	Company: 1 University lab: 3

Table 11: Entrepreneur Descriptives

id.	Name	Number of interview scripts	Number of entrepreneurial firms founded	Type of product	Main market domain	Academic job	Gender	Linkedin profile
4	Paolo Pirjanian	1	1	hardware	consumer	-	m	y
9	Helen Greiner	1	2	hardware	consumer	-	f	y
13	Steve Cousins	1	1	hardware	consumer	-	m	y
21	Aaron Edsinger	1	1	hardware	consumer	-	m	y
28	Maja Mataric	1	1	hardware	consumer	professor	f	y
31	Ayanna Howard	1	1	hardware	consumer	professor	f	y
32	Frederick Kaplan	1	1	hardware	consumer	professor	m	y
2	Russ Angold	1	2	wearable	healthcare	-	m	y
5	Moshe Shoham	1	2	hardware	healthcare	professor	m	y
11	Yulun Wang	1	1	hardware	healthcare	-	m	y
14	Rosen Jacob	1	2	hardware	healthcare	professor	m	y
18	Howie Choset	2	3	hardware	healthcare	professor	m	y
19	Cory Kidd	1	2	hardware	healthcare	-	m	y
22	Amit Goffer	1	3	wearable	healthcare	-	m	y
36	Ken Salisbury	1	2	hardware	healthcare	professor	m	y
16	Melonee Wise	1	1	hardware	logistics	-	f	y
17	Aldo Zini	1	1	hardware	logistics	-	m	y
20	Mitchell Weiss	1	1	hardware	logistics	-	m	y
23	Daniel Theobald	1	1	hardware	logistics	-	m	y
1	William Townsend	1	1	hardware	manufacturing	-	m	y
6	Rich Walker	1	1	hardware	manufacturing	-	m	y
7	Rodney Brooks	1	3	hardware	manufacturing	professor	m	y
10	Esben Ostergaard	1	1	hardware	manufacturing	-	m	y
25	Brian Carlisle	2	2	hardware	manufacturing	-	m	y

27	Ken Goldberg	2	1	hardware	manufacturing	professor	m	y
29	John Craig	1	2	software	manufacturing	-	m	y
33	Jean Paul Laumond	1	1	software	manufacturing	professor	m	n
37	Victor Scheinman	1	2	hardware	manufacturing	-	m	n
38	Bruce Shimano	1	2	hardware	manufacturing	-	m	n
3	Yoky Matsuoka	1	2	software	niche	-	f	y
8	Martin Buehler	1	1	hardware	niche	-	m	y
12	Rob Buckingham	1	1	hardware	niche	-	m	y
15	William "Red" Whittaker	2	2	hardware	niche	professor	m	y
24	Mel Torrie	1	1	software	niche	-	m	y
26	Howard Chizeck	1	1	software	niche	professor	m	y
30	Ralph Hollis	1	3	hardware	niche	-	m	n
34	Matt Mason	1	1	hardware	niche	professor	m	y
35	Richard Murray	1	1	software	niche	professor	m	y
		Total=42	Total=58				F=13%	

Table 12. Contribution of the empirical papers to four perspectives of technology evolution

	Technology-realist perspective	**Economic-realist perspective**	**Cognitive-interpretivist perspective**	**Social constructionist perspective**
		Chapter 2		
Variation	Challenge the perspective	Extend the perspective	Support and extend the perspective	Support and extend the perspective
	Technological variation does not simply emerge by evolutionary processes according to this study. It is not merely driven by random combinations or mutations of existing technologies as often assumed in relevant literature. Thus, the changes between different technological regimes cannot be explained by … or the law of nature that predetermines how a particular technology can evolve	Technology variation is driven by R&D spending, but the previous literature has not highlighted what is the determinant of the direction of R&D investment—in other words, the types of technology that receive investment. Technological visions and the way in which they are understood can be an important construct that affects the direction of future-oriented economic decisions and flow of investment.	Technology variation is created via diverse backgrounds from which different innovators' cognitive patterns are shaped, as supported in this study. Mainly building on this perspective, this study further suggests the importance of forward-looking cognition which is the mental representations of possibilities in the future, in addition to retrospective cognition which has been studied in the literature more extensively.	Technology variation is shaped through the process of social construction, which determines whose perspective is considered valuable, and reflected in actions. This study casts particular insights on how marginal actors can persuade powerful actors to invest in a future-oriented technology, and what is the advantages and disadvantages of using visionary rhetoric. This study contributes to our understandings of the emergence of a large technological field.
Selection	Support and extend the perspective	Support and extend the perspective	Support and extend the perspective	Support and extend the perspective
	Technology selection is driven by superior performance of a technology or being the winner under the presence of strong network effects. This study supports the existing assumption that a technology gets selected or de-selected based on performance. In the development of a large technological system, constraints can emerge in developing a core component as	Technology selection is driven by price/performance ratio, or whether the technology is cost-effective enough to sell in the market. Economies of scale are an important mechanism. While this study does not contradict this basic assumption, it further extends the literature by suggesting the importance of the "expectation" about the changes in price/performance ratio in the future.	Technology selection is driven by the fit between users' cognitive understandings or existing social categories and the technology itself. While supporting this perspective, this study further extends the theory by pointing out that the users' cognitive understandings can have a futuristic and temporal dimension. Users' cognitive understandings are not confined to what is the immediate use of a	Technology selection is driven by the fit between the existing power, network structure, and interests of stakeholders and the technology itself. While supporting the perspective, the findings of the study also suggest that material performance matters in terms of drawing interests from powerful stakeholders. The interest alignment triggered by proof of concepts

	a bottleneck, which stalls the evolution of the whole system.		technology, but promised use of a technology in a near future.	
Retention	Contribution limited	Contribution limited	Contribution limited	Support and extend the perspective
	Technology retention is achieved through path dependency. This study provides limited contribution to this perspective because this study looks at multiple, diverse technological designs that emerged from the same underlying technological field.	Technology retention is achieved through economies of scale. While this study provides limited insights into this aspect, the national level differences in the success or failure of a certain technology might be attributed to whether the country achieved economies of scale.	Technology retention is achieved through cognitive priming and lock-in. The contribution of this study to this aspect of technology evolution is limited because this chapter studies forward-looking cognition about a market construct that has not fully established yet.	Technology retention is achieved through entrenchment of power and network structures. This study indirectly speaks to this aspect of technology evolution by showing how vision-reality gap influences the stability or changes in the existing power and interests embedded in an emerging field.
		Chapter 3		
Variation	Contribution limited	Contribution limited	Support the perspective	Support the perspective
	Technology variation is created in different problem-solving processes, which often happen in academia. This study focuses more on how entrepreneurs formulate and construct a problem given a new technological means, with less emphasis on how technologies evolve from pre-existing ones.	Technology variation is created in different problem-solving processes in an individualized manner. This paper focuses less on how collective R&D investment flows into a particular domain to advance a technological field.	Technology variation is created through diverse cognitive backgrounds. This can also lead to different people interpreting the same technological means differently. This leads to potential entrepreneurs formulating different initial search problems. Vision shapes the kinds of networks that are formed; which networks to access. The vision creates a search space – not for technology but also for people.	Technology variation is created through entrepreneurs and stakeholders differently positioned in the power and network structures. The findings of the study correspond to this perspective, and this aspect plays a role as a moderator in this study.
Selection	Challenge the perspective	Challenge the perspective	Support the perspective	Support and extend the perspective
	This paper challenges the assumption that technology selection is driven by superior performance. This study shows	This paper partially conforms to the assumption that technology selection is driven by price/performance ratio.	Technology selection is driven by the fit between users' cognitive understandings and the technological design features.	Technology selection is driven by the fit between the existing power, network structure, and interests of stakeholders and the technology

	that performance superiority is only established when the configuration of features becomes clear that fits the market needs. In other words, technology superiority cannot be measured by one measure, but by a unique configuration of many features that is awaiting to be revealed. This challenges the assumption about selection by performance.	However, in parallel with the technology-realist perspective, it is not clear what is the criteria of performance in the beginning, and demand heterogeneity is particularly important in the formulation of entrepreneurial problem space. This paper challenges the core assumption about performance in the economic-realist literature.	This paper supports this perspective by showing that the ultimate goal of entrepreneurial problem formulation is to achieve product-market fit, which determines the success and failure of an entrepreneurial firm in the market.	itself. While the importance of this social and institutional fit is often emphasized in the literature, it is less addressed in the works on entrepreneurial search. This paper contributes to the understanding of social and institutional considerations in the process of entrepreneurial problem formulation.
Retention	Support and extend the perspective	Support and extend the perspective	Support and extend the perspective	Support and extend the perspective
	Technology retention is achieved through path dependency. This paper suggests how entrepreneurs construct and narrow the problem space so that their technology achieves enduring path dependency.	Technology retention is achieved through economies of scale. By examining early-stage entrepreneurial firms that aim to achieve this, this paper shows how entrepreneurs formulate problems in a way that increases the likelihood of achieving economies of scale in the future.	Technology retention is achieved through cognitive priming and lock-in. By examining early-stage entrepreneurial firms that aim to achieve this, this paper shows how entrepreneurs formulate problems in a way that increases the likelihood of achieving cognitive lock-in for their technological design.	Technology retention is achieved through entrenchment of power and network structures. By examining early-stage entrepreneurial firms that aim to achieve this, this paper shows how entrepreneurs formulate problems in a way that increases the likelihood of building an institutional structure that ensures the success and adoption of a technological design.

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

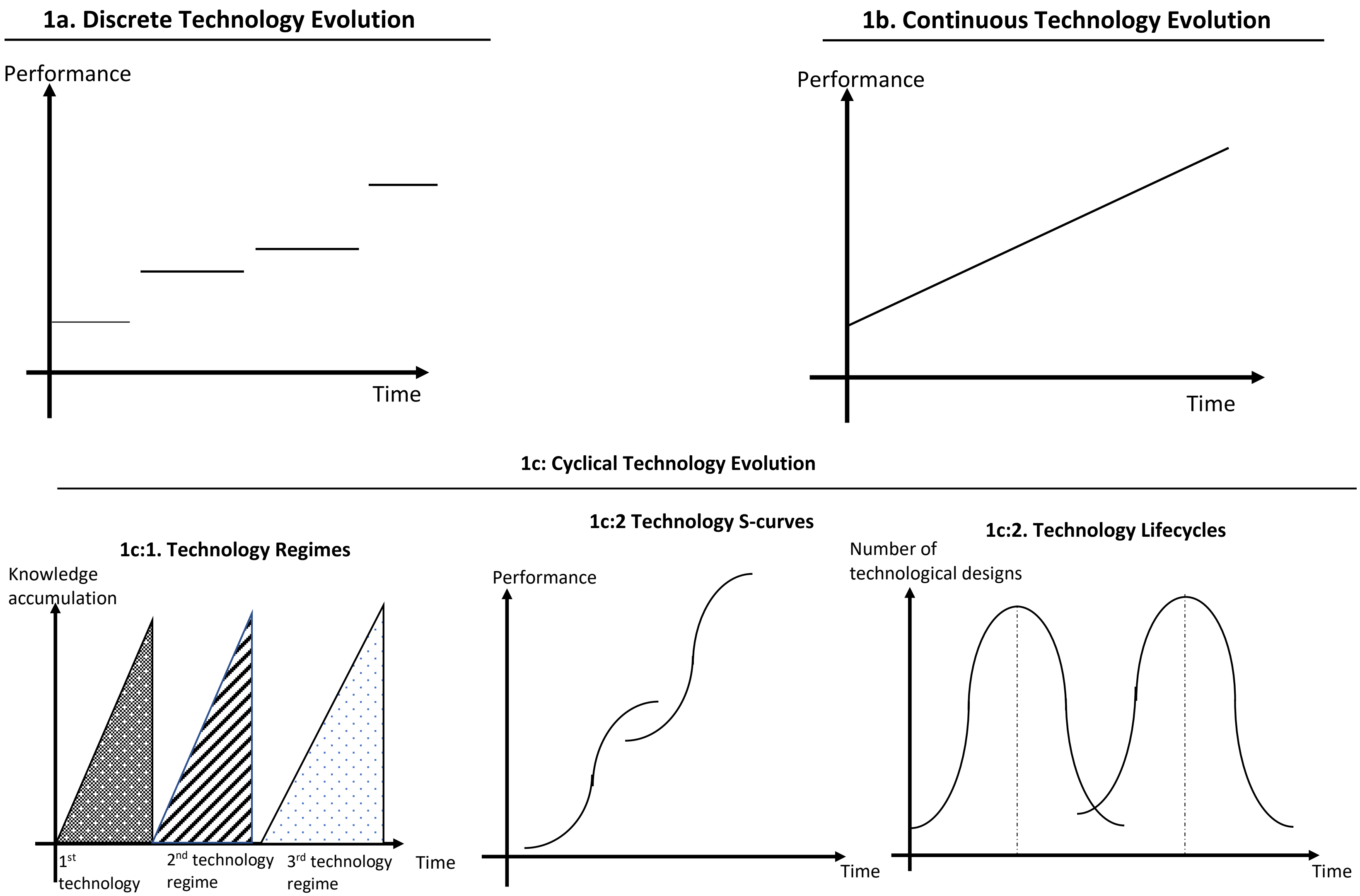


Figure 2: Technological Designs during the Evolution of the Bicycle

Name and Year	Technological Designs
Hobby-horse (1820s). The hobby-horse was one of the first bicycles that were 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 "The most important technological improvement (Bijker, 1997; Minetti et al., 2001)	
The high wheeler (1870s) The iconic high wheeler came on the market about ten-years after the boneshaker. The rational 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/

Figure 3: Model of Technological Evolution

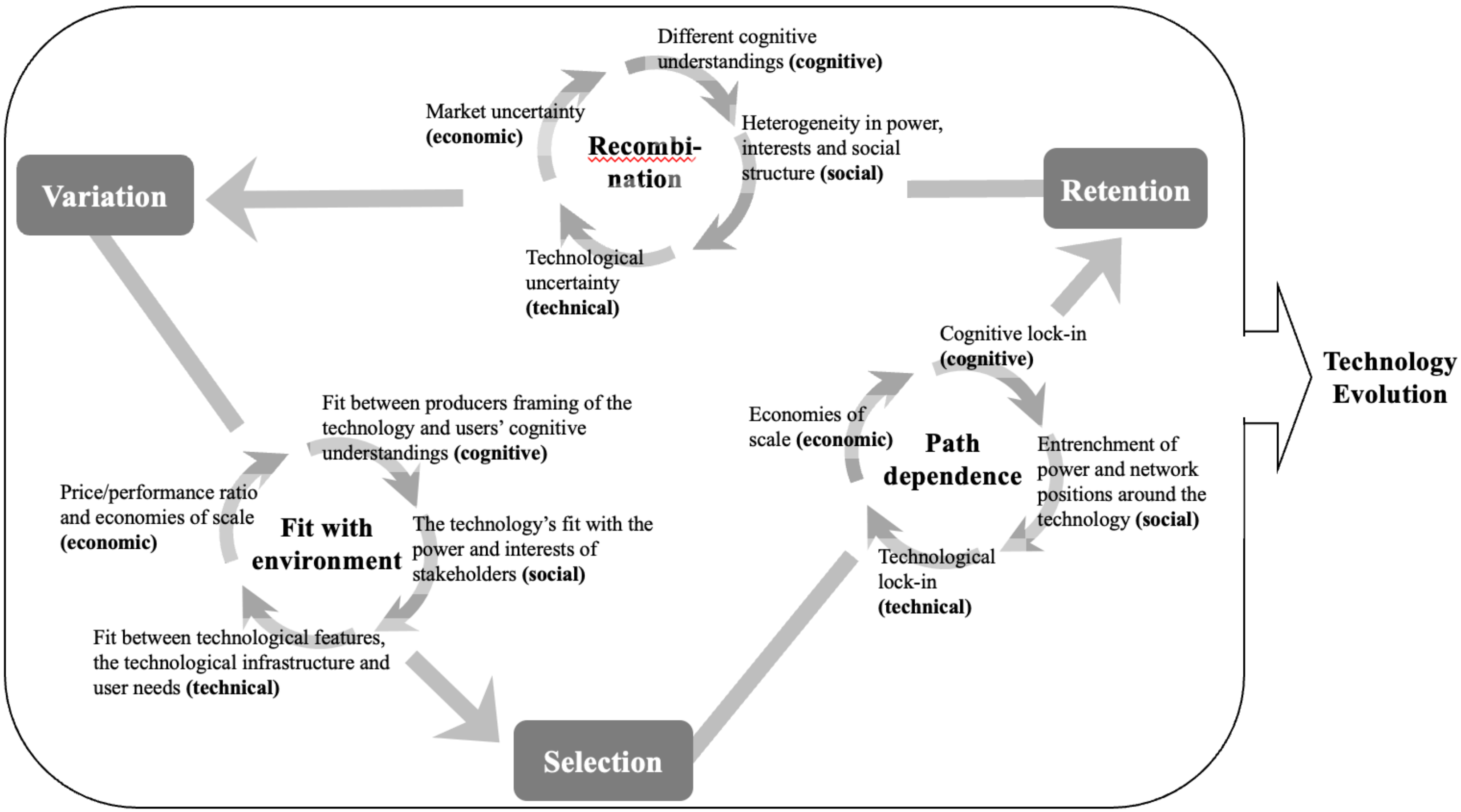


Figure 4. The Number of Papers in the Technology Evolution Literature Over Time

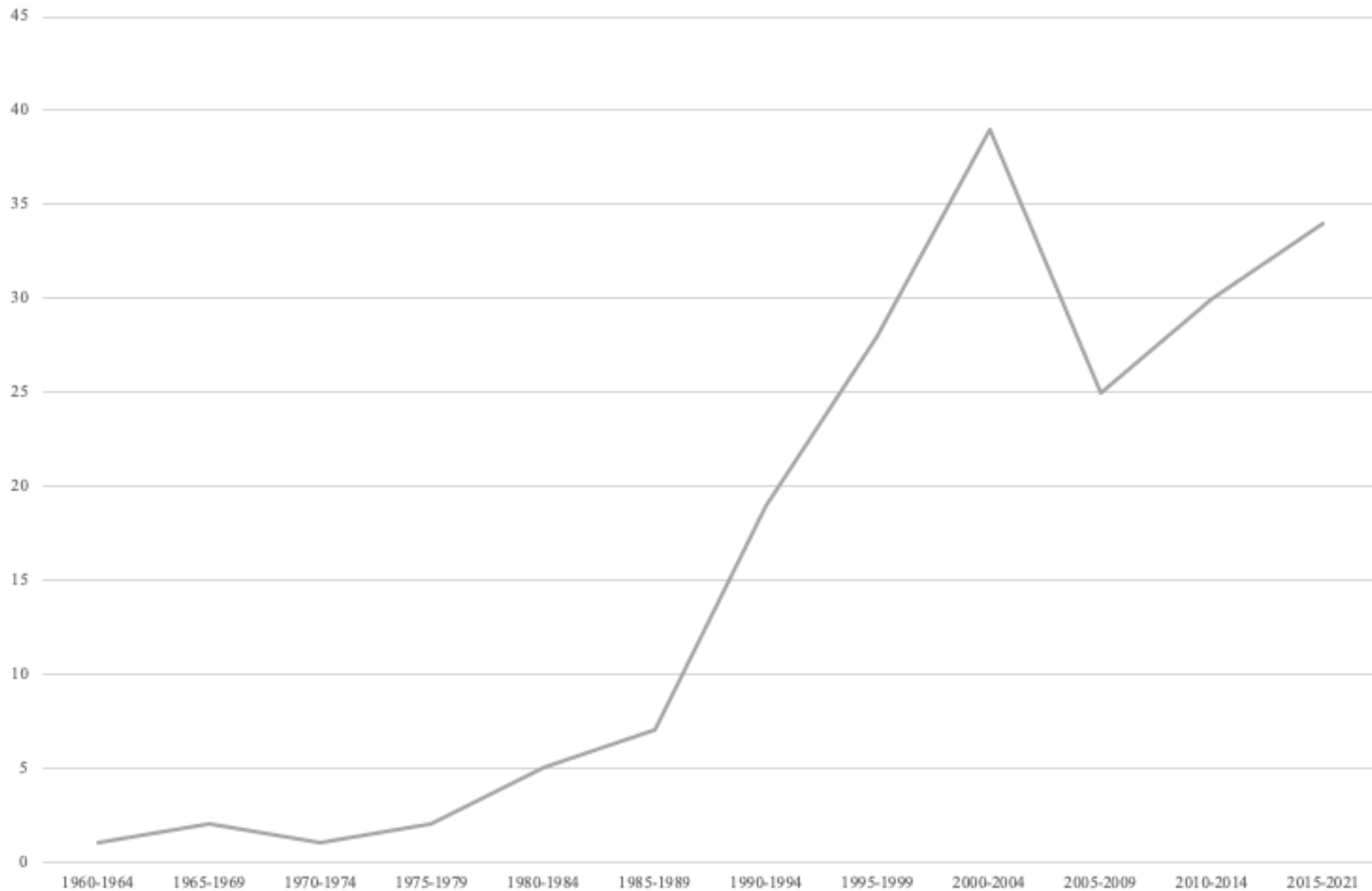


Figure 5. The Number of Papers in Each Perspective Over Time

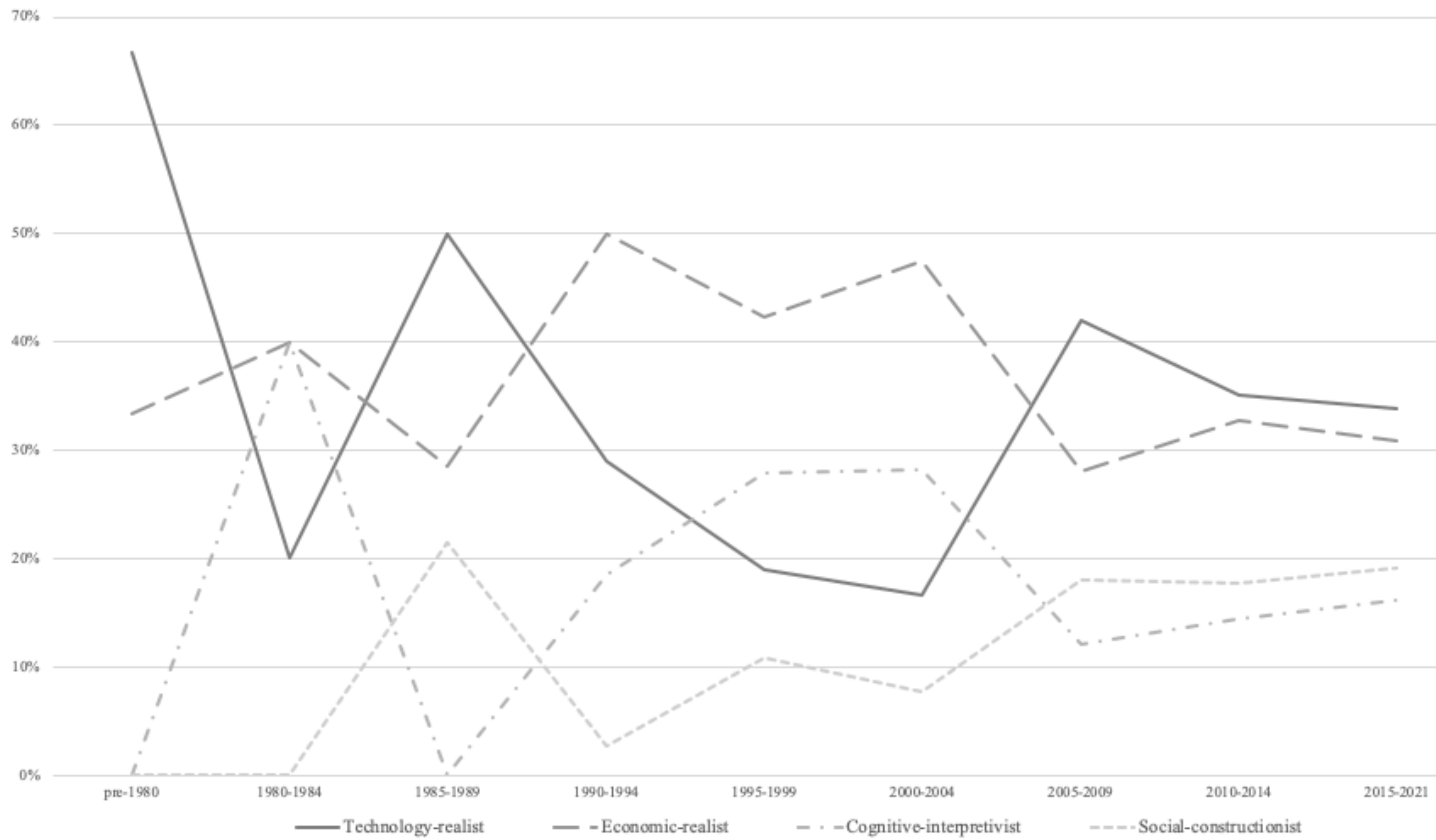


Figure 6. The Number of Lifecycles Covered in the Papers Over Time

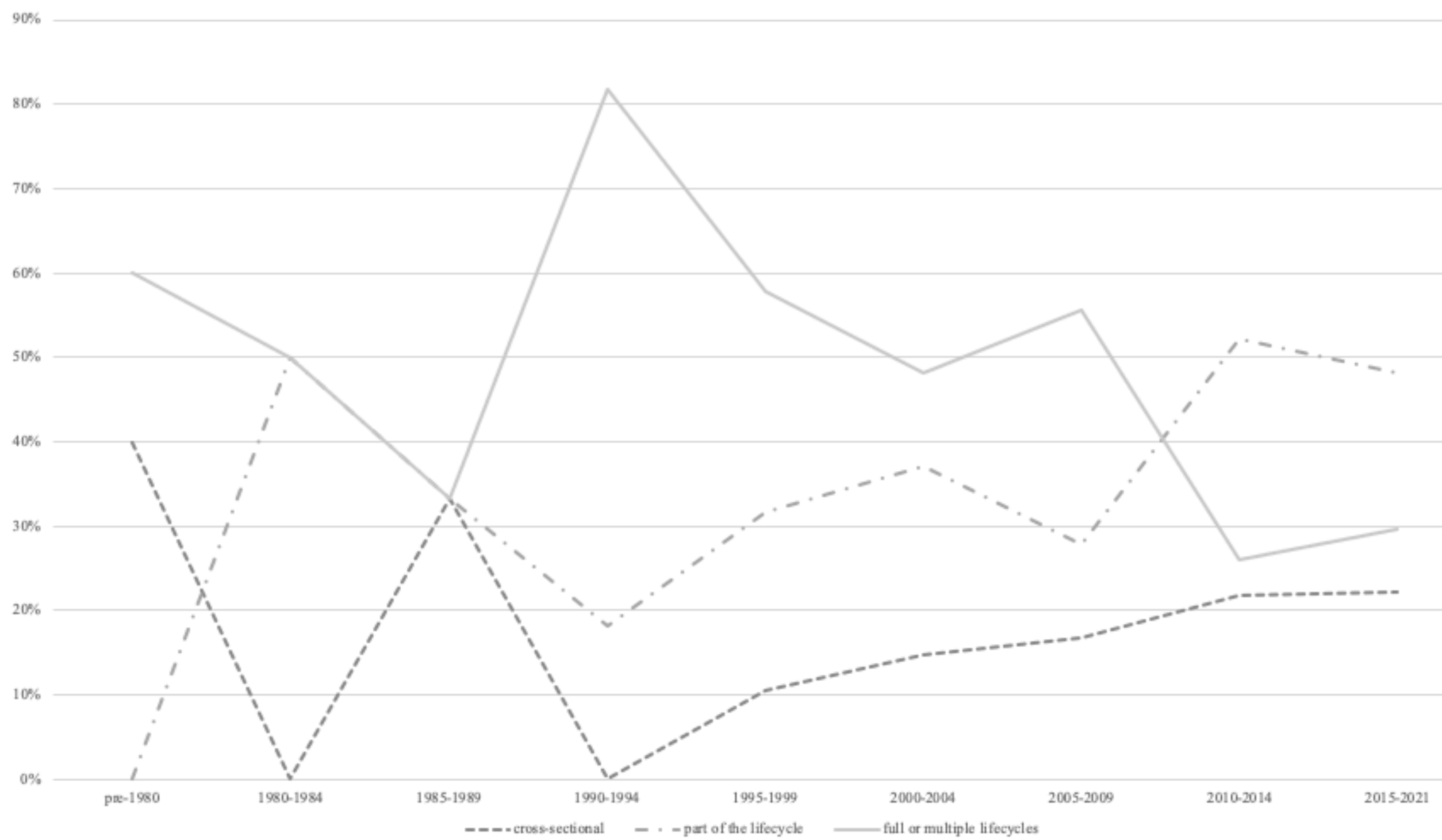


Figure 7. Process of Data Collection and Analysis

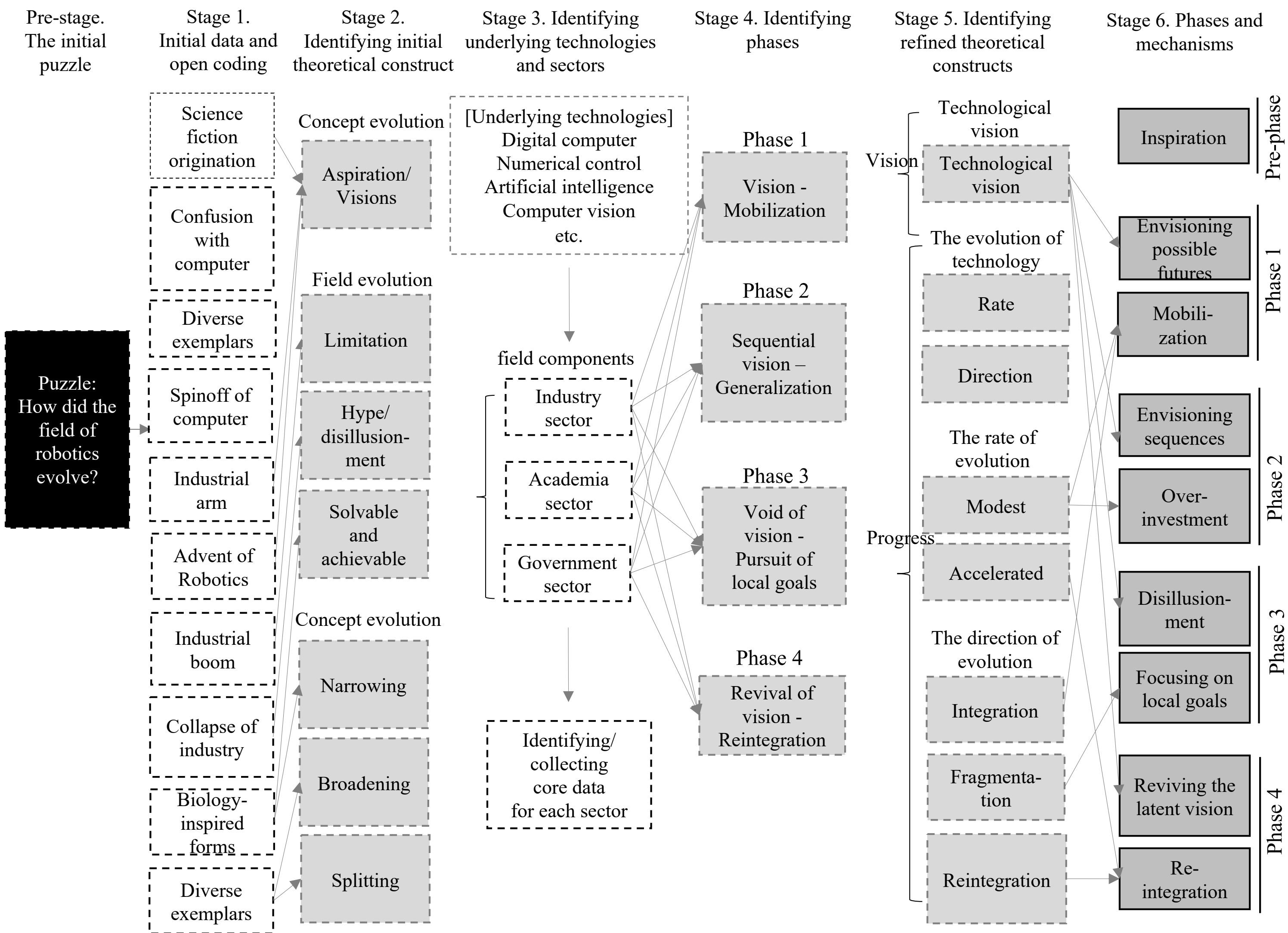


Figure 8. Time trend in the frequency of the term "Robot"

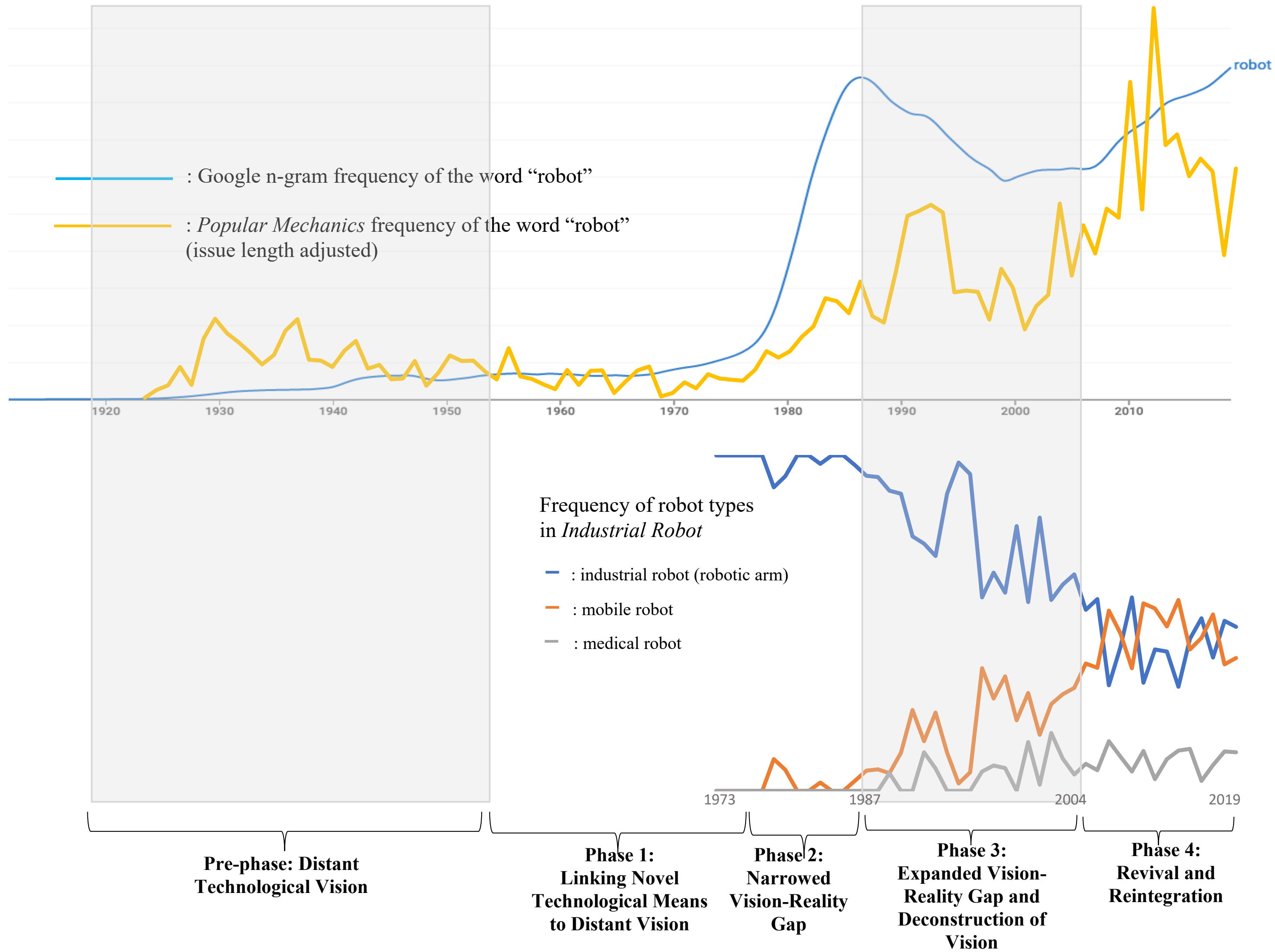


Figure 9. Process Model of the Co-evolution of Technological Vision and Technological Progress

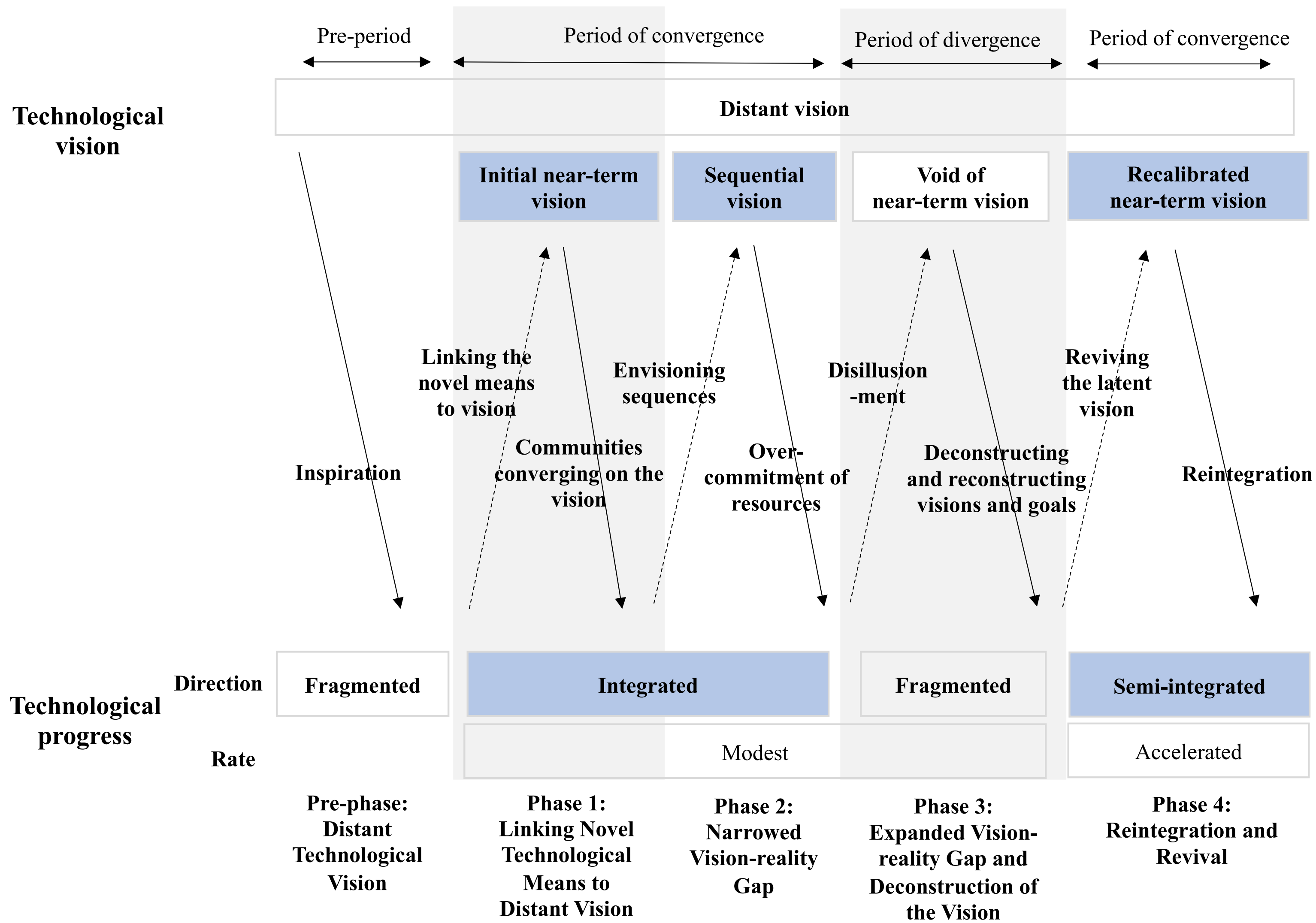
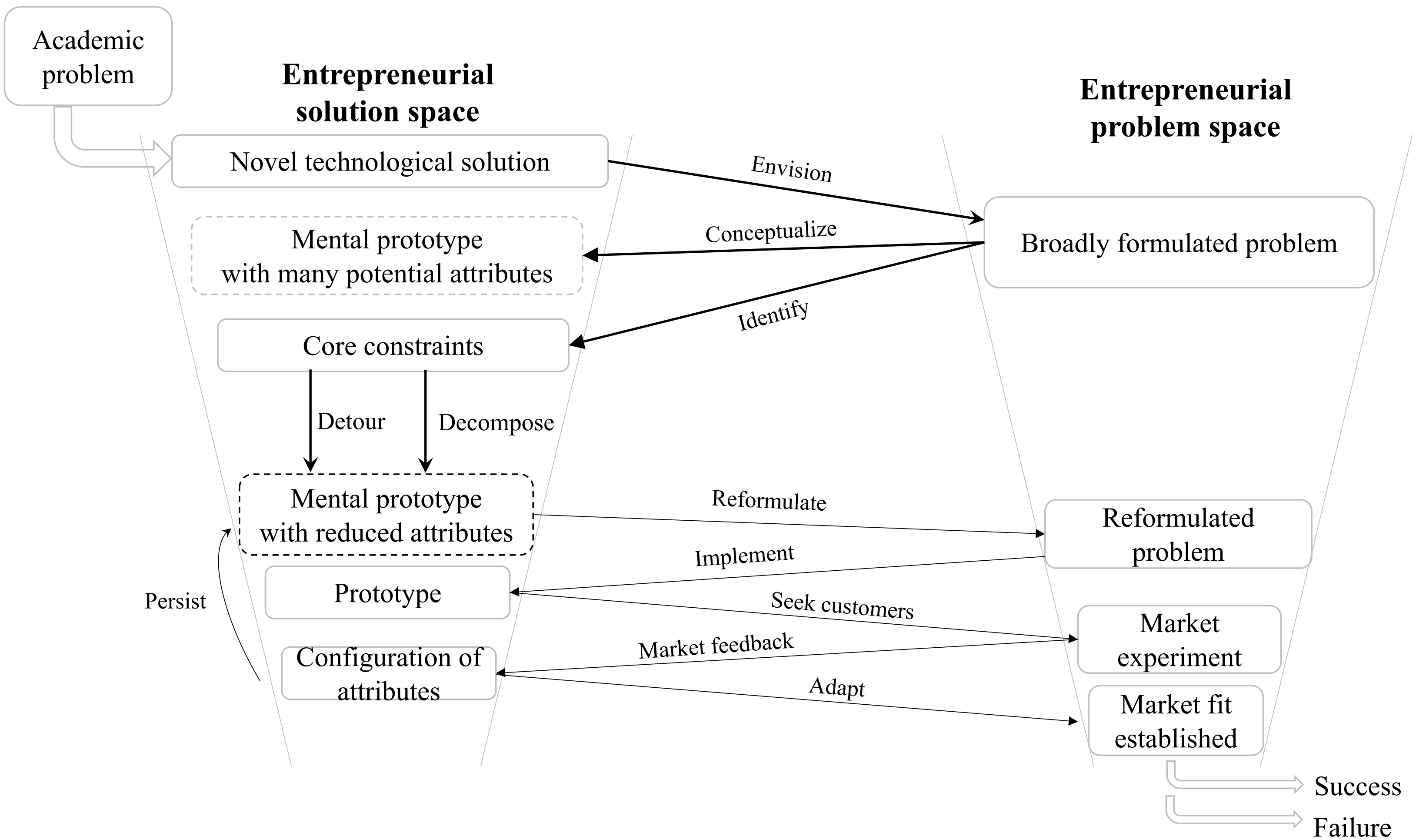


Figure 10. Process model of co-construction of entrepreneurial problems and solutions



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CURRICULUM VITAE

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