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CHARACTERIZING ENABLING INNOVATIONS AND ENABLING THINKING

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CHARACTERIZING ENABLING INNOVATIONS
AND ENABLING THINKING

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ABSTRACT

Solis Novelo, Freddy G. Ph.D., Purdue University, May 2015. Characterizing Enabling Innovations and Enabling Thinking. Major Professor: Dr. Joseph V. Sinfield.

The pursuit of innovation is engrained throughout society whether in business via the introduction of offerings, non-profits in their mission-driven initiatives, universities and agencies in their drive for discoveries and inventions, or governments in their desire to improve the quality of life of their citizens. Yet, despite these pursuits, innovations with long-lasting, significant impact represent an infrequent outcome in most domains. The seemingly random nature of these results stems, in part, from the definitions of innovation and the models based on such definitions. Although there is debate on this topic, a comprehensive and pragmatic perspective developed in this work defines innovation as the introduction of a *novel* or *different* idea into practice that has a positive *impact* on society. To date, models of innovation have focused on, for example, *new* technological advances, *new* approaches to connectivity in systems, *new* conceptual frameworks, or even *new* dimensions of performance – all effectively building on the first half of the definition of innovation and encouraging its pursuit based on the novelty of ideas. However, as explored herein, achieving profound results by innovating on demand might require a perspective that focuses on the *impact* of an innovation. In this view, innovation does not only entail doing new things, but consciously driving them towards achieving impact through proactive design behaviors. Explicit consideration of the impact dimension in innovation models has been missing, even though it may arguably be the most important since it represents the *outcome* of innovation.

With this in mind, this qualitative study focuses on creating a comprehensive impact-based perspective of innovation that: 1) classifies innovations by their impact and creates a model trajectory of innovations and their impact over time, and 2) develops an end-to-end design framework informed by the impact-based innovation model. To achieve this impact-based perspective, the study engaged in a multifaceted approach with two separate yet interrelated research streams.

The first research stream focused on characterizing what is herein termed the *enabling innovation* model. Classifying innovations by their impact and understanding the development of impact over time inherently requires a definition of innovation impact. A scholarship of integration study was employed to synthesize disparate impact perspectives throughout the policy, science, and business innovation literature into a transdisciplinary perspective of the impact of innovations. As a result, in this study, impact is defined as the degree to which an innovation alters the way individuals, groups, and societies live and act, and can be decomposed into the fundamental dimensions of *reach*, *significance*, and *paradigm change*. To create an impact-based classification and model trajectory of innovation, a set of nine strategically selected historical innovation cases were examined, using secondary historical research sources as data, to extract themes regarding common impact characteristics, development trajectories, and possible screening mechanisms. Based on these cases and impact dimensions, the model contrasts what are herein termed *enabling* innovations with *progressive* innovations. Enabling innovations exploit a new paradigm that alters worldviews, have broad reach across individuals, groups, and societies, and significant impact across measures of economics, environment, health, and culture. These innovations generate an impact cascade that affects many application spaces, take many architectural forms, and address multiple families of problems. At the other end of the spectrum, progressive innovations build on a working paradigm, have limited reach and drive focused changes across select measures of economics, environment, health, and culture. Both forms of innovation are complementary and fundamental to societal advance, and this enabling-progressive model suggests that a few innovations drive the majority of value creation in society. The research also investigated the development of enabling innovations, highlighting three key stages: *the stage of breakthroughs*, *the enabling window,* and *the progressive cascade*. Each of these stages has considerable variations in impact. Study of historical cases using the model as a guide highlight patterns that can be applied to identify, screen and pursue concepts with enabling potential, especially with regard to early decisions in the enabling window that can shape the future impact of an innovation.

The second research stream focused on creating a framework of patterns of thought and action that can guide the pursuit of enabling innovations. Successful capture of enabling innovations, particularly while in the enabling window, requires new behaviors to proactively envision, shape, and pursue enabling concepts. This research investigated these behaviors and, in particular, the differences with behaviors typically employed to drive progressive innovation activity. This framework of patterns and behaviors – herein termed the enabling thinking framework – was developed through a multifaceted approach, integrating evidence from: 1) a scholarship of integration study on design, innovation, entrepreneurism, and learning behaviors, 2) thematic analysis of the actions of stakeholders that participated in the history of the cases analyzed to build the enabling innovation model, and 3) thematic verbal protocol analysis of 28 performance tasks with a broad population of innovation consultants, corporate innovation leaders, and faculty and students recognized as innovative in their institution. The framework is anchored in the design process and consists of a set of design patterns and behaviors that are tailored to the challenges of achieving enabling innovations.

The combination of the enabling innovation model and enabling thinking framework makes this research study unique, because it frames the types of innovations to be pursued for high-impact and simultaneously outlines the competencies and key philosophies to achieve this type and scale of goal. Beyond defining enabling innovation, this work aims to open up a field of study that goes from simply "designing" to "designing for models of innovation" in which innovation archetypes can guide innovation pursuits throughout society – and facilitate intentional innovation.

CHAPTER 1. INTRODUCTION

"There is no such thing as a "resource" until man finds use for something in nature and thus endows it with economic value. Until then, every plant is a weed and every mineral is just another rock. Not much more than a century ago, neither mineral oil seeping out of the ground nor bauxite, the ore of aluminum were resources. They were nuisances; both render the soil infertile. The penicillin mold was a pest, not a resource. Bacteriologists went to great lengths to protect their bacterial cultures against contamination by it. Then in the 1920s, a London doctor, Alexander Fleming, realized that this "pest" was exactly the bacterial killer bacteriologists had been looking for – and the penicillin mold became a valuable resource… The American farmer had virtually no purchasing power in the early nineteenth century… Then one of the many harvesting-machine inventors, Cyrus McCormick, invented installment buying… Innovation, as these examples show, does not have to be technical, does not indeed have to be a "thing" altogether. Few technical innovations can compete in terms of impact with such social innovations as the newspaper or insurance… The hospital, in its modern form a social innovation of the Enlightenment of the eighteenth century, has had greater impact on health care than many advances in medicine."

-Peter F. Drucker[1], Innovation and Entrepreneurship

1.1 The Challenge of High Impact Innovation

This thesis focuses on furthering our understanding of innovation and the patterns of thought and action required to achieve it, particularly when the end-goal is to achieve innovation that is of high impact – the type of impact which, as exemplified in the above

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[1] Drucker (1986, pp. 30-31)

quote, is profound, lasting, and with potential to address the world's most complex challenges. Achieving this type of impact, however, likely requires a deeper understanding and a broader definition of innovation than that which has been commonly employed before.

Although a subject of considerable debate (e.g., Baregheh et al., 2009; Read, 2000; CSSI, 2004; Ferguson et al., 2013), innovation can be defined as the introduction of a new or different idea into use or practice that drives impact (Solis and Sinfield, 2014). Embedded in this definition are three critical constructs that need to be fully understood to purposely drive innovation: novelty, differentiation, and impact. Innovation has historically been studied in terms of its novelty and differentiation, particularly by exploring the characteristics of ideas that are new (previously unknown) or different (new combinations of old ideas) (Solis and Sinfield, 2014). Novelty comes in many forms and scholars have used words such as incremental and radical (Ettlie et al., 1986), core and peripheral (Gatignon et al., 2002), and sustaining and disruptive (Christensen, 1997), for example, to describe it. Yet, *impact*, which arguably is the most important dimension because it represents the *outcome* of an innovation, has only recently been a subject of study and is herein defined as the degree to which an innovation changes the way individuals, groups, and societies live and act (Solis and Sinfield, 2014).

"Upon careful examination, it is apparent that the foundation of prosperous societies rests upon major developments that have changed the way we live, improved our health and well-being, fostered economic growth, and reinforced our culture – i.e., innovations that have had broad and significant impact" (Sinfield and Solis, 2015). In the domains and science and engineering, for example, Lasers, X-rays, and Global Positioning Systems (GPS) have had broader and more significant cumulative impact, and cascading benefits, than other application-specific innovations and society needs more of these types of solutions. These innovations, herein termed *enabling innovations*, are the focus of this work, along with their characteristics and the patterns of thought and action that can help society systematically realize them.

This need to innovate with impact is engrained at all levels of society, whether considering the effort of companies and entrepreneurs to develop new products and services, agencies to spark new scientific discoveries and engineer new technologies, or governments and non-profits to find new ways to improve and protect the welfare and quality of life of their citizens. For example, organizations such as the National Academy of Engineering, the United Nations, and the World Bank have highlighted sets of problems they term, "grand challenges." These fundamental societal problems have broad implications and designing effective solutions would have a considerable positive impact on society. Examples of these challenges include reverse engineering the brain to understand how and why it works and fails, realizing personalized medicine to address individual variances in susceptibility and response to medication, and restoring and improving urban infrastructure to meet the basic needs of a growing population (NAE, 2008). However, even with "grand challenge" efforts that raise awareness of the need to innovate, often times the byproducts of innovation efforts, although useful, only generate incremental advance, mitigating problems for short periods of time or serving the needs of only a few, thus buying short durations of relief before pressures to innovate reignite. Step changes in performance, capability and/or conceptual thinking represent an infrequent outcome in most domains, and an outcome that is typically perceived to be at best serendipitous, and, all too often, too risky to be routinely pursued and achieved (Sinfield and Solis, 2015).

A deeper understanding of innovation impact is thus increasingly important to ensure human needs do not outpace societal innovation capabilities. In business, adoption curves are becoming steeper, narrowing the window of time for a competitive response due to heightened competitiveness, the accelerated pace of adoption and consumption (WSJ, 1998; DeGusta, 2012), and society's increasing interconnectedness. In government, the continuous growth of the world population constantly creates new challenges associated with food, water, energy, and healthcare (OECD, 2012; UN, 2013; EIA, 2013; FAO, 2012; WRI, 2013). Because of these trends, it seems that the pursuit of high-impact, enabling innovations, even if seemingly risky, cannot and should not be left to chance.

This thesis is thus motivated by the need to accelerate the development of innovations with broad, significant impact, by rethinking the way in which societal stakeholders pursue innovation. This overhaul requires: 1) changes in the ways society understands innovation; 2) changes in the ways programs and projects are conceived and resources to fuel innovation initiatives are selected and allocated; and 3) changes to the mindsets and competencies of those executing such pursuits, including the integration of the many bodies of work that have tried to address these issues previously. Overall, these needs require the creation of language and the articulation of both an impact-based model of innovation and a framework of patterns of thought and action that, if employed, could enhance the systematic pursuit of *enabling* innovations.

1.2 Research Question

With this motivation in mind, the work described herein focuses on answering the question: *What are the characteristics of high impact, enabling innovations, that clearly differentiate them from those that generate limited, progressive impact, and what are the patterns of thought and action that facilitate their systematic pursuit?* Breaking this question down unearths two clusters of subquestions that need to be addressed to answer this research question. These clusters are related to the characterization of enabling innovations and the characterization of the patterns of thought and action to achieve them.

Characterizing high impact, enabling innovations also implies addressing the following:

- How is impact more concretely and comprehensively defined?

- How can innovations be characterized by their impact?
- What are historical examples of enabling innovations?
- What are the trajectories to impact of enabling innovations?

Similarly, characterizing the patterns of thought and action to achieve enabling innovations implies addressing the following:

- What patterns of thought and action to achieve innovation have been examined in prior studies and what variations of these patterns or what new patterns, if any, should be employed for the pursuit of high impact innovation?
- What patterns of thought and action to achieve enabling innovation can be identified from the richly and rigorously documented histories of historical enabling innovations?
- How do patterns of thought and action to achieve enabling innovation manifest at the individual level of analysis when stakeholders are trying to address an innovation challenge?
- How can patterns of thought and action to achieve enabling innovation be conceptually organized in increasingly detailed and actionable ways that can facilitate their study and development of related content, assessment, and pedagogy?

1.3 Conceptual Overview of the Study of Enabling Innovation

To address these questions, this research employs a multifaceted approach based on two key research streams to develop: a) an impact-based model of innovation, termed the *enabling innovation model*, including a description of the characteristics of each innovation archetype in the model (i.e., enabling and progressive) and their impact trajectory; and b) a set of patterns of thought and action which facilitate the deliberate achievement of enabling innovation, organized around a conception of the design process, termed the *enabling thinking framework*. The integration of these research streams creates a unique, comprehensive treatment of enabling innovations, as shown in Figure 1.1.

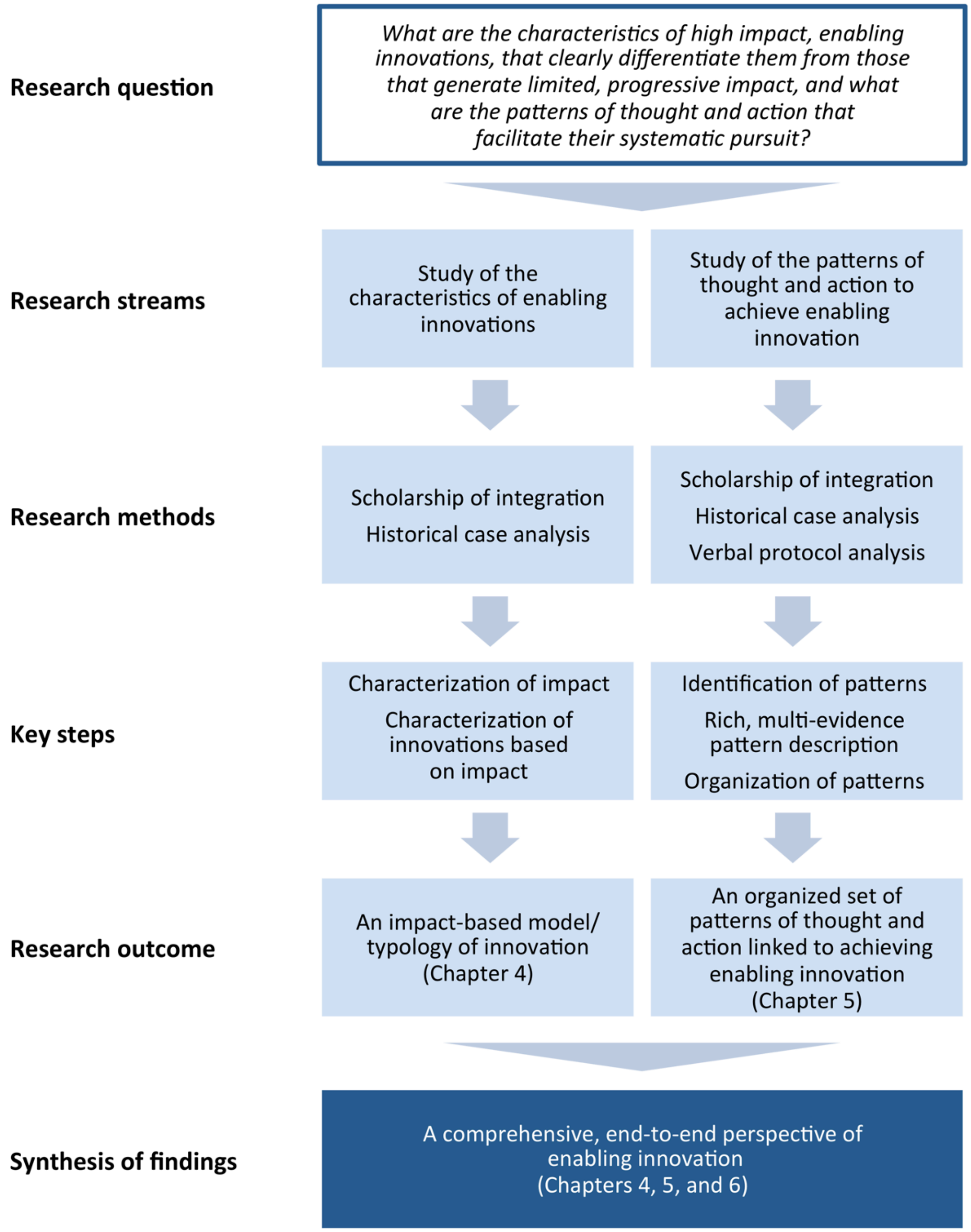


Figure 1.1 Dissertation Overview

Three distinct methods are triangulated to create the impact-based model and competency framework of enabling innovations: 1) scholarship of integration, 2) historical case study analyses, and 3) verbal protocol analysis of a performance task. Effectively, this work builds on scholarly efforts to understand innovation, historically documented cases of what in retrospect were enabling innovations, and simulated attempts to address a present day challenge that would likely require enabling innovation to be addressed.

The first method studies enabling innovations from the perspective of the scholarship of integration – a method that seeks to interpret, connect, and bring new insights to original research, thus fitting the research of others into larger intellectual patterns (Boyer, 1990). Innovation is a topic studied in many fields, for instance, management, design, entrepreneurship, science, psychology, education, economics, and engineering, which creates a broad array of helpful yet disconnected insights. If brought together and structured into frameworks and/or unifying language that describes the same phenomena, these insights become more compelling and help better pinpoint challenges and opportunities to more systematically drive enabling innovation.

The second method examines historical innovation cases and their outcomes – i.e., the impact generated by an innovation – thus creating an impact-based typology. It is acknowledged, however, that enabling innovations, as described herein, only strongly contribute to these outcomes, and that the impact generated after their introduction cannot be solely attributed to them in many instances, because causation is difficult to establish. Nonetheless, the examination of historical enabling innovations in Chapter 4 does reveal that these innovations are at the core of the impact that followed after their introduction. This historical examination also helps understand the patterns of thought and action that, whether employed proactively or serendipitously, facilitated their development.

The third method employs verbal protocol analysis to understand how participants approach an ill-structured performance task designed around a challenge which likely requires innovation(s) with impact on par with enabling innovations to be addressed. Thirty strategically selected subjects verbalized their approach to the same challenge and the resulting data was analyzed, searching for themes that exemplify patterns of thought and action to achieve enabling innovation. As further described in Chapter 3, participants included stakeholders that participate in diverse innovation roles throughout society, such as innovation consultants, R&D leaders, engineering and science faculty, entrepreneurs, and students from various disciplines. This analysis helps codify and more richly describe the actions that stakeholders can proactively take when they are in pursuit of enabling innovations.

Each method provides a unique perspective of the challenge of innovation; however, it is the interpolation of these three methods that yields a unique understanding of the patterns that underpin enabling innovations. Ultimately, the goal is to understand what an enabling innovation is (and what it is not), and the ways in which these innovations are realized.

Rather than adhering to a particular philosophical perspective (e.g., positivism, post-positivism, structuralism, constructivism) of the claims regarding enabling innovations developed through this multifaceted work, this dissertation has pragmatism as its philosophical underpinning. As such, the dissertation does not claim that the perspective of innovation and the patterns of thought and action identified through this work are the only ones necessary to achieve enabling innovation. Instead, the dissertation only provides a perspective of models, tools, and instruments that can help drive understanding and action that help society more systematically pursue (and achieve) enabling innovations.

1.4 Significance of the Study of Enabling Innovation

The primary contribution of this study is a theoretically, historically, and empirically grounded framework of high-impact, enabling innovations. This framework describes the characteristics of enabling innovations and the patterns of thought and action that can help achieve them. The thesis contributes to the innovation body of knowledge by providing a perspective of innovation that considers both how new or different an innovation is, and the impact that an innovation generates.

In addition, the study also contributes to the body of knowledge in the areas of design, education, and entrepreneurism. In the area of *design*, the study describes a set of design patterns and design behaviors tailored to the end goal of achieving enabling innovation. In this research, the phrase *design pattern* refers to a collection of design behaviors (Crismond and Adams, 2012), and *design behavior* refers to the combinations of individual instances/elements of work (Peeters et al., 2007) that represent both thought and action. Design is often investigated as a generic process applicable to many types of challenges alike, leaving out the variations in the design process that can result from a change in the nature of a design goal. Effectively, design is a generic cognitively-oriented activity that can take many forms (Visser, 2009). This study contributes by identifying a novel form of design – one focused on designing for a model/archetype of innovation. Designing for a model of innovation creates explicit links between specific types of innovation (here enabling innovation) and design approaches tailored toward such an end-goal. As such, even though researchers have studied individual behaviors (e.g., Ahmed and Christensen, 2009; Moreno et al., 2013) or subsets of the behaviors (e.g., Dyer et al., 2008) described in the enabling thinking framework, the identification of a collection behaviors to innovate intentionally with a specific type of impact in mind, and that are tied to an end-to-end conception of design processes, is a unique contribution of the study.

In the area of *education*, particularly design and innovation education, the study contrasts current conceptions of a design process and patterns with more specific conceptions that could better help students achieve their goals. In addition, the study provides rich descriptions of the patterns of thought and action that could serve as a foundation for designing curriculum to teach students to employ such patterns. In the area of *entrepreneurism*, this study describes a set of patterns of behavior that can be employed in the pursuit of entrepreneurial endeavors. The study focuses particularly on patterns and behaviors related to the pursuit of enabling innovations, and describes entrepreneurism as a general design philosophy and a way of thinking, rather than a set of methodologies or processes.

1.5 Organization of the Dissertation

The remainder of this dissertation is organized as follows. Chapter 2 describes the schools of thought that have informed this work and served as its foundation, namely design, education, entrepreneurship, and innovation. Chapter 3 describes the research methods employed to create the enabling innovation model and the enabling thinking framework. Chapter 4 describes a perspective of impact, highlights the differences between enabling and progressive innovation, and describes the enabling innovation model. Chapter 5 describes the enabling thinking framework, i.e., the competencies to realize enabling innovations, from a synthesis of evidence from scholarship of integration activity, historical case studies, and the search for themes in verbal protocols of a performance task. Chapter 6 synthesizes the findings, contributions, and implications of the study, highlights the limitations of the study, and provides recommendations for future work, and provides a summary of the dissertation. It should be noted that significant portions of these chapters have been published, have been submitted for publication, or are part of draft peer-reviewed journals and/or referred conference proceedings.

CHAPTER 2. DESIGN, INNOVATION, ENTREPRENEURISM, AND LEARNING AS FOUNDATIONAL SCHOOLS OF THOUGHT

2.1 Introduction

The comprehensive perspective of enabling innovation developed herein is founded on the integration of knowledge from the design, innovation, entrepreneurism, and learning schools of thought. Insights from each of these schools of thought can help one better understand key elements of any challenge: the problem space, the solution space, and the approach used to connect such spaces while framing problems and developing and implementing solutions, as shown in Figure 2.1.

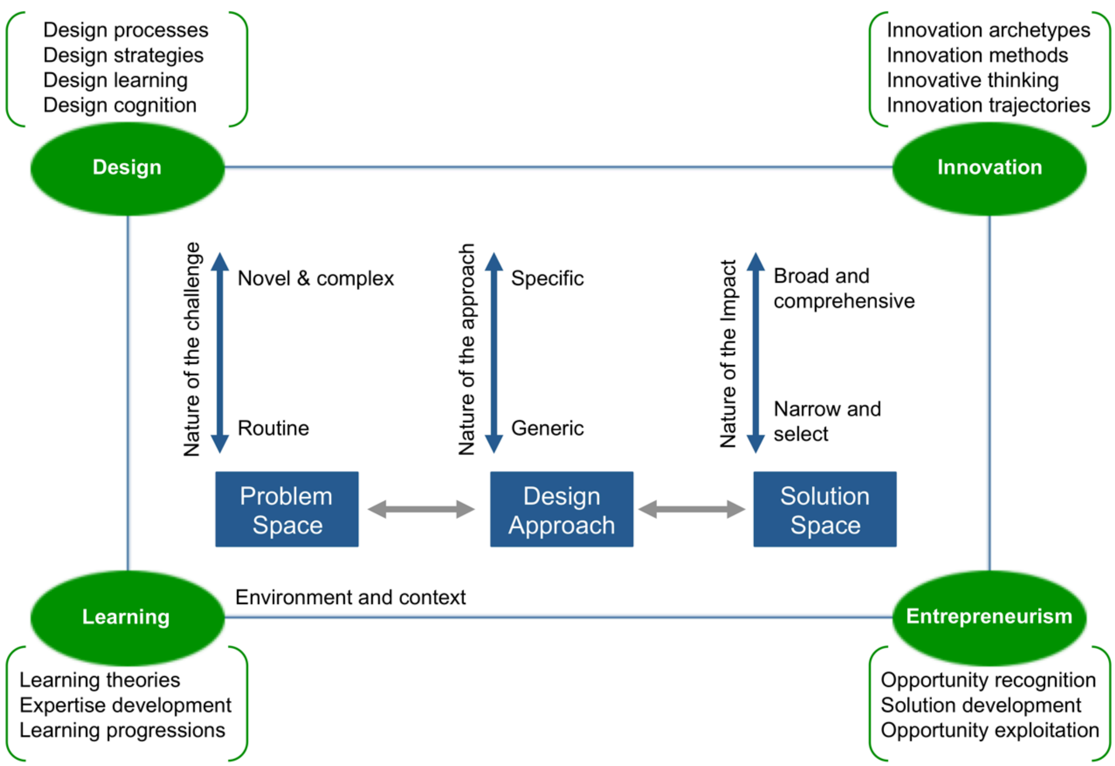
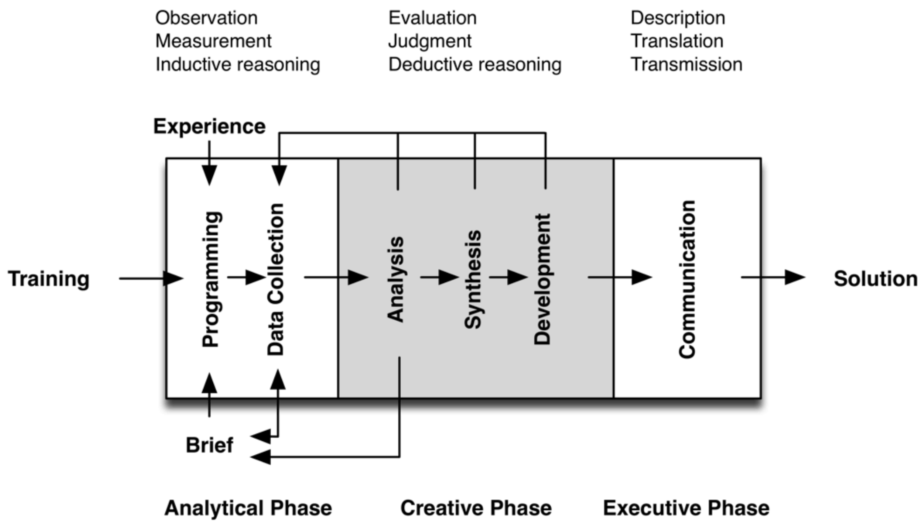


Figure 2.1 Linking Design, Innovation, Entrepreneurism, and Learning

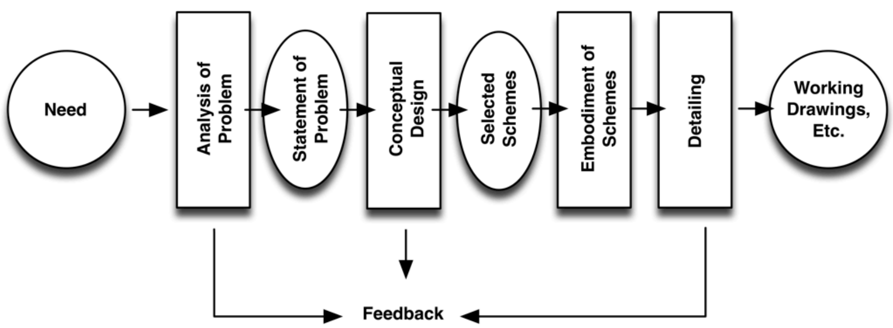
The study of *design*, a process and way of thinking to "devise courses of action aimed at changing existing situations into preferred ones" (Simon, 1996; Friedman, 2003), provides insight into means to approach ill-defined problem spaces that enhance the generation of ideas and their translation into practice (e.g., Atman et al., 1999; Adams et al., 2003; Cross, 2004, 2006; Atman et al., 2007; Visser, 2009). The study of *innovation,* particularly in the management sciences, has generated a rich understanding of solution spaces, specifically characterizing an array of innovation archetypes based on how new, different, or impactful an innovation is (e.g., Ettlie et al., 1984; Henderson and Clark, 1990; Christensen, 1997, Solis and Sinfield, 2014). Adding to these bodies of work, efforts in the management sciences, particularly in the study of *entrepreneurism*, provide insight into the mechanisms that facilitate recognition, creation, and exploitation of opportunities (to innovate) based on the patterns of the entrepreneur (Shane and Venkatamaran, 2000; Hitt et al., 2001; Shane, 2003; Sarasvathy, 2004; Baron, 2007; Short et al., 2009; Venkatamaran et al., 2012). Lastly, because innovation expertise is (to date) an unexplored construct, the *learning* sciences offer unique perspectives that provide possible ways to recognize and understand the mindsets and practices at different points of novice-expert continuums (Dreyfus and Dreyfus, 2005; Lawson and Dorst, 2009; Crismond and Adams, 2012), and how transitions between distinct levels of practice can be facilitated.

2.2 Design as a Goal-Oriented Activity and a Foundation for Change

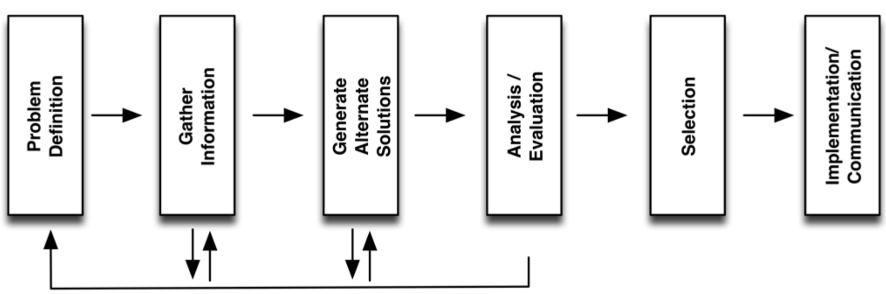
Multiple conceptions of design processes exist and, at the most fundamental level, such processes consist of analysis and synthesis stages (Koberg and Bagnall, 1972) that alternate between divergence and convergence in choices (Banathy, 1996) to imagine and deliver what does not yet exist (Nelson and Stolterman, 2003). The number and nature of design stages vary widely across conceptions of design processes (Dubberly, 2004; Pahl et al., 2007; Howard et al., 2008), as shown in Figure 2.2, with such conceptions typically including stages to define problems, gather information, generate alternate solutions, analyze, evaluate, select, communicate and implement (Atman et al., 1999; Mosborg et al., 2005).



(a)



(b)



(c)

Figure 2.2 Conceptions of Design Processes:

(a) Archer (1965); (b) French (1985); (c) Atman et al. (1999)

The transitions between these stages are non-linear and iterative (Adams, 2002; Ali and Adams, 2011), which inherently calls for self-awareness, reflection, and metacognition in the effective application of such transitions (Schön, 1983; Adams et al., 2003). Starting points are typically design briefs in which initial conceptions of goals and constraints of a design challenge are stated. Yet some of the earliest historical design process models named design starting points in different ways, such as "programming" (i.e., establishing critical issues and proposing courses of action) (Archer, 1965), "specifying system inputs and outputs" (Jones, 1970), and "goal definition" (Rittel and Webber, 1973). From these initial design stages, design processes are also said to "co-evolve" (see Figure 2.3), meaning that problem and solution are often shaped together (Dorst and Cross, 2001) in opportunistic ways (Cross, 2004), given the ill-structured nature of design challenges (Cross, 1987; Dorst, 2004; Thomas and Carrol, 1979; Visser, 2006; Simon, 1973; Daly et al., 2012a), which, at best, are only partially defined at the outset of work. This shaping/co-evolution of problem and solution spaces can occur by decomposing a problem-space or by making early solution conjectures that facilitate a more effective exploration of both spaces (Cross, 2004).

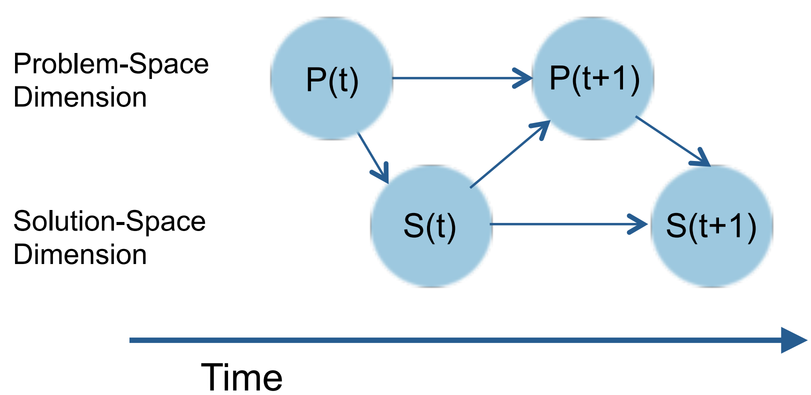


Figure 2.3 Design Co-Evolution (Adapted from Dorst and Cross, 2001)

If a specific type of impact is desired, such as from a specific type of innovation, then design strategies are likely to be more effective if they are tailored toward that impact. For example, specific conceptions of design processes, termed creative problem solving (CPS), target the challenge of creative design (which is related to, yet different from the end goal of innovation). CPS processes often focus on applied creativity by proposing methods and tools to stimulate ideas that are unconventional and depart from the status quo (e.g., Osborne, 1953; Parnes, 1967; DeBono, 1975; McCaffrey and Krishnamurty, 2014; Basadur et al., 1982; Basadur et al., 1994; Basadur et al., 2000; Pahl et al., 2007). These processes emphasize behaviors such as diverging and converging, deferral of judgment, and analogical reasoning, which aim to facilitate idea fluency and avoid premature "fixation" on ideas, since fixation limits the number of alternatives considered in the solution to a challenge (Cross, 2001; Purcell and Gero, 1996; Daly et al., 2012b). TRIZ, for example, is a problem-solving, analysis and forecasting method, which rests upon three fundamental principles: (1) problems and solutions are repeated across industries and sciences; (2) patterns of technological evolution are repeated across industries and sciences; and (3) creative solutions have historically used ideas from outside the field in which they were developed (Altshuller, 1984). This method thus prescribes approaches to generalize a problem and employ solutions/principles that have been found useful across contexts when translated back to a specific domain (Hua et al., 2006).

When the goal is to innovate, design processes could be tailored towards a specific type of desired innovation impact. For example, design processes could be tailored to deliver incremental innovation (relatively small changes compared to a predecessor) or radical innovation (step changes compared to a predecessor) (Verganti, 2008; Norman and Verganti, 2014). Beyond these archetypes, the innovation literature, particularly within the management and economic sciences, has characterized innovation using specific terms, which describe patterns of change in an outcome/solution space. These patterns are likely useful to consider in design activities, especially for complex societal challenges with no preconceived framing.

2.3 Innovation Archetypes as End-Goals to Differentiate Impact

A comprehensive description of an innovation involves characterizing its novelty, differentiation, and impact (Solis and Sinfield, 2014). Novelty refers to knowledge that is new (i.e., previously unknown), and different refers to insights that connect existing knowledge in counterintuitive or nonobvious ways. Impact, which has received less attention throughout the literature, is considered here as the degree to which an innovation changes the way individuals, groups, and societies live and act, and is arguably one of the most important components to address complex societal challenges (Solis and Sinfield, 2014). Based on the concepts of novelty and differentiation, innovation archetypes have historically been created to describe changes in fundamental form, underlying performance driven by the idea introduced, components of, and interactions with, existing systems, and perspectives of end users. The work herein adds to these perspectives by introducing a taxonomy of innovation impact which is described in depth in Chapter 4 of this study.

In terms of novelty, and differentiation, researchers have characterized innovations using the terms “product,” “process” (Utterback and Abernathy, 1975), “service” (Miles, 1993), “business model” (Shafer et al., 2005; Zott and Amit, 2007; Johnson et al., 2008; Sinfield et al., 2012), and “management” (Birkinshaw and Moi, 2006; Birkinshaw et al., 2008) innovations to describe the fundamental form of the change driven by an innovation. Other researchers have framed innovation on the basis of changes in underlying technology and contrasted “radical” innovations (revolutionary advances that significantly depart from current practice) with “incremental” innovations (minor improvements to current practice) (Duchesneau et al., 1979; Ettlie et al., 1984; Dewar and Dutton, 1986; Damanpour, 1996; Leifer et al., 2000). Still other researchers have characterized innovation on the basis of locus and type of change in existing systems (Gatignon et al., 2002), differentiating “core” from “peripheral” (Tushman and Murmann, 1998), “generational” from “architectural” (Henderson and Clark, 1990), and "interdependent" from "modular" (Baldwin and Clark, 2000; Schilling, 2000). Core innovations refer to changes to primary components in a dominant design (Abernathy and Utterback, 1978), and peripheral innovations refer to changes in secondary components in a dominant design. Architectural innovations refer to changes in system linkages with little to no changes in core components. Modular innovations refer to changes in components without changes in system linkages. Interdependent innovations refer to changes in both core components and system linkages. Generational innovations refer to changes in subsystems in dominant designs.

A different model frames innovation novelty and differentiation from the perspective of end users and their evaluation of dimensions of performance by contrasting "sustaining" and "disruptive" innovations (Bower and Christensen, 1995; Christensen, 1997; Christensen and Raynor, 2003; Anthony et al., 2008a). Dimensions of performance are defined as design features of a functional (i.e., related to properties or characteristics), social (i.e., related to the perceptions of stakeholders), or emotional (i.e., related to the internal states experienced by stakeholders when using a design) nature (see Anthony et al., 2008a; Solis et al., 2013). Sustaining innovations are those which "sustain" the dimensions of performance of the predecessor through small changes (incremental sustaining innovations) or large changes (radical sustaining innovations). Sustaining innovations create opportunities for "disruptive" innovations. From the perspective of end users, disruptive innovations offer solutions with lower, yet "good enough," performance along select mainstream performance dimensions, but in exchange provide new benefits such as simplicity, affordability, or accessibility (Christensen and Raynor, 2003; Anthony et al., 2008a). These tradeoffs enable provision of new benefits that are typically better aligned with the preferences of an often previously ignored set of end users relative to the benefits offered by more mainstream, sustaining innovations.

Less attention has been paid, however, to the link between innovations and their impact. Although many studies and reports describe impact from a policy perspective (e.g., OECD, 2011, Gurria, 2011; UN, 1969, 2000), the discussion of innovation as a mechanism to generate impact is inexistent or tenuously described in this type of literature. Others have studied the impact of science on the economy and society (e.g., Stokes, 1997; Godin and Dore, 2004; Dudley, 2013), yet again, without explicitly acknowledging the critical linkage role that innovation has in the creation of impact through science. The few studies that do call out the link between innovation and some outcomes that could be considered impact tend to have a localized business/commercial (e.g., Abernathy and Clarke, 1985; Feland et al., 2004; MGI, 2013) and economic (e.g., Perez, 2003; Christensen, 2014) scope. For example, Abernathy and Clarke (1985) classify innovations as "competence-enhancing" and "competence-destroying," and Christensen (2014) classified innovations based on their effect on economic growth as "performance-improving" innovations, "efficiency" innovations, and "market-creating" innovations. This thinking around competence and markets, however, was not intended or framed around the notion of impact. As such, no dominant model currently exists to classify innovations by their impact, most likely due to the ambiguity that surrounds the term impact and the focus of historical innovation archetypes on types of change (novelty and differentiation) rather than types of impact – which this thesis intends to address.

Awareness of innovation archetypes can help clarify problem and solution spaces and facilitate an approach that is tailored to, and more likely to succeed at, a particular type of innovation. The aforementioned perspectives on innovation, summarized in Table 2.1, can therefore be used to frame innovation based on the novelty, differentiation, and business/economic effects of an idea. More specifically, these perspectives can help stakeholders describe new underlying technologies, dominant designs, system components and interactions, perspectives of end users, and very localized (i.e., narrow in scope) descriptions of impact. This synthesis of existing archetypes thus highlights an opportunity to more comprehensively classify innovations by their impact. Without this impact-based classification, stakeholders and decision-makers might confound the desired results of their innovation efforts and the composition of their innovation portfolios.

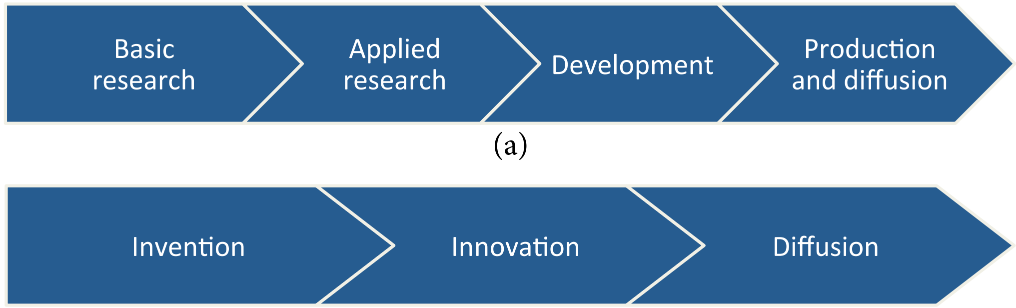
Table 2.1 Innovation Archetypes

Area of change	Innovation archetype	Definition
Form	Product	New products or changes in established products
	Process	New processes used in the generation of products
	Service	New or improved service concept
	Business model	New approaches to develop and deliver an offering
	Management	New management methodologies/practices
Underlying performance	Incremental	Minor departures from current practice
	Radical	Significant departures from current practice
Systems	Core	Changes to primary elements of a dominant design
	Peripheral	Changes to secondary elements of a dominant design
	Modular	Changes to system components without affecting system linkages
	Architectural	Changes to system linkages without affecting system components
	Interdependent	Changes to system components and linkages
End user perspective	Incremental sustaining	Sustains predecessor performance dimensions with small changes
	Radical sustaining	Sustains predecessor performance dimensions with significant step changes
	Disruptive	Trades off performance dimensions in the pursuit of simplicity, accessibility, convenience, or affordability
	Competence-enhancing	Enhances the value or applicability of a firm's competence
	Competence-destroying	Reduces or destroys a firm's existing competences or capabilities, rendering them obsolete
Business/ economic effects	Performance-improving	Replaces old products with new and better models
	Efficiency	Help companies make and sell mature (and established) products and services to their same set of customers
	Market making	Transform complicated and/or costly products so radically that they create a new consumers or markets

2.4 Innovation Trajectories Towards Change and Impact

In addition to studying innovation archetypes, scholars have also studied the trajectories of innovations and have developed several models to characterize them. The trajectories described herein first highlight the differences between linear and non-linear innovation models, and then describe an array of concepts that researchers have developed to further characterize the roles that these concepts play in innovation development trajectories. In combination, these models and related trajectories help explain the stages that an innovation undergoes in its path from novel concept, to introduction into practice, and in the context of this work, path towards impact. Most of these frameworks and concepts have been developed to describe technological evolution, despite their potential for application to broader innovation issues (which are the focus of this research). Until now, these concepts have been rooted in disparate schools of thought that were seldom connected and no unifying model was available. The enabling innovation model overcomes this challenge.

One of the first frameworks employed to describe innovation trajectories is the linear model of innovation, which although it is often attributed to Bush's *Science: the Endless Frontier* (1945), it has a rich (and debatable) history in its conceptual development (Godin, 2006). This model, shown in Figure 2.4, has the stages of basic research, applied research, development, and production and diffusion. According to Godin (2006), the model has been historically employed by the National Science Foundation (NSF, 1957) to lobby research funds and to provide advice for science policy making (Nelson, 1959). Others variations of this model employ a similar linear structure, also shown in Figure 2.4, with stages such as invention, innovation, and diffusion, which are grounded in anthropological studies of invention (Wissler, 1923; Dixon, 1928). The reader is referred to Godin (2013) for a comprehensive synthesis of these linear models.



(b)

Figure 2.4 Linear Models of Innovation:
(a) Bush (1945); Godin (2005);
(b) Wissler (1923); Dixon (1928); Rogers (1962); Godin (2013)

Linear models of innovation are, for the most part, now abandoned with non-linear models currently employed to guide innovation activities. One of the earliest non-linear models is Pasteur's Quadrant (Stokes, 1997; Dudley, 2013). Donald Stokes, former National Science Foundation advisor, realized that a two-dimensional space better describes how research is performed in practice (Dudley, 2013). Different types of research in the two axes of this space: one for the quest for fundamental understanding and the other representing the development of practical applications. These quadrants were named after well known scientists. The curiosity-driven, fundamental research was named after Niels Bohr, the focused problem-solving for practical invention was named after Thomas Edison, and the upper adjacent quadrant representing both a quest for fundamental understanding and practical developments is named after Louis Pasteur (Stokes, 1997), as shown in Figure 2.5. This model, named after Pasteur, whose fundamental contributions to microbiology aimed to solve practical concerns of the day, such as the treatment of disease (Dudley, 2013), represented a departure from the linear model of innovation, and has influenced the way research funding is allocated.

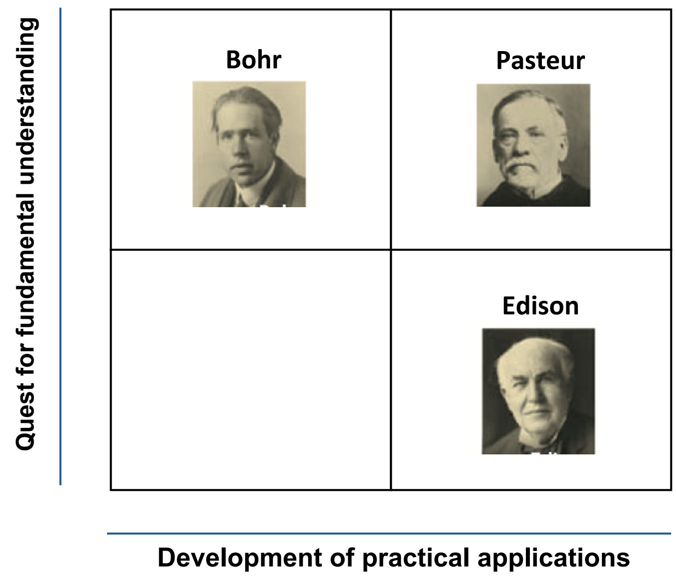


Figure 2.5 Pasteur's Quadrant Model (Adapted from Stokes, 1997)

Yet even non-linear models fail to provide a rich picture that describes the complexity of identifying and driving innovations toward achieving impact. For example, the Pasteur's Quadrant model may generate misunderstandings regarding the importance and usefulness of basic, curiosity-driven research, which are best synthesized by Dudley (2013, p. 339):

> *"…the quadrant model minimizes the interface between fundamental research and industrial development, giving the misleading impression that research performed in Pasteur's quadrant has the greatest impact on industry. This erroneous impression has given rise to the paradigm of use-inspired research that dominates current thinking. Funding research in Pasteur's quadrant also seems to spread the risk with the expectation that one cannot lose: money is spent to support research that progresses steadily towards specific practical goals, but if there are bottlenecks that impede development, working towards solving them will generate new fundamental knowledge. Many familiar features of the modern academic environment have been developed based on Pasteur's quadrant: research projects are often funded only if there is industrial partnership, and most universities have entrepreneurial centres to promote technology transfer."*

Many research endeavors that are often perceived as risky or purely curiosity-driven, have resulted in fundamental advances to society, for which both linear and non-linear models fail to account. Yet the importance of these efforts in the pursuit of innovation is perhaps best exemplified by Charles Townes (1999), inventor of the maser, the predecessor of the laser:

> *"What industrialist, looking for new cutting and welding devices, or what doctor, wanting a new surgical tool as the laser has turned out to be, would have urged the study of microwave spectroscopy? The whole field of quantum electronics is almost a textbook example of broadly applicable technology growing unexpectedly out of basic research."*

To further characterize these trajectories, researchers have thus created an array of concepts that describe in-depth aspects of the evolution of innovations – mostly from a technology-centric school of thought. These concepts include technological paradigms, S-curves, technology push and demand/need pull, dominant designs, enabling technologies, and generic purpose technologies.

The concept of paradigm has been employed in an array of contexts to describe macro level societal changes due to collections of inventions and innovations. For example, in science, Kuhn (1962) argues that scientific revolutions often start when a prior scientific paradigm is reshaped. In technology, Dosi (1982) emphasizes that paradigm changes stem from the interplay of scientific, economic, institutional, and technological variables, while Arthur (2007, 2009) emphasizes that radical invention rests on redefining the paradigms upon which dominant designs are founded. In economics, Perez (2003, 2009) highlights that paradigm changes are "techno-economic" in nature and are often triggered by technological revolutions. In a broader societal perspective, Geels and Schot (2007) characterize "sociotechnical transitions," which provide an umbrella term for changes in macro-economics, deep cultural patterns, and macro political developments. These macro level changes can happen with different frequencies, amplitudes, speeds, and scope (Suarez and Oliva, 2005). Suarez and Oliva (2005) and Geels and Schot (2007), for example, describe four types of change to a business climate (e.g., environment-organization changes such as economic reforms) and the societal landscape (e.g., deep cultural patterns, macro political and macro economic developments), respectively: regular (slow, linear change), hyperturbulence (high frequency and high speed of change in one dimension), specific shocks, disruptive change (infrequent, gradual change that has a high intensity effect in one dimension), and avalanches (which are infrequent, but high intensity, high speed, and simultaneously affect many dimensions of the environment). These concepts have thus been explored at the macro level, which is helpful for policy level decisions, but not at the micro level, which can help drive project, portfolio, and program level decision-making.

The concept of the S-curve has also been used to characterize innovation trajectories from the perspective of their changing rates of improvement. This concept is applicable to many domains, but in the context of the study of innovation such a concept has been analyzed as a "technology S-curve" (e.g., Fisher and Pry, 1971; Cooper and Schendel, 1976; Sahal, 1981; Foster, 1986; Christensen, 1992a, 1992b) – even though S-curves likely govern innovations beyond the technological domain. This concept, shown in Figure 2.6, posits that technological progress is slow in early stages, but as a concept becomes better understood the rate of performance improvement increases (Sahal, 1981). Technologies (and in the context of this work concepts in general), however, reach natural limits, eventually plateauing at some point. The S-curve model and corresponding transitions between S-curves can thus be used to characterize technological trajectories (and innovation trajectories in general).

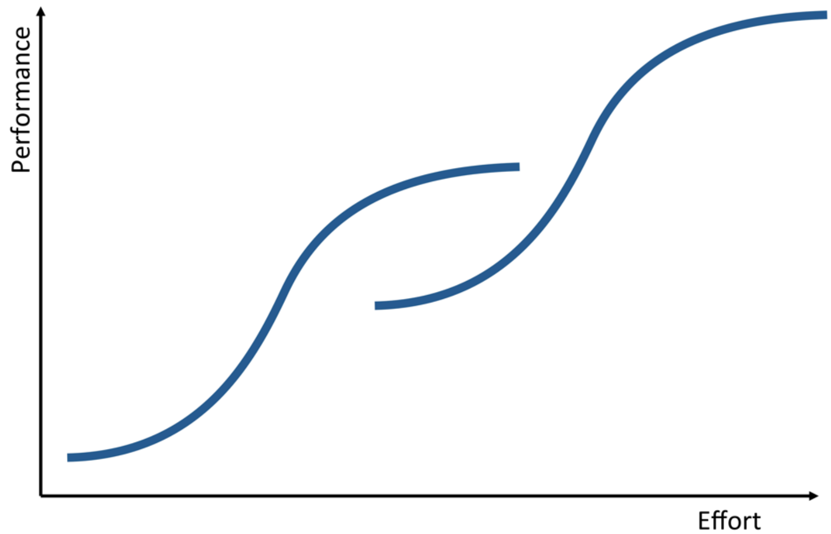


Figure 2.6 The Technology S-curve (adapted from Foster, 1986)

The trajectories of innovations have also been studied from a push-pull perspective contrasting the “pushing” of technologies into a market or the “pulling” of technologies by markets. In business contexts, perspectives on push-pull models have evolved, in what are typically known as R&D generations (Miller and Morris, 1999; Nobelius, 2004). First generation R&D focused on technology push and emphasized the activities of corporate research labs. Second generation R&D was characterized by a shift to market pull approaches and embedding R&D arms into business units. Third generation R&D activities focused on viewing R&D as a portfolio, with links to corporate strategy, and employing risk-reward methods to guide activities. Fourth generation R&D activities were characterized as integrative, where cross-functional teams were assigned to projects, and R&D interacted more heavily with suppliers and manufacturers. Fifth generation R&D focused on networked ecosystem development, further integrating diverse elements of the value chain into these activities, such as cross-company alliances, and clearly separating “R” from “D” (Nobelius, 2004). More recently, and beyond the business domain, researchers have departed from push-pull debates, and have argued that innovation is a result of “matching processes” between technologies and markets because uncertainty is always present in both technologies and markets (Freeman and Soete, 1997; Maine and Garnsey, 2006).

Yet another concept that has been employed to characterize trajectories is the dominant design school of thought, which explores the mechanisms by which designs consolidate in a given context. Even if likely applicable to broader contexts, this school of thought (Abernathy and Utterback, 1978; Suarez and Utterback, 1995; Grodal et al., 2014) describes the divergent-convergent process by which a design or set of designs of technological solutions establish dominance in a given domain (e.g., layout in keyboards, and touchscreen designs in smartphones). Dominant designs emerge after a period of design recombination, and more recently, researchers have described this process as a co-evolution of both design and linguistic/categorical recombination (see Grodal et al., 2014).

Finally, the concepts of "enabling technology" and "generic purpose technology" have aimed to acknowledge the role of innovation facilitating additional developments. In the technological innovation school of thought, Utterback (1994) defined enabling technologies as those that help support process improvement and a shift from process to product innovation (e.g., float glass production helps focus on developing new types of glass) (Maine and Garnsey, 2006); and DARPA (2010) defines enabling technologies as those which cannot stand alone and must be applied to perform a function. In the field of economics, general purpose technologies have been defined as those that have the "potential for use in a wide range of sectors" (Bresnahan and Trajtenberg, 1995; Lipsey et al., 1998). These technologies, for example the electrification of industry, are characterized by their generality in purpose, which translates to a broad array of uses and complementarity with products and processes (David and Wright, 1999). Yet, this concept is rooted in the field of economics, and because of this its implications are often discussed in terms of its effects on economic productivity and/or externalities (costs or benefits that affect a stakeholder who did not choose to incur in such costs or benefits) within and across products and economic sectors (see Helpman, 1998).

Overall, the aforementioned concepts have been disconnected from innovation trajectory models, from the innovation archetypes described in section 2.3 (with the exception of disruptive innovation which is grounded on S-curve theories), and have also not been explicitly linked to in-depth notions of societal impact. Yet, making these connections can help address Dudley's (2013) concern for a better understanding of the value of fundamental, curiosity-driven research. In addition, an important caveat in many of these innovation models/trajectories (with the exception of general purpose technologies) is that they consider innovation as the solely the byproduct of technological advance, which ignores the fact that innovations can also result from changes in conceptual thinking. In addition, design and problem solving patterns and behaviors have not been explicitly linked to the broad array of innovation archetypes and innovation trajectory models and concepts. This study aims to reconcile the aforementioned issues by creating an end-to-end, unifying model that can be used to comprehensively characterize *and* proactively pursue high-impact innovation.

2.5 Entrepreneurism as a Design Approach for Intentional Innovation

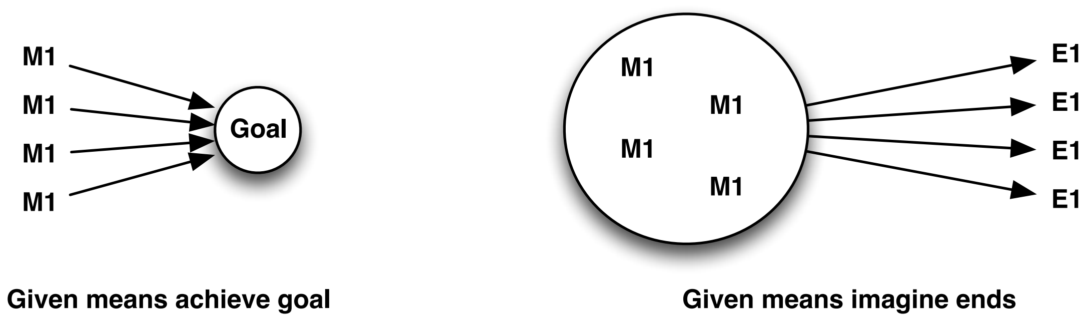
Although not always explicitly recognized throughout the literature, one type of design process that is linked to innovative impact (within a local context and a set of goals) and that has indeed examined its competencies/behaviors/patterns is the process by which entrepreneurs design a new enterprise. This design process, herein termed "entrepreneurial design," is unique, particularly when employed by entrepreneurs who innovate rather than imitate (Drucker, 1986; Cliff et al., 2006; Dyer et al., 2008). In these contexts, this process often has a design objective of proactively departing from the status quo in the pursuit of value for potential customers (value creation) and profit for their nascent enterprise/investors (value capture). At a fundamental level, and as shown in Figure 2.7, the entrepreneurial design process (Anthony et al., 2008a) consists of the stages of: 1) identification of opportunities (Shane and Venkatamaran, 2000; Shane, 2003), 2) design of offerings/solutions in response to such opportunities (Shane and

Venkatamaran, 2000; Sarasvathy, 2001a, 2001b, 2001b, 2003), and 3) the exploitation of opportunities by launching a new venture (Shane, 2003), which involves iterative efforts that require learning and experimentation (McGrath and MacMillan, 1995; McGrath, 1999; Sarasvathy, 2001a, 2001b). Just like multiple conceptions exist of design processes, there are also many ways in which entrepreneurial processes have been characterized (Moroz and Hindle, 2012). The entrepreneurial design process complements the focus on identifying needs or defining problems (common in the description of design processes) with the proactive identification of opportunities that have the potential to be of significant impact.

Figure 2.7 Entrepreneurial Design Process

This design process can be extrapolated and applied to a wide range of contexts in the pursuit of broader impact. For an entrepreneur, impact is often captured in the form of profit; however, the philosophy of focusing on opportunities is not limited to profit-maximizing objectives, but is also applicable to many other types of endeavor. Thus, regardless of context, underpinning entrepreneurial design is the philosophy of pursuing proactive efforts to identify opportunities that will create significant impact – which in turn drives what is herein termed intentional innovation.

To successfully employ this design process, entrepreneurs engage in a distinct mindset often recognized as "entrepreneurial." Most problems faced in the management sciences (and in fields such as engineering) often involve "causal reasoning" (i.e., optimizing the path to a predetermined goal given a set of means and constraints). Yet, the mindset of the entrepreneur allows paths to a goal (or goals) to emerge over time driven by the proactive pursuit of opportunities and the means at hand (i.e., imagining paths to goals/ends given a set of means and imagining new means to achieve a set of imagined ends). This mindset, also termed "effectual reasoning" (Sarasvathy, 2001a; 2001b, 2003) enables entrepreneurs to navigate the uncertainty associated with the pursuit of innovative impact (see Figure 2.8). Entrepreneurs thus alternate between causal and effectual reasoning in the design of new ventures – implying that they constrain and unconstrain challenges as well as diverge and converge iteratively and explore the problem and solution space repeatedly (i.e., cause and effect).



(a) (b)
Figure 2.8 (a) Causal and (b) Effectual Thinking (Sarasvathy, 2001a)

The entrepreneurial mindset enables designers to proactively link their nascent solutions to emerging contexts of application (Sinfield, 2008), thus shaping a path to successful innovation that embraces deviations from initial plans as opportunities to learn and re-direct their effort arise (Mintzberg and Waters, 1985; McGrath and MacMillan, 1995; Blank, 2005). In doing so, entrepreneurs engage in affordable losses by minimizing expenditures to reach their goals, build strategic partnerships with key stakeholders that help reduce uncertainty, and leverage contingencies using unexpected learning as inputs to their designs (Sarasvathy 2009), as shown in Figure 2.9.

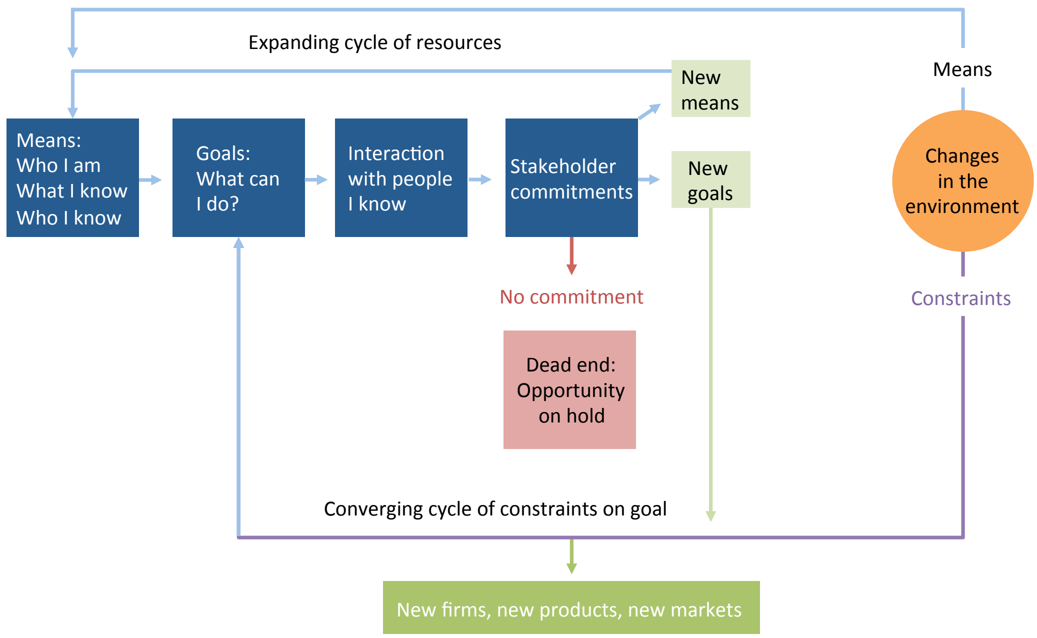


Figure 2.9 Effectuation Process and Principles (Sarasvathy, 2009)

The entrepreneurial design process, and its underlying design mindset, patterns, and behaviors are applicable to many types of design challenges across disciplines. An entrepreneurial design philosophy does not imply that the end goal is the birth of a new enterprise. Instead, this philosophy provides an underlying set of principles that can be employed to proactively innovate in any context. The challenges faced by the entrepreneur are consistent with the set of features that characterize generic design problem spaces, as outlined by Goel and Pirolli (1992). These features, typically used to distinguish design challenges from other types of tasks, include: the incomplete distribution of information, negotiable and non-negotiable nature of constraints, complexity of problems in size and scale, multiple component parts, contingent (not logical) interconnectivity of parts, better or worse (not right and wrong) answers, inputs are goals for a given context and outputs are specifications, partial (instead of complete) feedback loops until the solution is completed, high cost of errors, independent functioning of the artifact from the designer, distinction between specification and delivery, and temporal separation between specification and delivery. As more of these features are present in a task, it is more representative of the design domain and therefore its approaches are likely transferable to other types of tasks (Daly et al., 2012a). Further, enabling innovation challenges present unique features such as resource limitations, perceived and real/true uncertainty, risks and rewards, awareness of the need for a certain gain, multiple obstacles to implementation, and inertia that hinders a break from what is considered the norm. Since entrepreneurial design implies many of these features, it is herein assumed that many of the design activities and patterns of the entrepreneur are transferable to domains in which enabling innovation is desirable.

2.6 Learning as a Foundation for Competency Development

Design with the goal of enabling innovation (or any specific type of innovation) requires learning to recognize and employ patterns and behaviors that are often characteristic of this type of innovation. Definitions of learning and transfer abound, but in this work, learning is conceptualized as the process by which knowledge is increased or modified; and transfer is the process by which knowledge is applied to new situations (Greeno et al., 1999). Compared to the wide range of efforts in the learning sciences focused on the development of expertise (e.g., Glaser and Chi, 1988, Dreyfus and Dreyfus, 2005), including the study of design expertise (e.g., Cross, 2004; Lawson and Dorst, 2009) and adaptive expertise (e.g., Hatano and Inagaki, 1986; Garcia et al., 2011), innovation learning, transfer, and the development of expertise have received less attention.

To learn to design with specific types of innovation as an end goal, designers must undergo progressions in what are herein characterized as levels of practice. Inspired by the literature on learning progressions (Duncan and Hmelo-Silver, 2009; Duncan and Rivet, 2013), levels of practice describe conjectural models of increasingly sophisticated behaviors and highlight how a sequencing of skills and ideas of innovative practice unfold over time. Moving to a different level involves a transition period that requires conscious awareness of practice, unlearning old routines, and learning new patterns (Lawson and

Dorst, 2009; Crismond and Adams, 2012). In the field of design learning, these levels have often been studied by highlighting hierarchies in progression from novice to expert and beyond (Cross, 2004; Lawson and Dorst, 2009), as shown in the example in Figure 2.10.

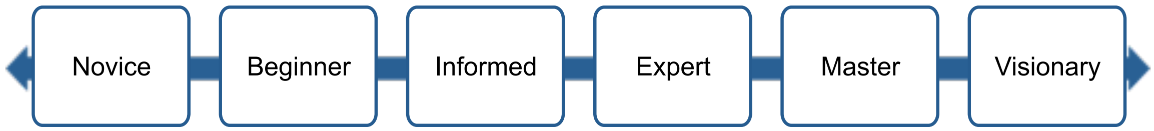


Figure 2.10 Conceptions of Levels of Practice in Design Activities

Yet conceptions of these levels of practice have greatly varied (Crismond and Adams, 2012) and are typically not tied to a specific desired impact pattern as the result of design activities. The focus of this dissertation is on levels of practice instead of learning progressions since the latter typically involve more comprehensive descriptions often including content, practices, epistemology (Duncan and Rivet, 2013), and instruction and assessments (Duncan and Hmelo-Silver, 2009), which, although important, fall outside of the scope of this research given that innovation experts have not yet been characterized to date. A comprehensive description of innovation learning would likely also entail description of the patterns of thinking, acting, and being of innovators, which go well beyond skill description and stepwise description of levels of practice leading to a multi-trajectory space of ways of becoming a professional. In educational environments this has been described in a framework that emphasizes the epistemological and ontological aspects of professional practice (Dall'Alba and Barnacle, 2007; Dall'Alba, 2009; Adams et al., 2011), i.e., the thinking, acting, and being that characterizes professionals, and, to date, none of these perspectives exist for the challenge of learning to innovate.

From a learning perspective, this dissertation provides a building block on learning to innovate using knowledge on design learning and design processes as a foundation, and focuses on how designers/innovators could transition from the patterns and behaviors of a beginner designer, to the patterns and behaviors of an informed designer, to the patterns and behaviors for enabling innovation. As such, learning to design for enabling innovation can be conceptualized as a transition between being a beginner designer (with little to no training in design), to a period of informed design (competence in overall/general design activities), as described by Crismond and Adams (2012), to a more specific type of informed design, that is, design with awareness of the pattern of enabling innovation and the end goal of driving enabling innovation. This "enabling designer" level of practice implies that, beyond awareness of skills and processes to design for innovation, practitioners must also be able to recognize patterns/archetypes of innovation in problem and solution spaces (i.e., the characteristics of the end goal) – and in this specific framework, enabling innovation.

2.7 Summary

This chapter integrated foundational concepts for the enabling innovation model and the enabling thinking framework. These concepts stem from four different schools of thought – innovation, design, entrepreneurism, and learning – with each school of thought contributing to the understanding of high impact innovation in unique ways. Design contributes to understanding an organized process and way of thinking that aims to convert existing situations into preferred ones, with a rich body of work that outlines the thinking, acting, and being that can help one achieve general design goals. Innovation research has defined a broad array of archetypes that characterize the novelty of ideas (e.g., radical, disruptive, modular, architectural) and created multiple models and concepts that describe many trajectories from idea to innovation (e.g., paradigm, S-curve, dominant design, enabling technology, generic purpose technology). Entrepreneurism is herein uniquely framed as a design approach for intentional innovation, in which designers search for opportunities and navigate a set of unique challenges employing an entrepreneurial/effectual mindset. Finally, making innovation systematic and teachable implies characterizing innovation expertise, an effort that can be informed from insights from the field of learning, such as learning progressions and theories of learning, expertise, and professional development. These concepts from design, innovation, entrepreneurism, and learning are seldom brought together even though their integration into larger patterns/models can give them meaning and provide them with a context and perspective. The following chapter describes the methodology employed to ingrate these schools of thought with data on historical innovation cases and performance tasks, thus creating an impact-based innovation model – the enabling innovation model – and the end-to-end enabling thinking framework that can guide enabling innovation pursuits.

CHAPTER 3. METHODOLOGY EMPLOYED TO DEVELOP THE ENABLING INNOVATION MODEL AND ENABLING THINKING FRAMEWORK

3.1 Introduction

This chapter describes the methodology employed to characterize the enabling innovation model and the enabling thinking framework. This methodology is herein discussed for each of these two research streams, outlining the methods, data sources, tools, key analysis steps, and quality measures employed, as shown in Figure 3.1.

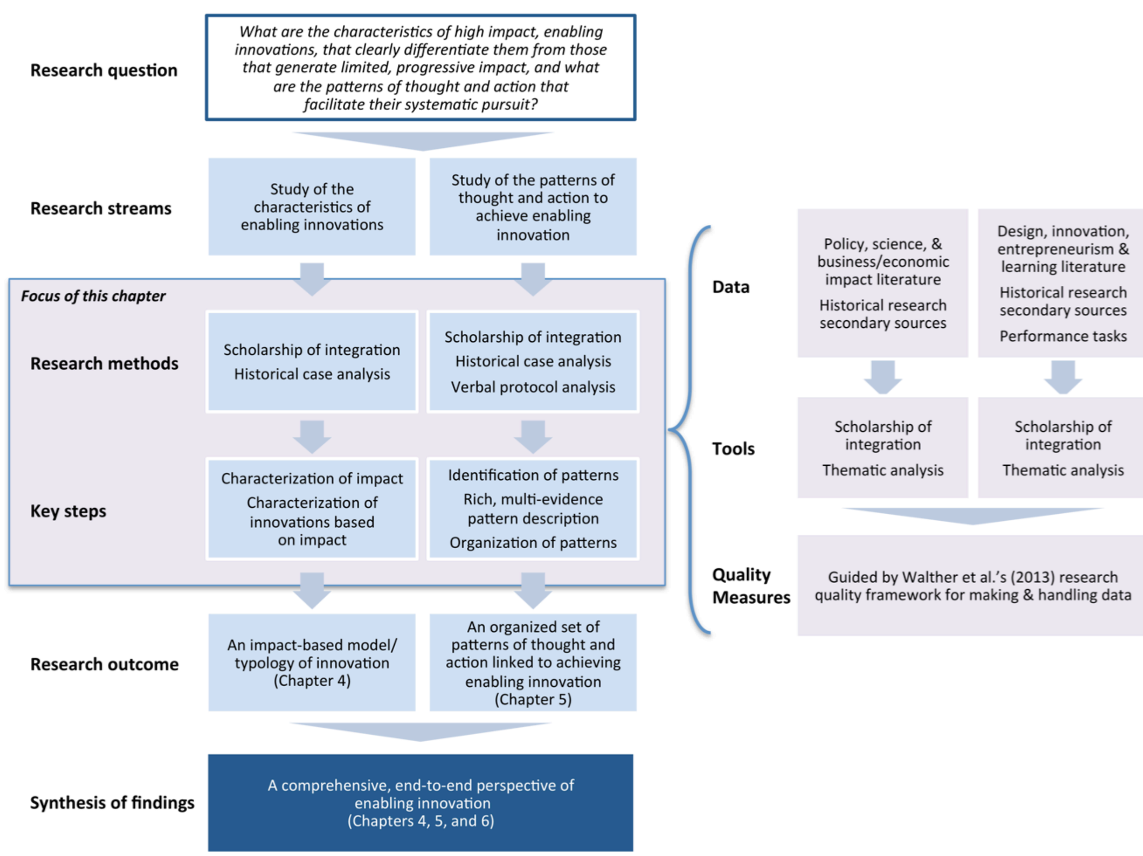


Figure 3.1 Overview of the Research Methodology

3.2 Methodology Employed to Develop the Enabling Innovation Model

The methodology employed to characterize enabling innovations focused on answering the question: "*What are the characteristics of high impact, enabling innovations, that clearly differentiate them from those that generate limited, progressive impact?* As shown in Figure 3.2, to answer this question, the author engaged in an iterative, multifaceted approach consisting of: 1) integrating innovation-related literature from a variety of schools of thought, particularly the schools of thought described in Chapter 2, employing the scholarship of integration (Boyer, 1990) (literature which can be classified by the presence or absence of explicit links between innovations and their impact); and 2) conducting content analysis of historical innovations that have had impact on par with the impact needed to address the complex societal challenges that motivate this work. Each of these approaches contributed in different ways to the work described herein. The scholarship of integration effort highlighted a gap in the ways to frame innovation, guided the synthesis of impact perspectives, and pinpointed the often tenuous link between innovations and impact throughout the literature. The content analysis of historical research helped articulate and contextualize the characteristics of enabling and progressive innovations.

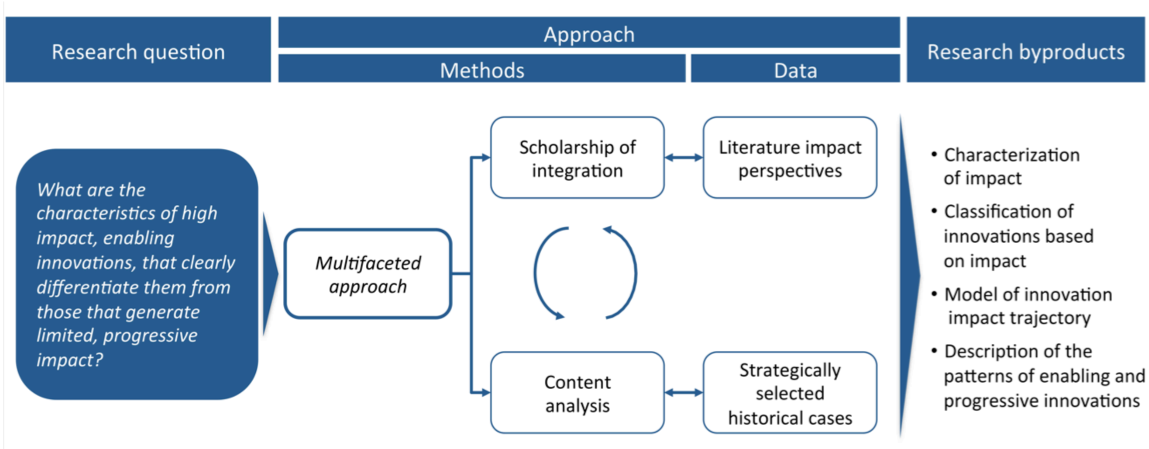


Figure 3.2 Multifaceted Approach Employed to Characterize Enabling Innovations

The result of this multifaceted approach is a new model that can be employed to examine innovations, grounded in scholarly research and evidence from historical innovations. The model describes the macro stages in the impact trajectory of innovations and zeroes in on patterns in the micro process by which enabling innovations come into being. Three caveats must be acknowledged before describing in more depth the approach taken to build this model. First, the goal of this work is not to conduct historical research in and of itself, but to identify themes from the content analysis of strategically selected historical research. Second, more traditional economic discussions (e.g., technology push versus demand pull, productivity improvements, and substitution) are embedded throughout this analysis – where relevant – but do not constitute a primary focus of the analysis since the economics aspects of innovation are herein considered a subcomponent of its overall impact (i.e., impact is defined broadly). Finally, although progressive innovations are important from an impact perspective, more emphasis is placed on enabling innovations given that many of the current schools of thought used to examine innovation fall under the umbrella of progressive innovation. Special emphasis is placed on what is characterized in this work as *the enabling window* – the stage in which enabling innovations transition from impact in select application spaces to an impact cascade.

3.2.1 Approach and Data

The two approaches – impact literature integration and historical case analysis – and corresponding data sources employed to develop the enabling innovation model are described in the following paragraphs. These iterative approaches were also informed by concepts in the four foundational schools of thought: design, innovation, entrepreneurism, and learning described in Chapter 2 of this study, especially concepts related to innovation archetypes and trajectories.

The first approach focused on integrating impact perspectives throughout the literature. As described in Chapter 1, a scholarship of integration (Boyer, 1990) extracts larger intellectual patterns from prior research efforts spread through a number of schools of thought. In this work, the scholarship of integration stream examined two specific types of sources that highlight gaps in the links between innovation and impact: a) policy (e.g., OECD, 2011, Gurria, 2011; UN, 1969, 2000; Geels and Schot, 2007) and science impact perspectives (e.g., Godin and Dore, 2004; Dudley, 2013), which tend to have tacit links to innovation; and b) impact perspectives with explicit links to innovation, which tend to have a localized business/commercial (e.g., Abernathy and Clarke, 1985; Feland et al., 2004; MGI, 2013) and economic scope (e.g., Perez, 2003; Christensen, 2014). For example, Abernathy and Clarke (1985) classified innovations as "competence-enhancing" and "competence-destroying," and Christensen (2014) classified innovations based on their impact on economic growth as "performance-improving," "efficiency," and "market-creating." A synthesis of these two types of literature streams is provided in Appendix A. These perspectives were aggregated into larger patterns that capture and conceptually organize the link between an innovation and its impact.

To further develop a definition of innovation impact, historical cases with varying measures of impact were triangulated with the aforementioned literature to better understand and characterize the impact construct, as shown in Appendix B. This initial set of historical cases stemmed from literature that explores the history of multiple innovations (e.g., Challoner, 2009; Constable and Somerville, 2003; Goddard, 2010) and literature that synthesizes multiple innovation cases into science (e.g., Kuhn, 1962) and invention frameworks (Arthur, 2007; 2009). As a byproduct of this synthesis, impact was characterized as the degree to which an innovation changes the way societal stakeholders live and act and is herein broken down into the fundamental components of reach, significance, and paradigm change (discussed in detail further along this chapter and in Solis and Sinfield [2014, 2015]).

The second approach focused on developing the enabling innovation model and consisted of theory building activities and content analysis of historical research cases. More specifically, insights from the framework proposed by Eisenhardt (1989, 1991) to build theories from case studies and thematic analysis (Braun and Clarke, 2006) were merged using historical research on innovations as data. The rationale for merging these two methodological approaches is rooted in the use of historical cases as data, and the flexible yet rigorous theoretical and epistemological assumptions underlying thematic analyses, which allow one to employ such a method in many ways and derive multiple types of interpretations (see Braun and Clarke [2006] for a discussion on these issues for thematic analysis).

Building theories and/or models from case studies is a "research strategy that uses one or more cases to develop constructs, and propositions from case-based evidence" (Eisenhardt, 1989, 1991; Eisenhardt and Graebner, 2007). It is important to clarify that in this work case study research philosophies are grounded in the methods and approaches described in the management literature and not in the education literature. In this school of thought, case study research is described as a process of selecting cases, establishing data collection methods and collecting data, analyzing data using within-case and cross-case pattern search, shaping hypotheses, enfolding literature, and reaching closure (see Eisenhardt, 1989). "Central to building theory from case studies is replication logic" (Eisenhardt, 1989), i.e., as described by Eisenhardt and Graebner (2007, p. 25): "each case serves as a distinct experiment that stands on its own as an analytic unit. Like a series of related laboratory experiments, multiple cases are discrete experiments that serve as replications, contrasts, and extensions to the emerging theory (Yin, 2009). But while laboratory experiments isolate the phenomena from their context, case studies emphasize the rich, real-world context in which the phenomena occur. The theory-building process occurs via recursive cycling among the case data, emerging theory, and later, extant literature." Diving deep into these "experiments" to achieve comparable logic was approached herein by using thematic analysis to unearth different types of themes from the data, though always keeping in mind the goal of integrating these themes into an innovation model.

Thematic analysis was employed as a tool to guide the content analysis of the historical cases. This method is typically employed to identify patterns (themes) within data and interpret various aspects of a research topic (Boyatzis, 1998). A theme represents a systematic "patterned response or meaning within a data set," and the relative importance of themes in this type of research does not necessarily depend on quantifiable measures of theme presence (Braun and Clarke, 2006). Instead, the importance of a theme stems from its ability to capture a pattern relevant to the research question. The thematic analysis in this work is performed at the latent level, i.e., it is focused on identifying underlying ideas, assumptions, and conceptual organization (Patton, 1990) of innovations and their impact, rather than simply describing and interpreting the historical case data, with a special emphasis on identifying common patterns underlying innovations that can be considered enabling. The search for these common patterns was guided by the research question and subquestions related to characterizing high impact innovations (e.g., characterizing impact and innovations by their impact, identifying historical examples of enabling innovations, understanding the trajectories of high impact innovations).

Nine strategically selected innovation cases that have generated impact on par with what are herein described as enabling innovations were used in this analysis, such as radar, the laser, x-rays, global positioning systems (GPS), anesthesia, antisepsis, the concept of unit of operations, microfinance, and crowdsourcing. As shown in Figure 3.3, the cases were strategically selected to show that high impact, enabling innovations can take many forms and may be artifacts (tangible human made objects or processes not naturally present) or concepts (related to the formation of abstract conceptualizations), technological or non-technological (related to the use of technology). This strategic selection of cases can be further analyzed, as shown in Figure 3.4, which shows that high-impact, enabling innovations can result from both chance and from intentional pursuits, their main driver is not only science and technology, but can be driven/motivated by medical, conceptual, and financial change, and can stem from both (technology) push and (market) pull approaches. As such, the classification of innovations based on their impact – as enabling or progressive – does not depend on any of the aforementioned conditions (e.g., push versus pull, technological versus non-technological). Instead, the common denominators across this sample set of cases are their impact outcomes.

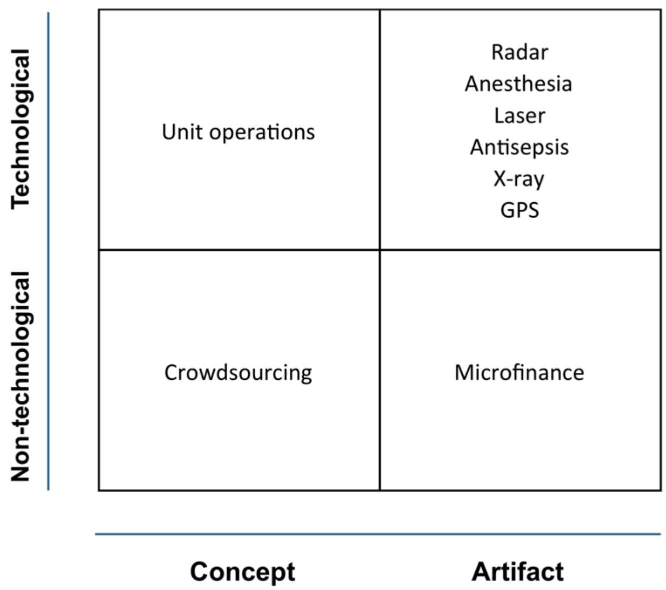


Figure 3.3 Strategic Selection of Cases Employed in this Study

The data sources for the thematic analysis consisted of published secondary historical accounts of the aforementioned innovations. Some of these secondary sources consist of direct/first-hand accounts (e.g., narratives, interviews) from/with stakeholders directly involved in the development and history of the innovation (e.g., Townes' [1999] account on the development of the laser; or Guier and Weiffenbach's [1998] account on the development of GPS). Other secondary sources consist of rich descriptions of the cases with a relatively large number of documented references (e.g., Arthur, 2009; Kuhn 1962; Sykes and Bunker, 2007).

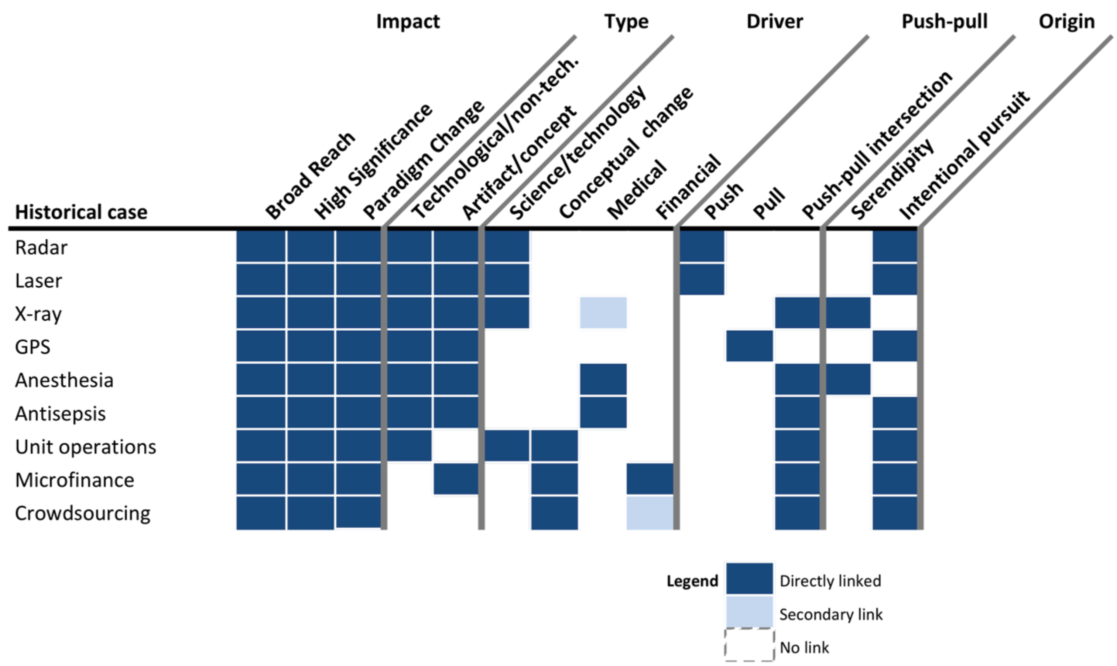


Figure 3.4 Strategic Sampling of Cases Suggesting Impact as a Common Theme

To ensure the quality of the historical sources employed, following Scott (1990), only sources with a relatively high degree of authenticity (whether evidence is genuine and from quality sources), credibility (whether evidence is typical of its kind), representativeness (whether sources are illustrative of the totality of relevant documents in the literature), and meaning (whether evidence is clear and comprehensible) were considered. This framework ensured that the secondary sources employed were of a relatively high quality, i.e., with a rich number of primary and/or secondary sources, triangulation of relatively high number of references, and relatively neutral perspectives on polarized issues (e.g., religion in anesthesia or patent races in the laser).

Table 3.1 exemplifies the data sources employed in this work and illustrative examples of case summaries created are provided in Appendix C. As a reminder, these sources were employed to conduct content analysis of historical research and not to conduct historical research in and of itself. In addition, the sources listed in Table 3.1 are only illustrative of the types of literature employed in the content analysis and do not constitute an exhaustive list of references for each case.

More than one source was employed for each case to facilitate triangulation between sources, and the identification of discrepancies. The use of multiple sources helped obtain more objective perspectives on the development of the historical cases, particularly those in which some historical aspects are polarized. Examples of polarized aspects of historical cases include patent wars in the history of the laser, and credits for the first discovery of x-rays. Nonetheless, discrepancies in these polarized accounts are herein assumed irrelevant to this study, given its focus on the underlying themes in the development of innovations with high societal impact.

These two approaches – i.e., a scholarship of integration and content analysis (thematic analysis) of historical cases – were iteratively employed to develop a framework that describes the intrinsic characteristics (i.e., to answer: *what are enabling innovations?*), the impact outcomes (i.e., to answer: *what impact do enabling innovations generate?*), and the trajectory model (i.e., to answer: *how do innovations transition from breakthrough to enabling and progressive stages?*) of enabling innovations. This iterative process involved shifting between deductive and inductive approaches (e.g., scanning the literature for gaps or prior theories, integrating it with emerging themes in the data, and assessing the fit of such themes with prior scholarly work) to test the classification and characteristics of enabling innovations formulated (see Carlile and Christensen, 2005).

Table 3.1 Sample Sources Employed in the Historical Research (not exhaustive)

Case	Sample source	Author (year)
Laser	How the laser happened	Townes (1999)
	The laser in America	Bromberg (1991)
	Beam: The race to make the laser	Hecht (2005)
X-ray	Naked to the bone: Medical imaging in the twentieth century	Kevles (1997)
	X-ray vision: The evolution of medical imaging and its human significance	Gunderman (2012)
	Technology in the hospital: Transforming patient care in the twentieth century	Howell (1995)
Radar	The invention that changed the world	Buderi (1996)
	Tracking the History of Radar	Blumtritt et al. (1994)
GPS	You are here: From the compass to GPS, the history and future of how we find ourselves	Bray (2014)
	GPS Declassified	Easton and Frazier (2001)
	Genesis of satellite navigation	Guier and Weiffenbach (1998)
Anesthesia	Anesthesia and the practice of medicine: Historical perspectives	Sykes and Bunker (2007)
	From craft to specialty: A medical and social history of anesthesia and its changing role in health care	Shephard (2009)
Antisepsis	A brief history of antiseptic surgery	Clark (1907)
	Infectious history	Lederberg (2000)
Unit of operations	Chemical engineering as a general purpose technology	Rosenberg (1998)
	The early history of chemical engineering: A reassessment	Cohen (1996)
	The industrial relations of science: Chemical engineering at MIT, 1900-1939	Servos (1980)
Microfinance	The economics of microfinance	Armendariz and Morduch (2007)
	Banker to the poor	Yunus and Jolis (1999)
Crowdsourcing	Conceptual foundations of crowdsourcing: A review of Information Systems research	Pedersen et al. (2013)
	The wisdom of crowds	Surowiecki (2005)
	Crowdsourcing as a solution to distant search	Afua et al. (2012)
	Crowdsourcing	Brabham (2013)

3.2.2 Research Quality Measures

This thesis followed the framework proposed by Walter et al. (2013) on research quality strategies for "*making data*" and "*handling data*" to achieve validation and process reliability. A summary of this framework with regards to this study is provided in Table 3.2 and is described throughout this section.

With regard to validation, the goal is to make sure "we see what we think we see" during the making data stage and to "call things by the right names" in the handing data stage (Walter et al., 2013, p. 639). Five types of validation are sought after; namely, theoretical validation (fit between phenomenon under investigation and theory/framework produced), procedural validation (features incorporated into the research design to improve the link between a theory/framework and a phenomenon), communicative validation (relevance in terms of language, meaning, and/or conventions of the research community), and pragmatic validation (the extent to which concepts are compatible with the empirical reality). In this study, strategies were employed to answer the five types of validation in making and handling the data as outlined in Table 3.2.

Purposive sampling was employed as a strategy for theoretical validation in making the data, while a process of negative case analysis (Lincoln and Guba, 1985) was employed in handling the data to develop the concepts, relationships and themes of the enabling innovation framework. For example, while most enabling innovation cases went through relatively long periods of time before achieving broad, significant impact (often spanning decades), the laser was relatively quick to achieve impact in many societal arenas (e.g., laser companies emerged one year after its invention and the first laser-based surgery was conducted within two years of its invention). Ultimately, as described further along this chapter, the analysis of cases that do not fit the norm of the sample helped reshape frameworks and insights for the enabling innovation model (and also the enabling thinking framework).

Table 3.2 Research quality measures and supporting strategies for the development of the enabling innovation model and related historical case analysis

	Making Data	Handling Data
Theoretical validation Do the concepts and relationships of the framework rightly correspond to the reality under investigation?	Purposive/strategic sampling of historical cases was employed, with a focus on cases that have high-impact as a common denominator, and are either technological or non-technological, technical or conceptual. The research design emerged throughout the course of the study as new insights regarding enabling innovations surfaced.	Negative cases, exceptions, and caveats were proactively sought after to examine their similarities and differences, the contexts under which patterns arise, and the exceptions and caveats in the set of historical cases analyzed.
Procedural validation Which features of the research design improve the fit between reality and the framework generated?	Cross-case triangulation was employed, in addition to triangulation with impact-related literature and innovation-related literature. Emphasis was also placed on using high quality historical research sources.	Thematic analysis was employed to understand themes and characteristics, and stages of an impact-based framework of innovations.
Communicative validation Is the knowledge constructed within the relevant communication community?	Interactions with dissertation committee members were proactively sought-after regarding the process by which the case data was generated and the process by which the model was created	Triangulation with innovation experts and peer-debriefing were employed. A thorough discussion enfolding/ integrating the model with existing literature is provided in Chapter 6. Publication in peer-reviewed outlets was pursued to ensure the relevance of the developed framework to the research and practitioner communities.
Pragmatic validation Do the concepts and knowledge claims withstand exposure to the reality investigated?	The diversity of the cases examined in the development of the framework help ensure that multiple viewpoints test the pragmatic qualities of the framework. As such, the diversity of cases examined make sure that the framework is applicable to a broad array of circumstances.	Emphasis was placed on developing a framework that can help identify/screen future enabling innovations as well as provide guidelines for their pursuit. The framework has been presented in various outlets and audiences have been exposed to the terms enabling and progressive innovation and their meanings, which has resulted in ideas for refinement of the framework.
Process reliability To what extent is the research process independent from random influences?	The strategy and process for selecting and analyzing historical case data was documented. No emphasis was placed on debatable aspects of history in the development of the framework.	The development of the framework was regularly discussed with and reviewed by members of the research team.

For procedural validation triangulation between multiple data sources to produce understanding was critical. For example, different types of cases (e.g., technological, non-technological, medical), from different time periods, and/or different fields were triangulated (Maxwell, 2005) with, for instance, insights from the policy literature that characterizes impact. For this triangulation process, emphasis was placed on using high quality sources. In handling the data, procedural validation was sought-after by employing a systematic and iterative process of searching for themes within the cases that are employed to build the enabling innovation model.

This procedural validation process is strengthened by the author's "interpretive awareness" (Sandberg, 2005), i.e., the explicit acknowledgement of the research subjectivity and the lenses employed in the author's interpretation. First, notions of innovation are highly disputed and the author's perspective is that innovation encompasses application (i.e., the introduction of ideas into practice) that leads to impact, and not only novelty and/or differentiation. Second, a dichotomy exists between researchers that perceive definite leaps in performance, versatility, or impact to be nonexistent (implying that they only believe in innovation as an incremental and evolutionary process) (e.g., Basalla, 1988), which is in contrast to the perspective of the author, who believes that innovation can come from both definite leaps and/or incremental processes. Third, the author is trained in both the engineering and management sciences and both of these schools of thought have informed the author's perspectives on innovation, particularly theories in the management sciences such as disruptive innovation, and theories common in engineering such as human centered design. Finally, and as described in Chapter 1 of this work, the philosophical orientation of the work is in the pragmatic domain and as such the interpretations of the author tend to have a highly pragmatic orientation.

Communicative validation in making and handling the data was sought-after by engaging with members of the research team and the research community. For example, in discussions with the research community, the author often receives the comment that high impact innovations are particularly easy to identify in hindsight. These discussions have partially contributed to the author's thinking on defining a set of "weak signals" (i.e., a set of patterns to screen/identify) that one can employ when identifying future enabling innovations.

Pragmatic validation was sought after by using a diverse set of cases and impact perspectives that reflect multiple aspects of the empirical reality and in presenting the framework in a variety of peer-reviewed outlets. Multiple sources were reviewed for each case and new case sources were reviewed that were iteratively synthesized and incorporated into the case summaries in Appendix C.

With regard to process reliability, the goal is to make the research process as independent as possible from random influences. In this research, the rationale for the choices made in the process of making data, and the choices and process for handling data were documented and iteratively discussed with and reviewed by members of the research team. In making the data, the process entailed examination of a relatively large number of cases for selection of the cases to be studied in more depth, identification of relevant literature for each case, review and synthesis of literature for each case, and a search for themes within and across cases that was highly iterative. New cases of different categories were iteratively added to the sample (e.g., microfinance and crowdsourcing were not part of the initial set of cases), and literature was constantly reviewed to help position the enabling innovation framework and its descriptive language.

3.3 Methodology Employed to Develop the Enabling Thinking Framework

As shown in Figure 3.5, to answer the research question: "*What patterns of thought and action facilitate the systematic pursuit of high impact, enabling innovations*"?, the author engaged in an iterative, multifaceted approach that consisted of: 1) integrating innovation-related literature using the scholarship of integration approach (Boyer, 1990) to link insights from seemingly disparate schools of thought, particularly the schools of thought described in Chapter 2; 2) conducting content analysis of literature related to the development of historical innovations that have had impact on par with the impact of enabling innovations; and 3) conducting a thematic analysis of 28 verbal protocols of a performance task conducted with innovation professionals, faculty, and students. The analysis of these inputs was highly iterative and complementary, implying that no particular perspective was more important than the others as they all contributed in unique ways to a richer, more pragmatic description of the patterns and behaviors described herein. As such, each of these approaches, when integrated, helps provide a comprehensive perspective on the process of innovating. The scholarship of integration method helps position the findings within the literature and helps to make meaningful connections between innovation literature found in seemingly unrelated fields. The content analysis of the historical innovations, herein considered enabling, helps define the relevance or importance of the patterns and behaviors in achieving enabling innovation – i.e., helping link the patterns and behaviors to impact. The thematic analysis of the performance tasks helps exemplify these patterns and behaviors in practice and makes the patterns and behaviors used by designers/problem solvers, which are often hidden in a final artifact/solution, more explicit. Details on each of these lenses are provided in the following sections.

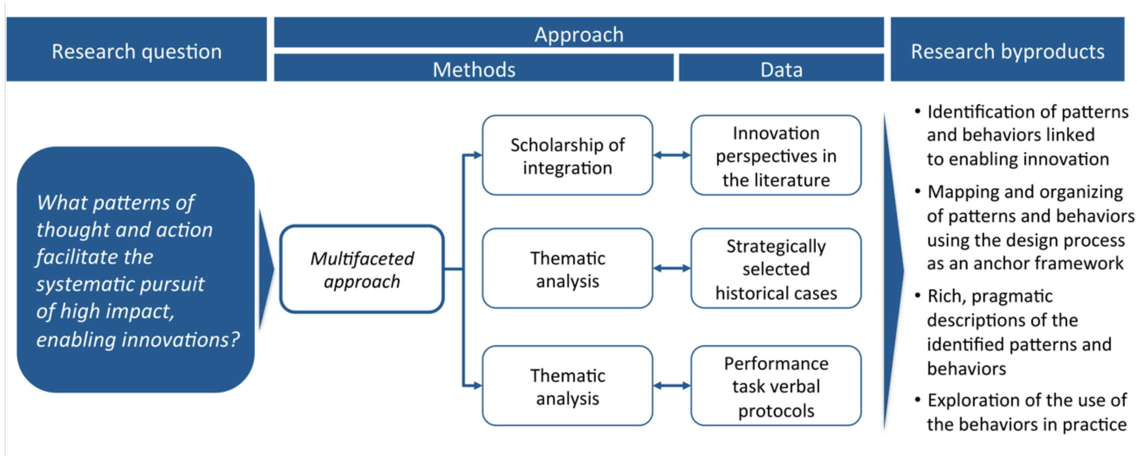


Figure 3.5 Overview of the Methodology Employed to Develop the Framework

3.3.1 The Method of the Scholarship of Integration

The "scholarship of integration" approach (Boyer, 1990) was employed to make connections across disciplines and place these connections in a larger context as a means to create new insights from original research (Boyer, 1990). The approach taken here was inspired by similar efforts in fields such as engineering design, business, and medicine (e.g., Crismond and Adams, 2012; Bartunek, 2007; Haynie et al., 2010; Chu, 1993; Barbato, 2000; Dauphinée and Martin, 2000; Weick, 1996; Hofmeyer et al., 2007). These prior efforts collectively emphasize that the scholarship of integration is critical to advance scholarly activities, span boundaries between scholarly fields of work, *and* translate the implications of this work for practice.

This integration effort in particular focused on identifying and characterizing design patterns and behaviors that lead to enabling innovation. Guided and bounded by the subquestion: "*What design patterns and behaviors from the innovation, entrepreneurism, design, and learning schools of thought can lead to high impact, enabling innovations?*" an extensive cross/inter/trans-disciplinary literature integration effort was conducted to identify patterns and behaviors studied throughout the literature, synthesize them in the context of the enabling innovation model described in Chapter 3, and triangulate them with evidence from historical cases and the verbal protocol analysis.

The approach to integrating insights from these sources followed four key steps suggested by Crismond and Adams (2012), modified to better fit the research questions of this study, namely: 1) creating boundaries for the design performance that guided the search; 2) generating key performance dimensions that can guide the integration of literature sources; 3) "representing/translating" the identified patterns an organized framework, and 4) triangulating the findings of the scholarship of integration approach with the other approaches in this multifaceted study. The following sections describe these steps in more detail.

3.3.1.1 Bounding Design Performance for Enabling Innovation in Levels of Practice

In the first step, boundaries for design performance were generated because an underlying goal driving the identification of such patterns and behaviors is to facilitate their use in practice as well as their integration with teaching, learning, and assessment of design and innovation competencies. This integration implies that in addition to understanding the behaviors in and of themselves, there is a need to understand how these behaviors develop and how they fit with current design and innovation paradigms.

These boundaries in design performance are herein defined as *levels of practice*. These levels of practice, are inspired by the literature on learning progressions (Duncan and Rivet, 2013; Crismond and Adams, 2012), and describe the nature and sequencing of patterns and behaviors that designers should develop over time for use in practice. To put the enabling thinking framework in context, the beginner and informed designer patterns highlighted in Crismond and Adams (2012) are contrasted here with the patterns for enabling innovation. Beginner designers are designers with little to no training in design, while informed designers are competent in design activities and their capabilities lie somewhere between a novice and an expert (Crismond, 2005), and these levels of practice can likely be used to describe any type of designer.

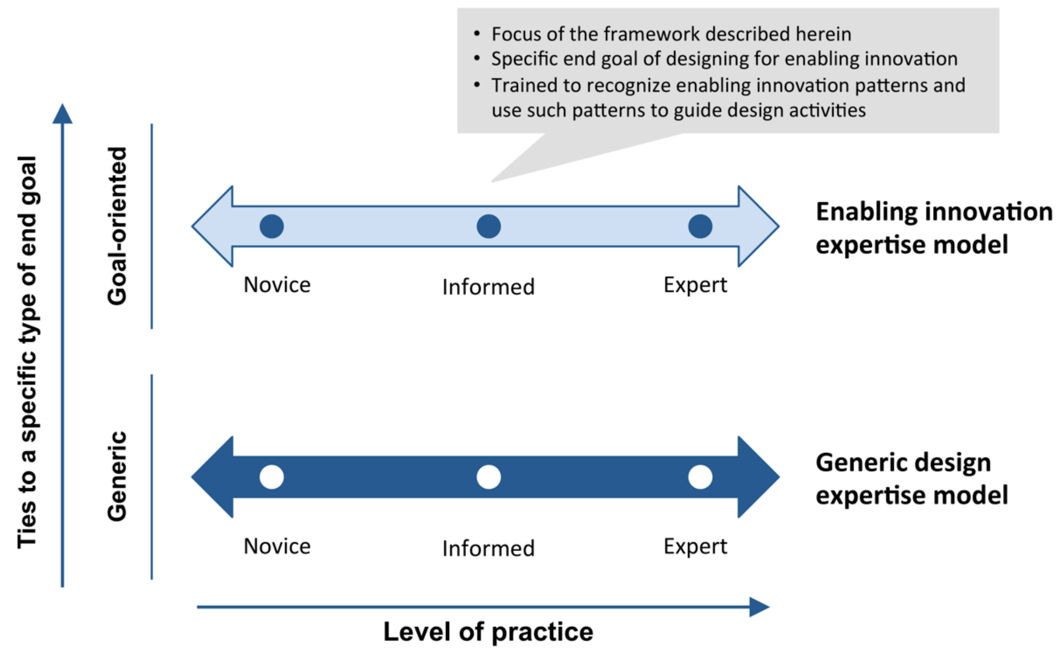


Figure 3.6 Positioning of the Enabling Framework in Expert-Novice Continuums

The enabling innovation level of practice departs from generic perspectives of design by pursuing the specific end goal of achieving enabling innovation through a distinct set of competencies. A major challenge in generalized conceptions of design and problem solving processes is that the subtle actions that make a difference in very specific circumstances and types of desired outcomes might be diluted (Visser, 2009). Thus, a robust enabling thinking framework must employ a specific mindset that recognizes enabling innovation patterns to guide design activities (see Figure 3.6). As such, the enabling thinking framework is assumed to be on a different progression of levels of practice – i.e., an enabling innovation expertise progression, because general design models do not usually account for patterns in innovation outcomes as a goal. Effectively, in the proposed end-to-end design process, enabling thinking behaviors are not "advanced versions" of basic design skills (à la classic definitions of novices and experts). Instead, the behaviors reflect a level of practice that characterizes a designer that has the specific end goal of proactively driving *enabling innovation* and has the competencies to realize it.

3.3.1.2 Engaging in a Meta-Analysis Guided by Key Dimensions of Design Performance

With the level of design practice in mind, a set of dimensions that can help further bound enabling innovation design performance is needed to guide the discovery efforts. In this study in particular the following set of dimensions were employed:

- *Pragmatic nature of the patterns and behaviors.* The behaviors to be identified need to be actionable and pragmatic, leaving out conceptions of innovation behaviors that are more attitudinal in nature or related to personality traits. This performance dimension thus ensures that the patterns and behaviors identified in the framework are observable, can be proactively practiced, and potentially taught.
- *Relationship to innovation and enabling innovation.* Although many patterns and behaviors related to innovation exist, such behaviors are typically developed with a perspective on innovation as novelty and not necessarily as innovation as novelty *and* impact. Thus, this particular perspective of innovation was employed when identifying behaviors throughout the literature ensuring that the behaviors (individually and/or as a collection) drive towards novelty and the dimensions of impact of the enabling innovation model – reach, significance, and paradigm change.
- *Bodies of work explored.* The design, innovation, entrepreneurism, and learning schools of thought were the focus of this effort. Insights from each of these schools of thought can help one better understand key elements of any design challenge: the problem space, the solution space, and the approach used to

connect such spaces in the framing of problems and development and implementation of solutions, as described in Chapter 2 of this dissertation.

- *Uniqueness of the behaviors.* Although the literature has discussed variants of the behaviors described herein, the naming/labeling of the behaviors in this framework is tied to the end goal of achieving enabling innovation. Some behaviors, such as prioritizing are often listed as critical thinking skills, but in this framework, a link to innovation or enabling innovation is created. Other behaviors recognized as innovation behaviors throughout the literature are herein adapted to fit the enabling innovation model. Finally, some behaviors described herein are new/unique and have not been discussed before throughout the literature (although some weak links can be established).
- *Potential for use across disciplines.* The language employed to describe the patterns and behaviors identified herein aims to be applicable to disciplines beyond engineering and engineering design.

The aforementioned dimensions of enabling innovation design performance were employed to guide the review of diverse literature streams. The scholarship of integration effort reviewed multiple literature streams that have focused on the topics of design, innovation, entrepreneurism, and learning, spanning fields of study, including but not limited to: management science, strategic management, entrepreneurship, organizational behavior, economics, engineering, science, technology, psychology, and design. Thus, knowledge about the subject was gathered from journals such as *The Academy of Management Journal, Academy of Management Review, Administrative Science Quarterly, Journal of Business Venturing, Journal of Engineering Entrepreneurship, Journal of Management, Management Science, International Journal of Management Science, Organization Science, Organization Behavior and Human Performance, Strategic Management Journal, Strategic Entrepreneurship Journal, Entrepreneurship Theory and Practice, California Management Review, Harvard Business Review, MIT Sloan Management Review, MIT Technology Review, Applied Cognitive Psychology, Journal of*

Applied Psychology, Psychological Science, Science, Research Policy, Cognition and Instruction, Cognitive Science, Journal of Engineering Education, International Journal of Engineering Education, ASME Journal of Mechanical Design, IEEE Systems Journal, Creativity and Innovation Management International Journal of Innovation Science, International Journal of Design Creativity and Innovation, Journal of Product Innovation Management, Journal of Design Research, Design Theory and Methodology, Design Issues, and Design Studies. Multiple books (e.g., Anthony et al., 2008; Christensen, 1997; Christensen and Raynor, 2003; Dyer et al., 2009; Kumar, 2012) based on empirical research and practical fieldwork in related areas were also studied. The knowledge summarized in these books is also diverse and multi-disciplinary, again making integration efforts valuable.

3.3.1.3 Representing the Patterns and Behaviors in an Organized Framework

The third step consists of "representing/translating" the identified patterns into an organized framework. Several iterations of the framework to design for enabling innovation were created. Criteria employed to iteratively create the representation of the framework include: 1) incorporation of a progression of levels of practice, 2) a logical arrangement of patterns and behaviors by design stage, 3) communicability and ease of use of the organizing framework for stakeholders across disciplines.

3.3.1.4 Triangulating Findings with the Other Methodological Approaches

Although the first conception of the framework stemmed from the scholarship of integration approach, subsequent framework iterations triangulated the different methodological approaches such as thematic analysis of historical research and a verbal protocol analysis of performance tasks in this multifaceted study. Details on this triangulation process are provided in section 3.3.4.

3.3.2 The Method of Historical Research Case Analysis

The second approach in this multifaceted study involved searching for evidence of innovation behaviors through thematic analysis of historical research thus establishing links between the previously defined patterns and behaviors and historical enabling innovation impact. The data sources for this thematic analysis involved the set of cases and historical research sources identified in section 3.2. These sources were employed to search for examples of the identified innovation behaviors in the actions of stakeholders highlighted as well as to search for themes of new behaviors that the other two approaches had not identified. Actions of stakeholders documented in these historical research sources that were identified as examples of a particular behavior were triangulated with additional literature to ensure that such actions were indeed taken by a stakeholder.

Finding examples of enabling thinking patterns and behaviors in the historical cases helps establish a link between the use of such behaviors and achieving enabling innovation. This link is important because it suggests that the use of such behaviors played a role, in intended or unintended ways, in the development of historical enabling innovations. As such, observing documented instances of the behaviors in the context of historical enabling innovations complements the lens of the verbal protocol analysis of performance tasks in which the behaviors can only be "seen/observed" from the lens of the present, which by default, lacks the impact of implementation.

The enabling thinking patterns and behaviors identified through the thematic analysis of historical research (i.e., those that were not originally identified through the scholarship of integration or performance tasks) were triangulated with the integration and performance task methodological approaches. As an example, even though "observing" has been highlighted as an innovation behavior (Dyer et al., 2008), the notion of "noticing" and its importance to innovation is herein identified and described in this study, particularly through careful examination of the history of X-ray devices. At each stage of the innovation's impact trajectory, "noticing" was a key behavior, from Roentgen's notice of a glow emanating from a Crooke's tube in his lab, to understanding the role of materials and ray collimation in the enabling stage. This insight thus guided the search for examples of "noticing" in the scholarship of integration and performance task data.

3.3.3 The Method of the Verbal Protocol Analysis of Performance Tasks

The third method employed in the search for patterns and behaviors that help realize enabling innovations is the lens of verbal protocol analysis (VPA), which is a method for accessing, recording, and analyzing behaviors. This method is based on theories of information processing in which cognitive processes are verbalized as short-term memory is accessed (Ericsson and Simon, 1993). In VPA, subjects think aloud as they perform tasks, providing researchers with data that can be analyzed to provide insight into the phenomenon under investigation. The reader is referred to Ericsson and Simon (1993), Cross et al. (1997), Atman et al., (1999, 2007); Mosborg et al. (2005, 2006); and Adams et al. (2003) for more information on verbal protocol analysis and design tasks.

3.3.3.1 Performance Task

A VPA of a performance task was conducted to generate rich descriptions of design and innovation behaviors, with a special emphasis on searching for examples of what are herein termed enabling innovation behaviors. In this VPA, participants were asked to think aloud as they engaged in a design task centered on increasing the adoption of electric vehicles (EVs), shown in Figure 3.7. This design task prompt was iteratively refined after two pilots with graduate students in which changes to the phrasing and open-ended nature of the task were implemented (based on guidance from faculty with extensive experience with verbal protocols). The topic of EV adoption, a 21st Century White House Grand Challenge, was selected since it resembles the type of challenge that will likely require enabling innovation(s) in its solution. No solution to this ill-defined challenge is currently available and no single insight is likely to solve the problem due to its complexity. The task is inclusive of engineering, design, science, and broader societal issues. Further, addressing this challenge likely requires perspectives of more than one stakeholder category. As such, the task creates an opportunity to observe different levels of performance in design activities when approached by individuals with different training and personal and professional experiences.

Increasing the Adoption of Electric Vehicles

A national committee composed of government officials, academics, and industry executives is interested in significantly increasing the adoption of electric vehicles (EVs). Your goal is to design and provide implementation details for concrete ideas that, if pursued, could significantly increase the adoption of EVs in five years. The committee believes that this goal is critical to the US given the cascading societal impacts that EV adoption would have on the economy, energy, transportation, and the environment. They are committed to providing funds to develop ideas.

According to the Department of Energy, there are three types of electric vehicles: (1) traditional fuel-powered hybrids, which are never plugged in to charge, (2) vehicles that run on electricity and once the electric power runs out utilize fuel to power the electric motor or an internal combustion engine, and (3) all-electric vehicles, also called battery electric vehicles, which only run on electricity. Fuel-powered hybrids have historically played a prominent role in increasing fuel efficiency and reducing carbon emissions. The committee is more interested, however, in pushing vehicles that only run on electricity and vehicles that run on electricity and then switch to fuel.

Given your experience with complex challenges, they have tasked you with coming up with a "90-minute answer." There are no guidelines or constraints provided by the agency; the only requisite is that your response be as concrete and specific as possible and have the potential to generate a significant increase in EV adoption, which currently stands at approximately 115,000 vehicles in service, in five years. You will have the next 90 minutes to develop your recommendation(s).

For this task you may use the computer in the room to browse the web and collect information, if you wish. Please limit your use of the computer to collecting information that is publicly available (i.e., do not use confidential or proprietary documents to which you may have access).

Please verbally explain your approach and recommendation as clearly and completely as possible. Someone should be able to further develop it without any questions. The deliverable to the committee will include as many details of your ideas – e.g., diagrams, back of the envelope calculations, slides, storyboards, models, sketches, or other specifications you may wish to create.

Figure 3.7 Electric Vehicle Performance Task Prompt

These performance tasks were conducted either at the participants' location or via video-based conferencing (e.g., Skype). Participants had a maximum of 90 minutes to complete the task and the protocols were audiotaped for transcription. The duration of the task was set at two hours and selected to be able to fit the often difficult schedules of the professionals involved (90 minutes for the performance task and up to 30 minutes for an interview debrief). A computer was allowed in the room for information gathering purposes. Participants who chose to use the computer were encouraged to only collect and utilize publicly available information and to continue to think aloud as they searched for information online. All participants were also encouraged to email the performance task administrator with any ideas they might think of after leaving the session to acknowledge the fact that some ideas likely require an incubation time period (but zero participants chose to do so).

Following the completion of the tasks, semi-structured interview debriefs were conducted, which lasted 15-30 minutes in duration. The goal of these debriefs was to better understand the rationale behind the participants' behaviors and to relate such behaviors to other personal and professional experiences (of course within the limitations of participants' self awareness of their habits of mind). The debrief was also utilized to understand how participants would have engaged in phases of the design process that they did not pursue explicitly during the performance task (e.g., communicating partial/final design decisions or implementation plans). This interview debrief was prompted by the question: "Can you summarize your recommendation and approach and tell me why the strategies employed are important to you?" Other follow up questions included (but were not limited to):

- "What does this step/action you mentioned mean to you?"
- "How do you think you developed the ability to use this strategy/approach?"
- "How does this step in your approach relate to other cases or experiences?"
- "What does innovation mean to you?"

- "How would your approach change with a peer/teammate in the room?"
- "Who would you have talked to/engaged with if given the opportunity during this task and why?"
- "How would you have communicated/pitched your solution to the committee?"
- "If your ideas were approved by the committee, what steps would you have taken to implement them?"

3.3.3.2 Participants

Performance task participants were selected from diverse groups as the goal was to observe variations in approaches to the performance task. These groups include: 1) professionals working for global design or innovation consulting firms with 5+ years of professional experience; 2) participants in corporate innovation roles such as chief innovation strategists and corporate innovation leaders; 3) faculty from diverse backgrounds/disciplines known in their institution as "innovators"; and 4) participants from the engineering domain, specifically undergraduate students, graduate students, MBA students with an engineering background, and engineers in industry.

These target groups enable one to qualitatively understand the influence that educational background, domain expertise in the subject area of the performance task, habits of mind, and professional experiences might have on the framing of the problem and the solution imagined when they are prompted to innovate (although quantitative analysis could be performed as future work). Participants in the consulting and corporate innovation roles were selected as a target group since their day-to-day professional activities demand them to innovate when prompted (i.e., "on demand") and typically work with/in Fortune 500 firms. In this study, participants in consulting and corporate innovation roles included senior partners at global management consulting firms, and current and former brand managers and R&D leaders in Fortune 100 corporations. Entrepreneurs were selected given their unique design approach and perspectives on solution design, end-user discovery, and implementation. Participants in the engineering domain were selected to better understand how design behaviors manifest at different educational levels (i.e., undergraduate, graduate, faculty, alums). Award winning faculty who are known as “innovators” by others in their institution were selected to detect differences in approach with the other groups. Although the goal of this study was to observe variations in approach regardless of discipline, by contrasting participants, one can obtain insight into such differences (and group-based analyses could be performed in future work).

Twenty-eight (28) subjects with diverse gender, ethnic, and educational backgrounds completed the performance task, as shown in Table 3.3. Recruitment for these participants was conducted using snowball methods (Creswell, 2005), given the difficulty in access to the target groups (particularly those in consulting and corporate innovation roles). Student and faculty participants were identified based on social recommendations, i.e., they were identified by mentors or peers who considered that the participants might be able to provide insight into the goals of the study given their track record in their respective domain. All recruitment and study procedures were in accordance with IRB regulations (see IRB approval form in Appendix D). All verbal protocols were transcribed for analyses using a professional transcription service and cross-checked by the author for accuracy in transcription.

Table 3.3 Performance Task Participants

Pseudonym	Gender	Self-Identified Educational Background	Current role	Years of Experience
Jack	Male	Mechanical Engineering	Corporate R&D Leader	15+
Forrest	Male	Food Science	Innovation consultant (former R&D leader)	15+
Victor	Male	Industrial Engineering and Business	Innovation consultant (former R&D leader)	15+
Max	Male	Business	Innovation consultant	15+
Nicole	Female	Marketing	Innovation consultant	15+
Drew	Male	Industrial Design and Business	Innovation consultant	15+
Henry	Male	Philosophy & Sociology	Innovation consultant	15+
Mike	Male	Medicine	Innovation consultant	10-14
Don	Male	Physics & Engineering	Innovation consultant	10-14
Kate	Female	Biology & Psychology	Innovation consultant	6-9
Ken	Male	Electrical Engineering and Business	Innovation consultant	0-5
Noah	Male	Civil Engineering	Entrepreneur	15+
Nancy	Female	Industrial Engineering and Business	Operations research engineer	10-14
Anna	Female	Business	Policy liaison/consultant	15+
Susan	Female	Polymer Science	Faculty	15+
Sam	Male	Nutrition Science	Faculty	15+
Leo	Male	Economics	Faculty	15+
Charles	Male	Chemical Engineering	Faculty	15+
Dan	Male	Finance	MBA student	0-5
Walter	Male	Mechanical Engineering	MBA student	0-5

Table 3.3 Continued

Pseudonym	**Gender**	**Self-Identified Educational Background**	**Current role**	**Years of Experience**
Felix	Male	Mechanical Engineering	Graduate student and entrepreneur	0-5
Rand	Male	Industrial Engineering	Undergraduate student and entrepreneur	0-5
Neal	Male	Materials Science Engineering	Undergraduate student and entrepreneur	0-5
Ron	Male	Mechanical Engineering	Undergraduate student and entrepreneur	0-5
Nick	Male	Computer Engineering	Undergraduate student	0-5
Lee	Male	Electrical and Computer Engineering	Undergraduate student	0-5
Aaron	Male	Computer Engineering	Undergraduate student	0-5
Bonnie	Female	Electrical Engineering	Undergraduate student	0-5

3.3.3.3 *Analysis*

For the 28 verbal protocols, analyses included narrative summaries of the participants' approach to the EV performance task and thematic analysis to search for innovation/design patterns and behaviors. The goal of these analyses is to be able to see/observe a wide range of innovation patterns and behaviors employed by participants and understand their connection to the design process and the enabling innovation model. Details and examples on each of these approaches are provided in the following paragraphs.

Narrative summaries were created to concisely describe and quickly grasp the differences and similarities in participant strategies and to describe the solutions proposed by participants. This type of analysis resembles what Saldaña (2009) has referred to as narrative coding, which is often used as a preliminary approach to understand the storied, structured form of the data. The transcripts were read in detail and then summarized by attempting to capture major turns of activity, aiming for factual description (Mosborg et al., 2006). Emphasis was placed on using the participants' language and on avoiding the use of the author's language in regards to patterns, behaviors, and solutions, to avoid over interpretation of the data. The interview debrief question that asked participants to summarize their approach and recommendation helped ensure that these narratives were consistent with participants' language and perspectives. As a member of the research team, the author's major professor also read through the narratives to search for signs of overinterpretation.

Select narrative summaries from participants in diverse categories group/category can be found in Appendix E, and an example narrative summary is shown herein for illustration purposes. This example narrative summary is for Mike, an innovation consultant. The example illustrates Mike's tendency to structure problem and solution spaces, to employ analogies throughout his structuring process, and also illustrates his proposed solution to the performance task:

> *Mike co-evolved problem and solution spaces, with a special emphasis in iteratively structuring/categorizing both of these spaces. He started by sharpening the concreteness of the problem and creating an overarching framework that could guide his own thinking. For each of the main categories of his framework, he diverged possible issues, structured them by creating categories, assessed the exhaustiveness/expansiveness of the problem space, and diverged again. Effectively, Mike seemed to be trying to dimensionalize the problem very clearly and in different ways. Once he had conceptually structured the problem/challenge, he immersed himself in what he called "external stimuli" by going online and trying to capture as many thoughts as came to mind as he looked for information. While searching he focused on looking for information he (in his own words) "knew he did not know" and also engaged in analogical reasoning in counterintuitive adjacent spaces (e.g., "how did smoking go from being socially accepted in the 1950's to the social stigma it is today?"). He used these external stimuli to simultaneously shape the solution spacewhile refining the problem space until he reached saturation (of course, within the pragmatic boundaries of the 90-minute time limit). Mike then started a synthesis process in which he structured and sorted/prioritized critical issues in the problem and solution space. His ideas included connecting EVs to solar technology, creating a competition similar to the "X-Prize" exclusively for EV advances, tax breaks, open source EV knowledge sharing platforms, EV lanes, EV campaigns analogous to "Got Milk?", government mandated EV parking spots, and real-time and near real-time systems that communicate savings and environmental contribution back to end users. Mike continued with a discussion of timelines and implementation highlighting the notion of keeping multiple options open since some initiatives may gain more traction than others. He finalized with a discussion of organizational issues such as governance, staffing, and overhead.*

Each of the participants analyzed in this paper utilized a different approach to the design task and generated a wide range of alternatives/solutions to address the EV challenge (common themes/clusters of approaches and solutions can be identified as shown in Table 3.4 and a conception of these themes developed by the author prior to conducting the performance tasks is shown in Appendix F). The narrative descriptions of participants' approaches to the EV task help illustrate some of these differences and facilitate an understanding of their overarching strategy.

Based on the narrative summaries and common themes in approaches and solutions that were identified, a narrower set of participants was selected for analysis. The rationale for reducing the data set employed in analysis is guided by the desired outcome of the study – the creation of a framework of enabling thinking – which makes expert-novice comparisons (informed-enabling in this case) outside of the scope of the study. Participants that did not seem to engage in at least one or more evolving/emerging conceptions of the patterns of the enabling thinking level of practice (described in Chapter 5) for some design process stages (e.g., problem definition, gathering information, evaluation) were dropped from the data set. Dropped participants (with the exception of Walter, Rand, and Bonnie) were the undergraduate and graduate student groups. Effectively, the group of dropped participants only offered perspectives previously described in the literature (i.e., patterns of beginner and informed design).

Once this narrow set of participants was defined, thematic analysis, a method to identifying themes within data (Boyatzis, 1998), was also employed to identify examples of design patterns and behaviors employed by the participants. As aforementioned, a theme captures a systematic patterned response or meaning within a data set, and the relative importance of themes in this type of research does not necessarily depend on quantifiable measures of theme presence (Braun and Clarke, 2006). Instead, the importance of a theme stems from its ability to capture a pattern relevant to the research question. With this in mind, this research sought to capture two types of themes: 1) examples of design/innovation patterns and behaviors identified through the other research approaches (i.e., scholarship of integration and content analysis of secondary historical research), and 2) design patterns and behaviors not previously identified through the other research approaches.

Table 3.4 Contrasting Participants Analyzed and Participants Dropped from the Study

Participant group	Design Approach Themes	Solution Themes	Illustrative Group Quot
Analyzed: Don, Ken, Mike, Kate, Max, Henry, Walter, Victor, Drew, Sam, Rand, Charles, Nicole, Susan, Noah, Leo, Anna, Forrest, Bonnie, Jack, Nancy	• In-depth exploration of problems, solutions and implications, search for first principles • Use of existing frameworks and modified frameworks based on prior, experiences, research, and the unique problem at hand • Proactively sought to depart from the status quo • Analyzed issues from multiple perspectives • Had a tendency to consider technical, economic, systems, social, and emotional implications of problems/challenges	• Suggested a portfolio of different categories of initiatives (e.g., government-driven, industry-driven, non-profit driven) • Had a tendency to consider technical, economic, systems, social, and emotional implications of solutions • Often combined pragmatic (e.g., awareness campaigns) and relatively unconventional solutions (e.g., car sharing business model) in the portfolio • Outlined and discussed plans to address possible ecosystem and idea-specific critical issues • Had a tendency to link ideas to possible outcomes	Okay what I would say is that we've taken a user-centric data-driven approach, defining a vehicle that we think would be successful on the market, could achieve the desired market share of 1 percent in 2014 and growing to 2 percent and beyond in 2015 and '16. We've made some – we've been – we've made some very difficult tradeoff decisions in trying to get this product to market. I would say the concept to keep in mind is that we've tried to develop a minimum viable product, something that will get out – we can get out – to the market, which will drive adoption but does not necessarily have to be over-engineered, right? Let's get the product to market and learn from there and we can develop iterations of the product from that point. The other difficult tradeoff decisions or opportunities are to outsource as much of this effort as possible. We don't have manufacturing capability, we don't wanna build them. We don't. The infrastructure is not in place today for having charging facilities. We need to find a partner to do that. We don't wanna be in that business. We recognize the need to service vehicles. We have to be in that business in the short term but we wanna be out of it within three to five years but I think we've designed as a result of an attractive and viable product that can be – that can get us – into market and help us to grow from there.

Table 3.4 Continued

Participant group	**Design Approach Themes**	**Solution Themes**	**Illustrative Group Quot**
Dropped: Dan, Lee, Aaron, Felix, Nick, Neal, Ron,	• Explored problems and solutions superficially (i.e., with a relative lack of details in ideas), lack of search for first principles and/or second or third order effects of ideas • Focused on select categories of problems/challenges (e.g., technical, economic, business and marketing) • Bypassed key ecosystem issues • Fixate on a few select problems or solution clusters throughout the task	• Fixated on a few select solution categories (e.g., create an EV-based racing competition that can drive technological advances) • Discussed solution without sufficient detail that characterizes novelty or potential impact of ideas • Seemed unaware of importance of novelty and potential impact if suggested ideas	" Yes, my recommendation to increase adoption of EV cars by [year] will be to, number one, incentivize customers to buy electronic vehicles cars by giving them the advantages of a normal car with equal price or lower price. At the same time, partner with NGOs and reach out to all states and US which will promote electronic vehicle cars. Thirdly, my recommendation is also to, you know, promote the use of EV cars and penalize the use of regular cars. Fourthly, my recommendation is also to make sure that, you know, government should incentivize the manufacturers so they can spend more and make better cars which are fuel-efficient. So these are my key recommendations, which will increase the adoption of EV cars."

As a note, the focus of this analysis is to create an exploratory framework based on participants' approaches (triangulated with the other research methods), and not the analysis/evaluation of their solutions (although a future study could focus on this). The rationale for this choice to not study solutions is based on the fact that the participants (across all groups) are known as "innovators" by the social connections that recommended them. In addition, there is difficulty in assessing solutions for which no benchmark or basis of comparison currently exists and for which true implementable impact cannot be measured. Effectively, participant selection was based on "known innovativeness" meaning that examining their approach did not provide a measure of ability to innovate, and only provided examples of behaviors they would typically use as "innovators" (and such examples were triangulated with the additional methodological approaches). As an example of this issue, some participants proposed a similar model to the one proposed by the project Better Place – an EV battery swapping startup that was initially promising and was often featured in popular press outlets but unfortunately went bankrupt – while others were highly critical of such a model. Therefore, this solution, and similar other proposed solutions in the solution clusters shown in Appendix F are difficult to evaluate objectively – likely even by EV experts.

An initial version of the enabling thinking framework developed through the scholarship of integration with an initial set of definitions was used to search for examples of instances of the design patterns and behaviors identified through the scholarship of integration and the historical content analysis. This initial framework was organized by design process stages (e.g., defining problem, gathering information, analysis), design pattern, and design behaviors. Preliminary analysis of five performance tasks (Dan, Kate, Ken, Mike, Max) helped search for initial examples to further refine this framework. The performance tasks used in this preliminary analysis were selected due to the variations in the number of (the initial set of) behaviors employed, with Dan being the participant who employed the least number of behaviors and Max the participant that employed most of the behaviors. It is important to note, nonetheless, that no single participant employed all patterns/behaviors.

Overall, the process for developing the framework (from the perspective of the performance tasks) entailed: 1) reading the transcript and creating the aforementioned narrative summaries to gain familiarity with the transcript and its content, 2) tagging/coding relevant segments of a transcript with a design stage or design stages, 3) assigning a design pattern(s) (beginner, informed, enabling) to each transcript segment (*beginner* or *informed* based on insights from Crismond and Adams [2012] and *enabling* if links to evolving notions of the enabling innovation model were identified), 4) assigning relevant behaviors to each segment as examples of the constituent patterns and behaviors in the enabling thinking framework (or a tag of "other" if a behavior did not seem to fit any behaviors in the framework). This process was repeated as the framework evolved, as described in section 3.3.4.

In this process, relevant segments of a transcript were defined as those that captured major turns of activity (Mosborg et al., 2006), and were as short as a sentence and as long as a few (two or three) paragraphs. More than one pattern or behavior category could be applied, if relevant, at any point in time, and all transcripts went through this coding process twice. Patterns and behaviors that could not be captured within the existing codebook were coded as "other" for further analysis. All thematic analysis procedures were conducted in Dedoose, which is a qualitative and mixed methods cloud-based research tool. An illustrative example of this process is provided in Table 3.5 for Nicole, who in this excerpt was discussing some of the frustrations and sensitivities that people currently have with EVs from technical, economic, sociological, and psychological perspectives. This process was employed to tag/code over 1000 segments across the data set that were used to search for relevant pattern and behavior examples.

To capture design patterns and behaviors not previously identified through the other methodological approaches, all instances tagged/coded as "other" (over 150 instances) throughout the thematic analysis process were reviewed, searching for underlying themes (i.e., patterns and behaviors) not considered in the framework. The search for additional patterns and behaviors was highly iterative and the language to name/describe the evolving categories underwent several iterations, primarily through discussion with the author's major professor. This search for underlying categories increased the number of behaviors considered and helped the author understand variations of behaviors driven by specific circumstances and desired goals.

Table 3.5 Example Theme Coding Instance

Quote	**Participant:** Nicole
But I've heard people, there's a frustration because the upfront cost of a Volt is higher than what you'd expect of a car that looks similar to it because of the technology under it. So there's why am I paying more for this thing? And the response is because you'll save money on gas. But people very much make the decisions on the here and now and I'm taking more money out of my pocket then I would expect to for what I'm seeing with the belief that I will very slowly make it back over time in a way that I may not actually feel. Because you don't remember - two years after you bought a car. Hey, my old car is going to the gas station every week and now I'm going every two weeks. Your normal resets so you don't feel the benefits I think to the extent that probably the government can subsidize the increased upfront costs. That can drive adoption. I think also on the range anxiety side, just as I was saying, I don't know where power outlets are…	**Design process stage(s):** • Gathering information • Defining problems **Patterns:** See systems, technical, economic, sociological, and psychological forces **Behaviors** • Employing multiple perspectives • Noticing forces at play • Creating empathy-based mental models

3.3.4 Integrating the Multiple Methods

In summary, the multifaceted approach – scholarship of integration, historical case thematic analysis, and verbal protocol analysis – was employed to iteratively search for instances that exemplify behaviors in the enabling thinking framework and to search for new behaviors that might not have been initially considered. As such, in this analysis, the quantitative aspects of the thematic analysis of historical research and the performance tasks are less relevant than generating a rich qualitative understanding of patterns and behaviors as the goal is not to quantify differences between groups or which behaviors are used more than others. Effectively, the analyses was designed to identify a gamut of strategies, patterns, and behaviors that can be employed when a designer's goal is to innovate – particularly in challenges where both enabling and progressive innovations can be pursued – and to link such strategies to historical enabling innovations.

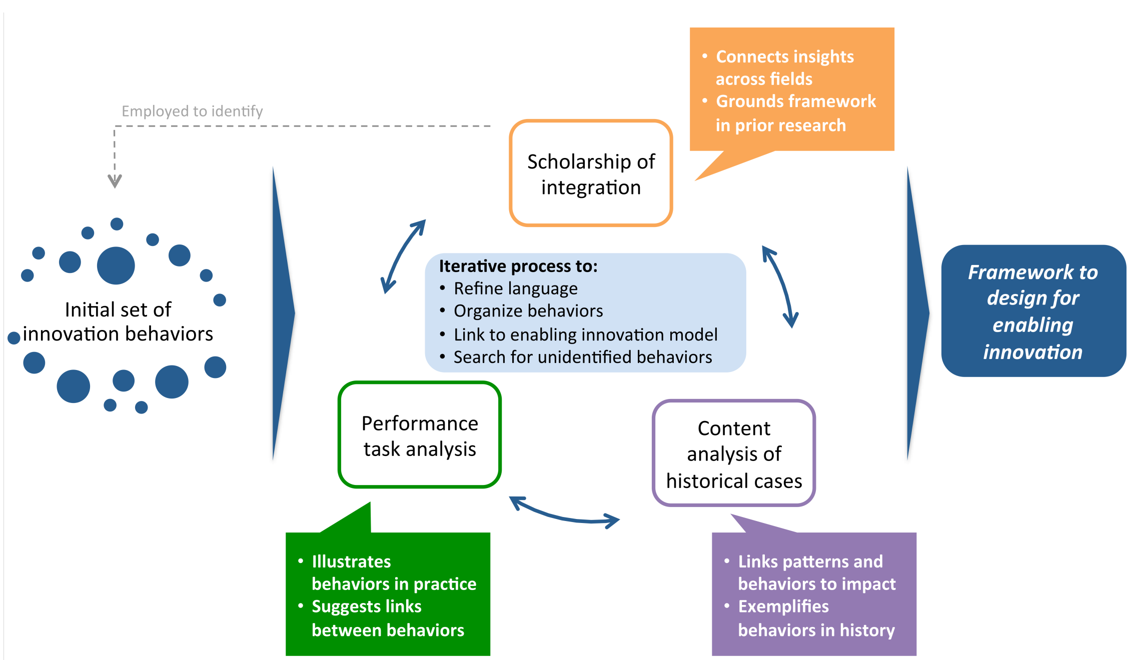


Figure 3.8 Integrating the Multifaceted Approach

The process to integrate these insights was highly iterative among the three approaches and the integration proceeded through parallel, rather than sequential efforts, as shown in Figure 3.8. After identifying an initial set of behaviors through the scholarship of integration approach and a set of informal conversations with innovation practitioners, the iteration process focused on searching for behaviors not previously identified, refining the language used to describe previously identified behaviors, linking the behaviors to the characteristics of the type of innovation sought after (here enabling innovations), and organizing the patterns and behaviors into a framework to design with the end goal of enabling innovation. The process underwent multiple iterations until returns diminished and saturation was reached (i.e., no new patterns/behaviors were identified) (Saldaña, 2009).

3.3.5 Research Quality Measures

This analysis method also followed the framework proposed by Walther et al., (2013), which describes research quality strategies for "making data" and "handling data" to achieve validation and process reliability. A summary of this framework with regard to this study's multifaceted approach is provided in Table 3.6, and a description of how each element of this framework was considered in an attempt to achieve validation and process reliability are described throughout this section.

Table 3.6 Research Quality Measures and Supporting Strategies Employed to Develop the Enabling Thinking Framework (for the Scholarship of Integration, Historical Case Analysis, and VPA)

	Making Data	**Handling Data**
Theoretical validation Do the concepts and relationships of the framework rightly correspond to the reality under investigation?	Purposive sampling was employed in all facets of the study and the research design emerged throughout the study. A scholarship of integration effort outlined an initial framework. A performance task was pursued to further explore such framework to link empirical data and the framework. Because the performance task solutions cannot be probed for impact, historical cases where examined to link the framework to impact.	The complexity in defining coherent relationships between patterns and behaviors was captured in the many iterations of the framework. Special attention was placed on negative cases, performance task quotes, literature, or case histories that seemingly contradicted the framework's organization and modifications to the framework were made to fit negative cases.
Procedural validation Which features of the research design improve the fit between reality and the framework generated?	Triangulation between approaches was employed. These approaches included a scholarship of integration, analysis of historical research, and a performance task.	Thematic analysis was employed to search for examples of behaviors in iterations of the framework and to search for previously unidentified behaviors.
Communicative validation Is the knowledge constructed within the relevant communication community?	Interactions with dissertation committee members regarding the process of making data were proactively sought-after.	Triangulations with innovation experts and peer debriefing were employed, as well as positioning of each pattern/ behavior within the literature. Publication in peer-reviewed outlets is being pursued to ensure that the knowledge derived from the framework is appropriately communicated to the research and practice communities.
Pragmatic validation Do the concepts and knowledge claims withstand exposure to the reality investigated?	The study employs a broad array of data sources and analysis methods. Effectively, the schools of thought reviewed in the integration approach are diverse. The cases examined in the historical research are diverse and multiple sources were employed per case. Also, performance task participants come from diverse backgrounds.	Emphasis was placed on developing a framework that can help screen future enabling innovations as well as provide guidelines for their pursuit. The framework has been (and will continue to be) presented in various outlets and audiences have been exposed to the terms enabling and progressive innovation and their meanings, which has resulted in ideas for refinement of the framework.
Process reliability To what extent is the research process independent from random influences?	The strategy and process for making data was documented for the multiple approaches, was guided by existing literature that outlines best practices, and was informed by discussions with the research team.	The development of the framework was regularly discussed with and reviewed by members of the research team.

When aiming to achieve validation, the goal is to make sure “we see what we think we see” while making data and to “call things by the right names” while handing data (Walter et al., 2013, p. 639). In Walter et al.’s (2013) framework, five types of validation are sought after; namely, theoretical validation (fit between phenomenon under investigation and theory/framework produced), procedural validation (features incorporated into the research design to improve the link between a theory/framework and a phenomenon), communicative validation (relevance in terms of language, meaning, and/or conventions of the research community), and pragmatic validation (the extent to which concepts are compatible with the empirical reality). In this study, strategies were employed for these five types of validation in both making and handling the data.

With regard to *theoretical validation*, an emergent research design was employed in making the data and negative case analysis was employed in handling the data. This emerging research design helped the author understand “whether the theories or knowledge produced appropriately correspond to the empirical reality observed” (Walther et al., 2013, p. 641). For example, the historical case analysis stream was pursued once the author understood that no link between proposed solutions and demonstrated impact could be established from the analysis of the verbal protocols, even if a panel of committee experts were to be employed because the performance task has no solution.

To *make the data*, the research design process underwent several iterations and several data collection strategies emerged throughout the course of the study that resulted in a unique framework of innovation patterns and behaviors. While the research began with a scholarship of integration that yielded an initial framework of patterns and behaviors, several alternatives were considered (e.g., a phenomenographic study to understand perceptions of innovation, and a Delphi study in which researchers and practitioners converged towards a group of innovative behaviors and their definitions). Because of the desire to link innovation behaviors to design performance, a performance task was conducted. However, throughout the course of the performance task the author realized that the while the link between behavior and performance could be potentially inferred through the analysis of verbal protocols, the link between innovation patterns, behaviors, and impact was not as evident (because of the inability to see impact today as outlined earlier). Because of this, the same set of cases employed to create the model of enabling innovation (see Table 3.1) were explored in depth, searching for examples of innovation patterns and behaviors in the framework in secondary historical sources that richly document the stories of high impact, enabling innovations. Throughout these approaches to making data, purposive sampling was employed to ensure that the data appropriately answers the research questions.

To *handle the data*, negative case analysis and analytic induction were employed. These approaches to "handling data" took a different meaning in each of the methods that were interpolated in the development of the framework and are described in the following paragraphs.

In the scholarship of integration, patterns and behaviors are often described in the context of generic notions of innovation, design, and entrepreneurship rather than as an approach toward designing for a given goal. As such, many of the identified behaviors had to be reformulated to evolve in language that more specifically targets the development of enabling innovations. For example, analogical reasoning (also often called associative thinking) has been thoroughly investigated in the fields of design and management. However, through interpolation with the other approaches in the study, certain analogy-making strategies that are helpful to design for enabling innovation, particularly those that help connect the underlying principles of ideas, were better understood, as described in Chapter 5 of this dissertation.

In the content analysis of historical research, not all cases have documented histories of employing all patterns and/or behaviors. This might seem like a contradiction to the idea that employing the framework will lead to enabling innovation; nonetheless, two reasons help explain this apparent lack of consistency in the use of the behaviors throughout history: a) because of their specific context and challenges, each documented case history will be narrated from the perspectives of their most important challenges, and b) the narrator's/author's perspective of the most important barriers, factors, and contextual influences – critical incidents – in the development of an enabling innovation will be more prominently highlighted in the narratives/historical accounts while other actions might not be thoroughly documented. Thus, some patterns seem to be "more relevant" to some cases than others, which is expected when employing the framework described herein to present day, real-world challenges.

For example, in the verbal protocol analysis, some participants made use of a subset of patterns and behaviors but were not able to formulate a concrete solution to the problem despite doing a comprehensive exploration of the problem space in the performance task. For example, Don explored tradeoffs across the different dimensions of the problem only to realize that this is the type of problem that could potentially be (in his own terms) "brute forced" based on the methodologies that his firm employs. He then recommended (as his solution) a longer type of engagement in which some of these methods are employed systematically. Similar to Don, other participants quickly realized the magnitude of the challenge, and although they engaged in the hypothetical problem-solving/design exercise, they quickly acknowledged that 90 minutes is likely not enough to address this challenge.

With regard to *procedural validation*, features were incorporated into the research design to improve the fit between the framework and reality, and better support the claims that emerge from the study. With regard to making the data, triangulation within and between approaches was employed, and in handling the data, the author's possible biases that might have had an influence on the results of the study are herein documented, as outlined in the following paragraphs.

In *making the data*, triangulation (Maxwell, 2005) between approaches and datasets was employed to achieve procedural validation. This triangulation exercise was important because the performance task did not lend itself to describing certain phases of the design process (e.g., envision/strategy and implementation), while historical documentation of enabling innovation cases tends to highlight certain aspects of a case that are considered critical to the narrator/author of the case while ignoring others. In like manner, the literature often discusses behaviors to innovate, yet in generic ways that are not tied to a specific type of desired outcome, and the triangulation between methods helps understand how these behaviors change/are subtly altered when the desired outcome is a specific type of innovation. For example, triangulation between approaches, namely, integration, content analysis, and performance task, was employed to identify redundant behaviors. If a hypothesized behavior was not observed in at least one of the approaches, it was dropped from the study and not further considered. As an example, in the "persuade to facilitated acceptance or use" pattern, the behavior of "managing resistance to conceptual change" was dropped due to its overlap with the other behaviors in this pattern, and due to a lack of clear examples in the three aforementioned approaches. Triangulation within approaches was also proactively sought. In the scholarship of integration, literature from diverse schools of thought and journals within each school of thought were reviewed. In the content analysis of secondary historical research, multiple data sources were employed per case. In the performance task, diversity in participants (e.g., in demographics, occupation, training, and experience) was sought, aiming for multiple participants from each category, within the pragmatic limitations of the snowball recruiting method. These approaches were iteratively interpolated and triangulated to refine the language used to describe the enabling innovation patterns and behaviors.

In *handling the data*, procedural validation processes are strengthened by the author's "interpretive awareness" (Sandberg, 2005), i.e., the explicit acknowledgement of the research subjectivity and the lenses employed in the author's interpretation. First, notions of innovation are highly disputed and the author's perspective is that innovation encompasses application and impact, and not only novelty and/or differentiation, which has implications for the patterns employed in recognizing and pursuing innovation. Effectively, the notion of an "innovative behavior" (and/or pattern) must address the challenges of generating ideas that are novel and also the challenges of generating impact. This broader perspective of innovation thus expands beyond behaviors that emphasize the novelty of ideas to behaviors related to, for instance, selecting contexts of application, encouraging adoption, and the fueling of ideas with resources that enable one to pursue them. Second, some researchers perceive that definite leaps in performance, versatility, or impact are inexistent (implying that they only believe in innovation as an incremental and evolutionary process) (e.g., Basalla, 1988), which contrasts with the perspective of the author, who believes that innovation can come from both definite leaps and/or incremental processes. This worldview of innovation therefore implies a bias/belief in the author that recognizing the specific type of innovation that is being pursued (i.e., the innovation pattern) should influence the behaviors and patterns employed to pursue it. The work described on this dissertation focuses on a new innovation model, i.e., enabling innovation, and thus the patterns and behaviors described in this work/research are tailored towards that specific form of innovation. Third, the author's training in the engineering and management sciences has informed his perspectives on innovation, particularly theories in the management sciences such as disruptive innovation, and theories common in engineering such as systems design, and human centered design. This training also likely shaped the authors implicit and explicit knowledge and beliefs regarding behaviors commonly employed (and likely encouraged) in these schools of thought and helped contrast such behaviors with behaviors that are herein identified as specific to the enabling innovation model. Finally, the philosophical orientation of the work is pragmatic in nature and as such the interpretations of the author tend to have a highly pragmatic orientation. This philosophical orientation also highlights the abductive (rather than inductive or deductive) reasoning employed in developing this work (even though inductive and deductive future work can easily be derived from the findings of this study).

Communicative validation in *making* and *handling* data was sought after by engaging with members of the research team and the research community. For instance, in discussions with the research community, the author often receives comments and questions regarding the organization of the patterns and behaviors within the framework and the links between the patterns and behaviors identified. These discussions have partially contributed to the author's thinking on how the behaviors and patterns can be employed in more than one design process and how certain actions with the goal of innovating often encompass more than one design process stage at a time. In addition, the scholarship of integration effort also helped position the identified behaviors within relevant theories of design and innovation. Peer debriefing was proactively sought-after by engaging with other researchers (graduate students and faculty) and seeking feedback on the framework. Typical feedback includes discussions on data being available only to make sense of the past, the difficulty of applying behaviors for future ideas, and causal links between specific behaviors and impact that are difficult to establish (and for these reasons the dissertation is considered abductive and the model described herein a framework rather than a theory). Future studies on emerging framework anomalies can however move the enabling thinking framework from a descriptive to a normative stage (Carlile and Christensen, 2005).

Pragmatic validation was sought by using a diverse set of cases and impact perspectives that reflect multiple aspects of the empirical reality of pursuing innovations and by seeking to publish the framework in a variety of peer-reviewed outlets (e.g., Journal of Engineering Education, Journal of Mechanical Design, California Management Review). Transcripts were checked by the author for accuracy. The performance task was iterated with guidance of a more senior faculty advisor experienced with verbal protocol analyses and performance tasks and was also informed by Mosborg et al.'s (2006) guide on verbal protocol analysis. Discussions with participants and the research team helped refine findings and iterations of the framework.

Process reliability aims to make the research process as independent as possible from random influences (Walther et al., 2013). In this study, data gathering procedures were iteratively developed and all research procedures were documented. All sources of historical research are documented as described in Chapter 3 including case and source selection criteria. In addition, all data for the performance tasks were documented in a systematic way (e.g., using a digital recorder, getting professional transcriptions, engaging in transcription checking) (Gibbs 2007). One exception to this systematic data collection was the location of the performance task interviews. While some were conducted in person, others were conducted via online video conferencing due to the relatively distant location of some participants. Video conferencing, however, did allow participants to have face-to-face interaction with the researcher and most participants emailed electronic/scanned copies of their notes, drawings, and figures after the session was over. In handling the data, interpretation procedures were also conducted in systematic ways. A specific focus of this work is on being systematic in evolving the language used to describe the patterns and behaviors for enabling innovation, and all language iterations were documented by the author. The levels of coding employed helped differentiate and ground findings within the literature (when coding design process stages) while simultaneously allowing one to explore the object/subject of the study (patterns and behaviors) in a more interpretive and pragmatic way. Finally, asking participants to summarize at the end of the performance task helped the researcher avoid overinterpretation of their actions and solutions.

3.4 Illustrating the Process Employed to Build the Model and Framework

The model and framework were built iteratively, with advances in each major research stream informing the other. This section illustrates the iterative, non-linear process employed and the evolution of these research streams.

This research study has its origins in a desire to understand high impact innovation and the competencies to pursue such a type of innovation. Examination of the literature on innovation archetypes revealed a gap in the means to characterize innovation impact over time (see Figure 3.9). More specifically, the organization of existing innovation archetypes in a map of innovation impact vs. time highlighted that no existing classification describes and characterizes innovations with the highest degree of impact – the type of impact that transforms society.

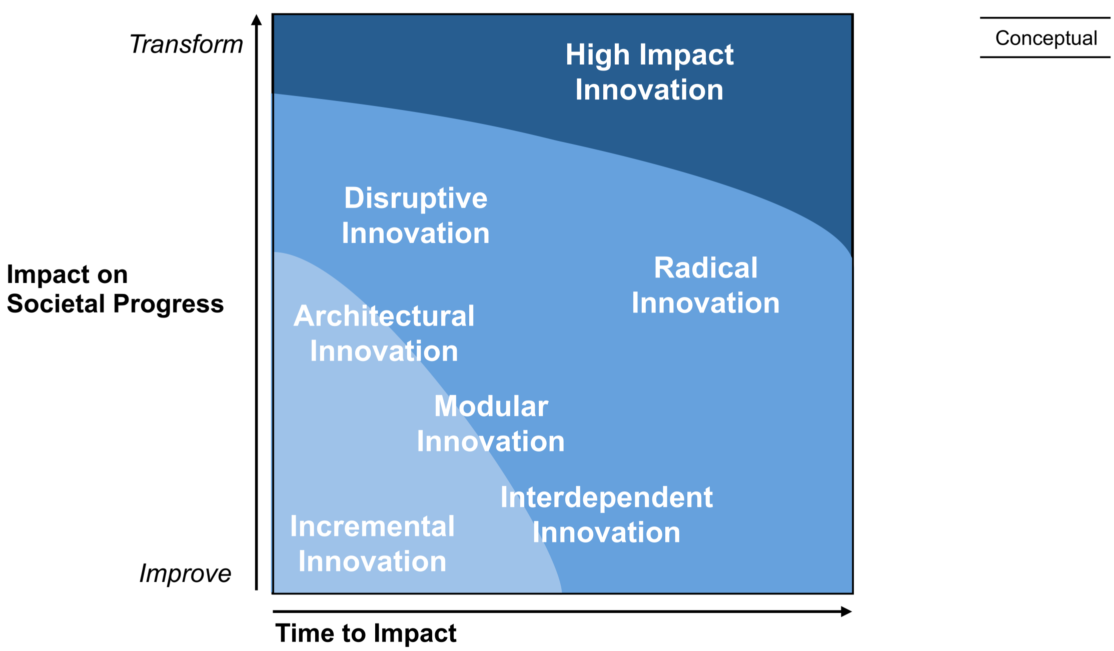


Figure 3.9 Conceptual Organization of Innovation Archetypes
prior to the Enabling Innovation Model

Similarly, an initial set of innovation behaviors were identified after exploration of the design, innovation, and entrepreneurship literature (see Figure 3.10). Examination of these behaviors revealed a missing link to innovation archetypes. Effectively, the author realized, for instance, that "challenging the status quo" could take different meanings if the desired innovation archetype/end-goal changed (e.g., disruptive, sustaining, radical, incremental, or even what was originally termed "high impact" innovation and later understood as enabling innovation). In addition, the author realized that a few select behaviors were likely critical to all stages to the design process, and realized that no unique links existed to the enabling innovation model (i.e., the possibilities for application of this subset of innovation behaviors was broad). Subsequent analysis of this broadly applicable subset of innovation behaviors led to what is described in Chapter 5 as a set of "core" innovation behaviors.

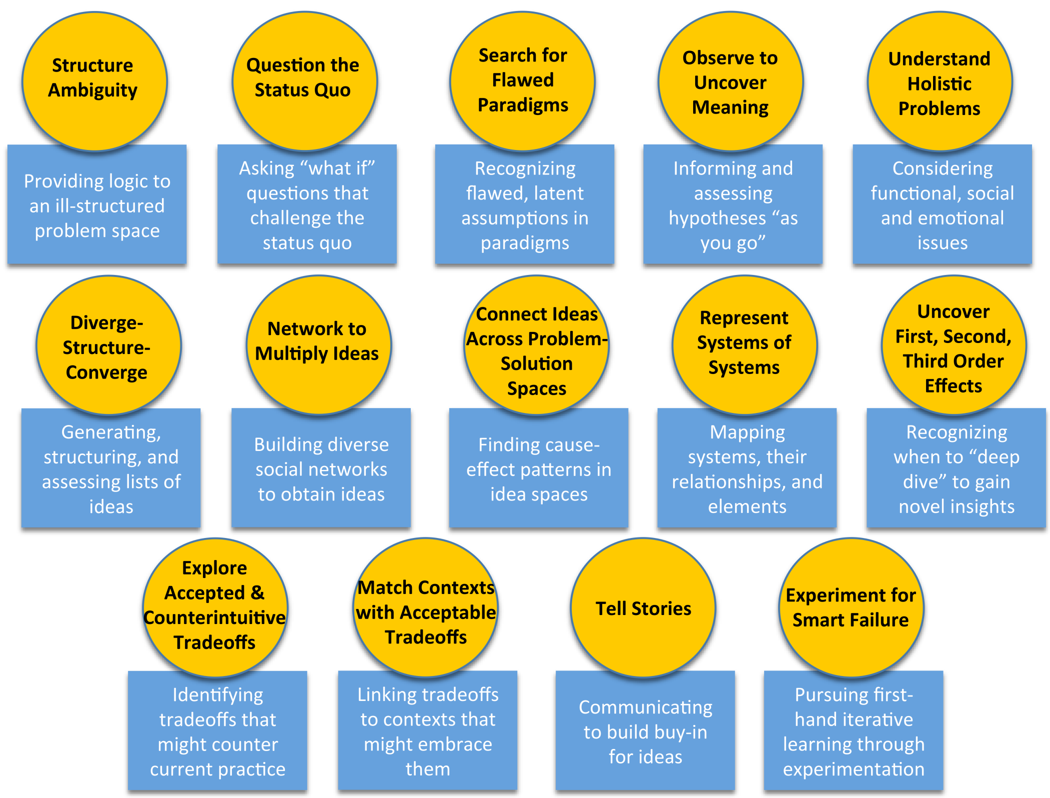


Figure 3.10 Initial Set of Innovation Behaviors Identified in this Study

These initial perspectives of innovation archetypes and innovation behaviors served as the foundation for the enabling innovation model and enabling thinking framework developed through the methodological approaches described in this chapter. Building on these initial perspectives, multiple iterations of the model and framework were developed over time. Each of these iterations incorporated, for instance, new perspectives of themes related to the development of innovation impact, or new unique behaviors that are specific to achieving enabling innovation. A critical link that is important to highlight is the connection between the enabling innovation model and enabling thinking framework. Effectively, throughout the research process, new findings and conceptual developments on the enabling innovation model and its underlying characteristics informed the development of the enabling thinking framework, and vice versa.

The evolution of the enabling innovation model and enabling thinking framework is illustrated in Figure 3.11 and Figures 3.12, 3.13, and 3.14. For example, Figure 3.11 exemplifies different perspectives on the enabling innovation model over time and the increase in complexity of the model as more patterns/themes were better understood. Similarly, Figure 3.12, Figure 3.13, and Figure 3.14 exemplify different generations of the enabling thinking framework, illustrating, for example, its transition from a linear "block model" type of representation, to non-linear conceptions of the framework. The reader should note that the numbering represents the order in which such preliminary models were developed. In addition, these model and framework iterations are only illustrative – and not exhaustive – and are only intended to exemplify the evolution of the model and framework as a result of iterations in the methodological approaches described herein.

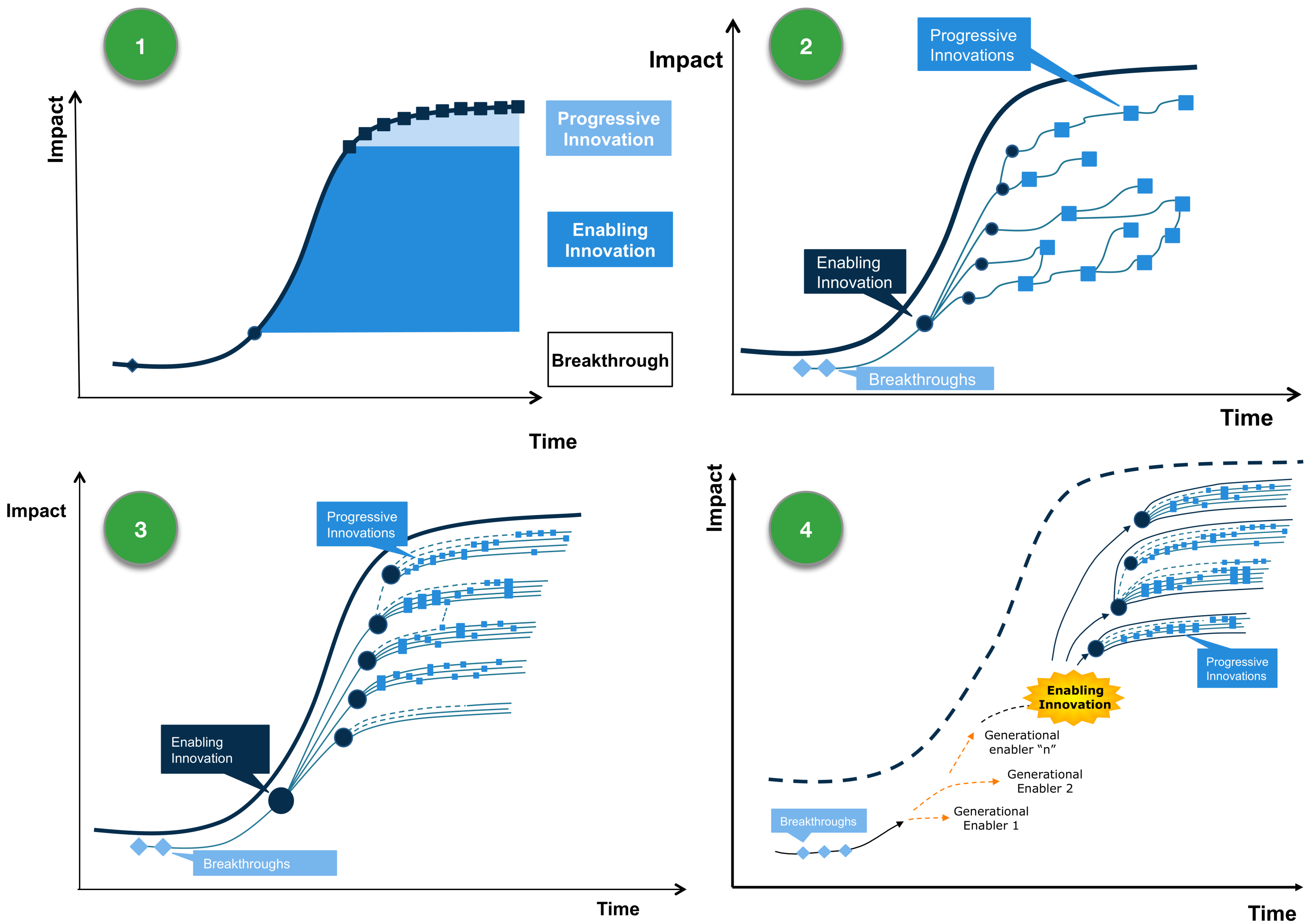


Figure 3.11 Illustrative Iterations of the Enabling Innovation Model

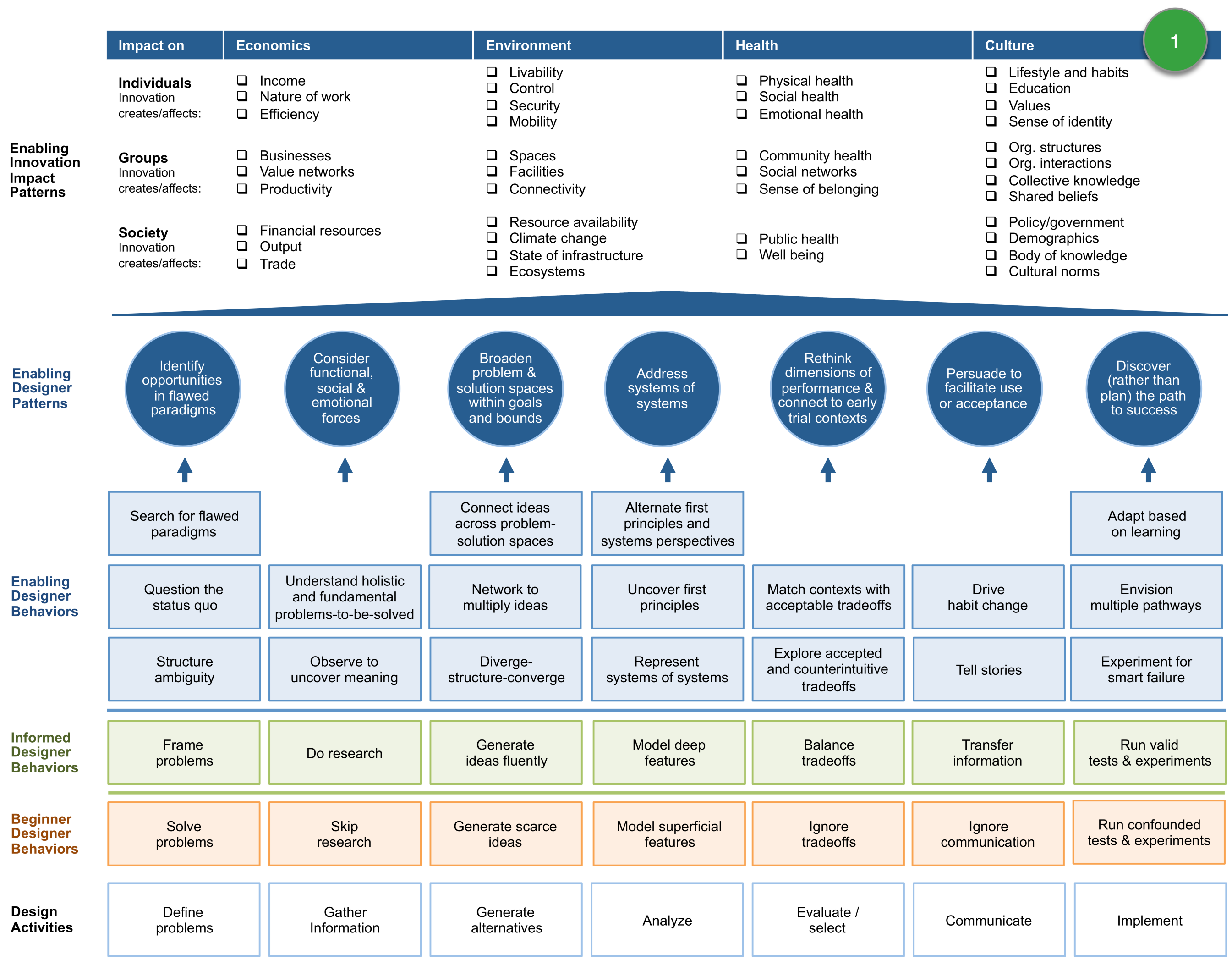


Figure 3.12 Illustrative Iteration of the Enabling Thinking Framework (1/3)

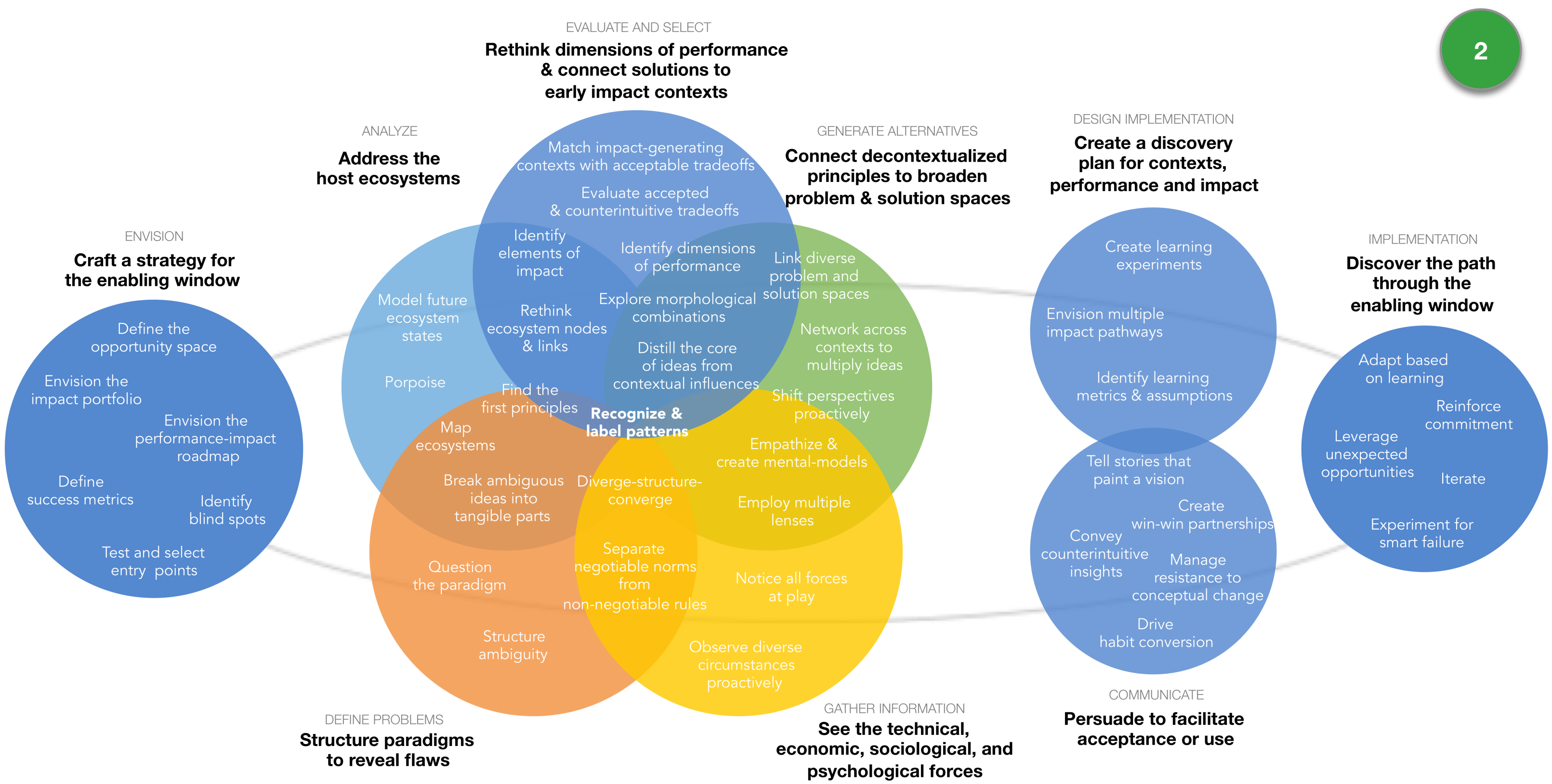


Figure 3.13 Illustrative Iteration of the Enabling Thinking Framework (2/3)

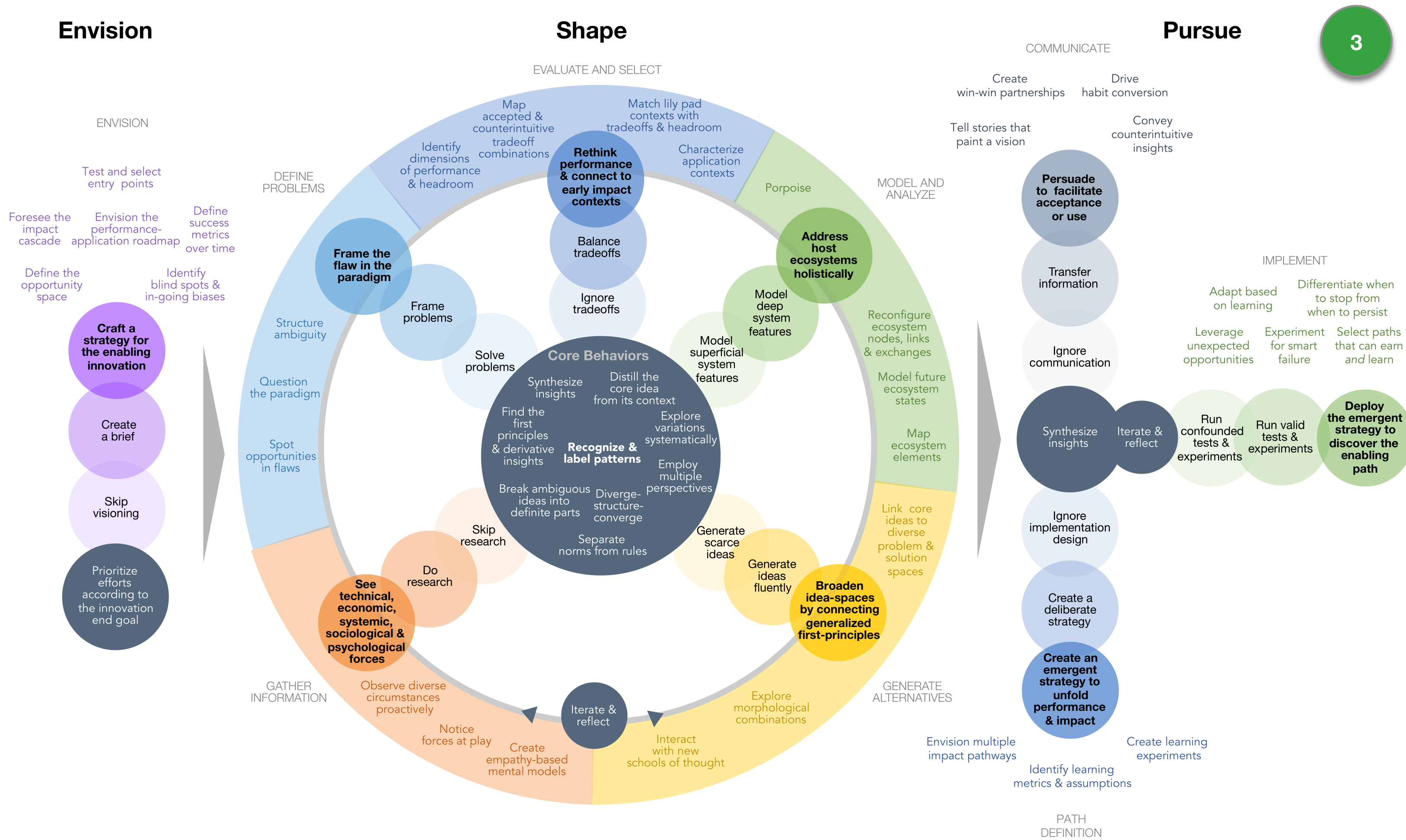


Figure 3.14 Illustrative Iteration of the Enabling Thinking Framework (3/3)

As a result of this iterative, non-linear process that triangulated all the aforementioned methodological approaches, the enabling innovation model and enabling thinking framework were developed. These major research byproducts are described in Chapter 4 and Chapter 5, respectively.

CHAPTER 4. THE ENABLING INNOVATION MODEL

"The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them"

- Sir William Lawrence Bragg, 1915 Nobel Prize for Physics

4.1 Introduction

This chapter focuses on characterizing a new way to think about innovations, using the terms *enabling* and *progressive* to describe the impact that they generate. The chapter identifies the dimensions that can be used to characterize impact because such dimensions are at the core of the classification of innovations as enabling and progressive. Fundamental impact dimensions are used to recognize patterns (i.e., the classification of stimuli into mutually exclusive categories [Reed, 1972]) that differentiate between enabling and progressive innovations. In this thesis, enabling innovations are defined as innovations that exploit a new or different paradigm and have broad reach, cascading effects, and comprehensive significance – characteristics which will be described further along in this chapter. In contrast, progressive innovations exploit opportunities within an established paradigm with relatively narrow reach and significance. The relationship between these types of innovation can be described in a model trajectory of the impact of enabling and progressive innovations that highlights three keys stages: the breakthrough stage, the enabling window, and the progressive cascade. This model trajectory was developed from an integration of prior scholarly research and a cross-case content analysis of historical innovations herein identified as enabling. In addition, principles that can be used to identify concepts with enabling innovation potential are also described.

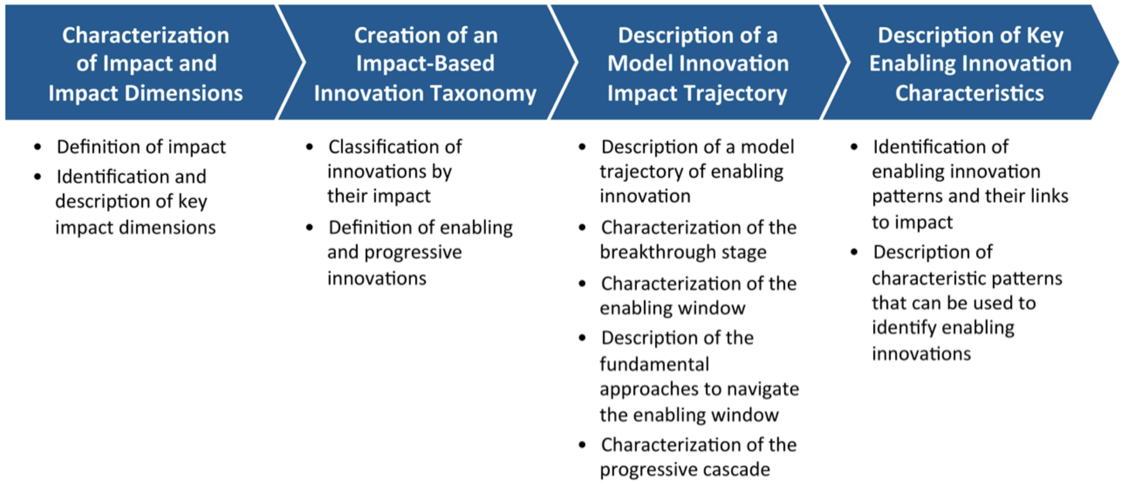


Figure 4.1 Chapter Overview

This chapter is organized as shown in Figure 4.1. The chapter begins by defining impact and its key dimensions. The impact-based classification of innovations as enabling and progressive is then discussed, followed by a description of a model of the impact trajectory of innovations. Then, the characteristic patterns and impact outcomes at each stage of this model are described. Because the focus of this dissertation is on enabling innovations, special emphasis is placed on the characteristic patterns, construct boundaries, and impact of this innovation archetype. These discussions are framed from the perspective of proactively identifying future enabling innovations. The chapter concludes with a brief summary of the chapter's insights.

4.2 Characterizing Impact

At the core of the enabling innovation model is the construct of impact, and to understand the importance of impact in this model, it is helpful to reflect upon the definition of innovation. Although there is certainly considerable debate on this topic (Baregheh et al., 2009; Read, 2000; CSSI, 2004; Ferguson et al., 2013), a comprehensive perspective that is both clarifying and pragmatic defines innovation as the introduction of a novel or different idea into use or practice that has a positive impact on society (Solis and Sinfield, 2014).

There are three key terms in the definition of innovation: novelty, differentiation, and impact. *Novelty* typically refers to knowledge (i.e., ideas) that are new or previously unknown, and *different* refers to counterintuitive or nonobvious insight relative to what is pursued or in use today (Solis and Sinfield, 2014). Innovation novelty and differentiation come in many forms and scholars and practitioners alike have used words such as incremental, radical, core, and peripheral, among others, to describe it.

Robust schools of thought exist to characterize innovation novelty and differentiation. However, impact, arguably the most important dimension since it represents the *outcome* of an innovation, has only recently been a subject of study and is herein defined as the degree to which an innovation alters the way individuals, groups, and society live and act.

As discussed in Chapter 2, studies that focus on impact often do so with tenuous links to innovation or describe links to innovation that are very localized in language and scope. For example, economists who have studied the impacts of general purpose technologies have done so from the economic perspective of productivity gains and substitution, while business scholars typically study the impact of innovations in terms of diffusion and market effects.

This dissertation reframes the construct of impact and its link to innovation. In this framing, impact can be further dimensionalized by breaking it down into three key elements: *reach*, *significance*, and *paradigm change*, as shown in Figure 4.2. These three elements are critical to creating the typology of innovations based on their impact that is the focus of this dissertation chapter.

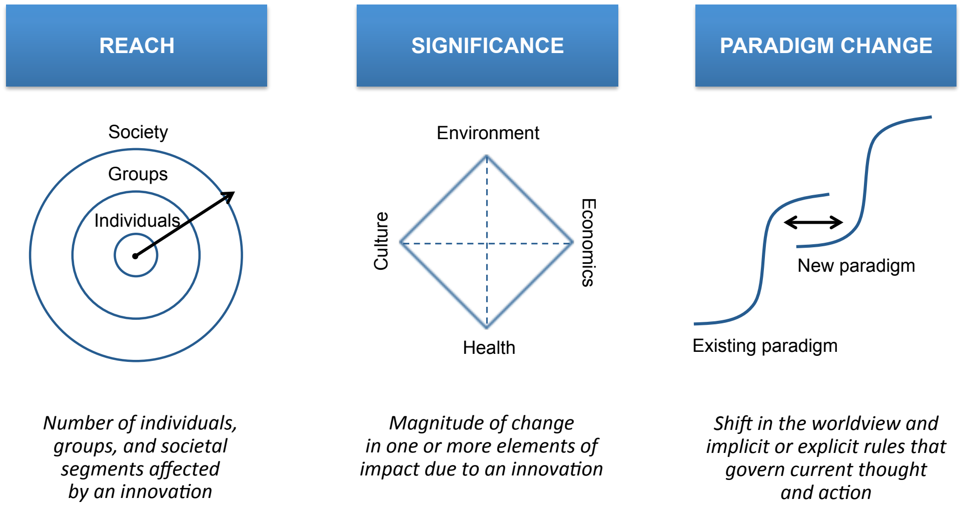


Figure 4.2 Dimensionalizing Impact

Reach refers to the number of individuals, groups, and societal segments affected by an innovation. A broad reach is often associated with a cascading effect, which facilitates interconnected developments around a similar type of "meta-problem" that an innovation solves, and new circumstances across individuals, groups, and societal segments in which the innovation can be applied. For example, atomic clocks, which were developed as a byproduct of efforts to build a maser and laser, are employed in timekeeping, navigation systems, television broadcasting and scientific pursuits, and thus have reached multiple individuals, groups, and societal segments throughout the globe. Effectively, the reach of an innovation indicates the breadth of its influence in terms of the number individuals, groups, and societal segments affected.

Significance refers to the magnitude of change driven by an innovation across measures of economics, environment, health, and culture. For each level of innovation reach, different areas of significance were identified through the integration of impact perspectives and the analysis of the aforementioned case studies, as shown in Figure 4.3. Examples of these areas include, at the individual level, improvements in physical, social, and emotional health, the ability to control the environment, changes to the nature of work, and to lifestyle and habits. Examples at the group level include the creation of new collective knowledge, effects on community health, changes to spaces and connectivity, and changes to value networks and business and organizations. Examples at the societal level include macro measures of economic growth, investment and productivity, demographic shifts, changes to the state of infrastructure and natural resources, and changes to public health and well-being.

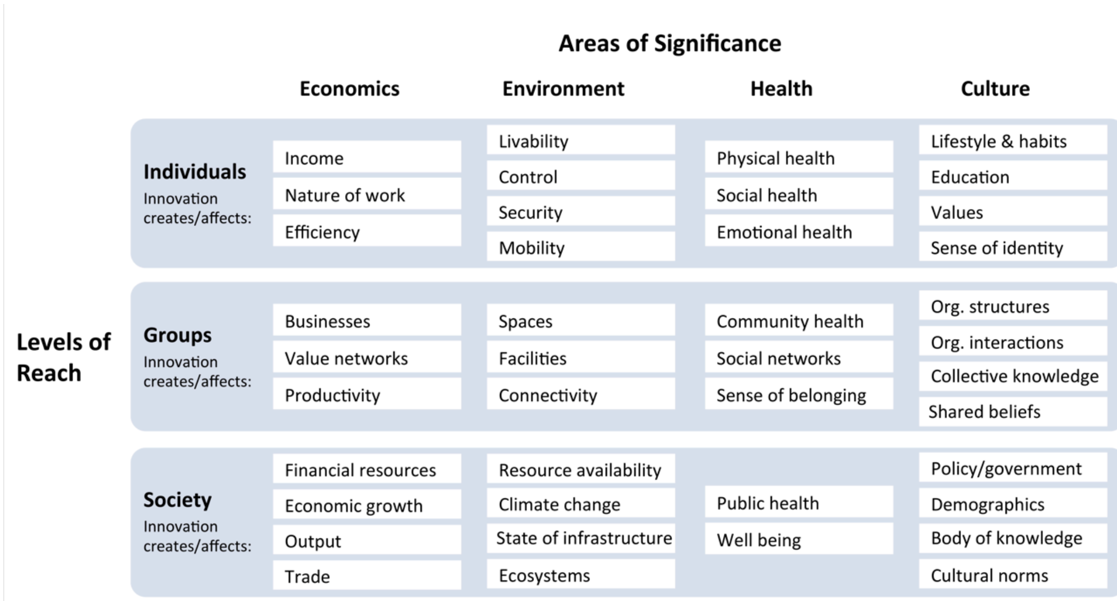


Figure 4.3 Levels of Reach and Areas of Significance of an Innovation

Each of these areas of significance is defined in Table 4.1. These definitions are important to create a model of innovation based on the impact that it generates. For instance, GPS drove the creation of companies, increased the precision of multiple processes throughout many industries, created new value networks, and drove new technologies that impacted culture, lifestyle, habits, and physical, social, and emotional health. These areas of significance can be further broken down into more discrete pieces, to better understand the changes between an innovation and its impact, and to potentially create metrics that quantify the impact of an innovation.

Table 4.1 Levels of Reach and Areas of Significance of Innovations

Innovation creates/affects:	Individuals	Groups	Society
Economics	• *Income:* changes to earnings and consumption patterns • *Nature of work:* changes to the way work activities are performed • *Efficiency:* changes to individual ratios of output to input	• *Businesses:* changes to businesses and or creation of new businesses • *Value networks:* changes to the systemic configurations by which different stakeholders produce value • *Productivity:* changes to the organization ratios of output to input	• *Financial resources:* changes to societal funds/resources available • *Economic growth:* changes to the value of societal goods or services over time • *Output:* changes to the productivity of societal segments over time • *Trade:* changes to societal exchange patterns over time
Environment	• *Livability:* changes to the hospitability/suitability of an environment • *Control:* changes to the ability to control an environment • *Security:* changes to the sense of safety • *Mobility:* changes to the ability to move within an environment	• *Spaces:* changes to the areas in which a group conducts its activities • *Facilities:* changes to the locations/infrastructure in which a group conducts its activities • *Connectivity:* changes to mechanisms that facilitate group interactions	• *Resource availability:* Changes in the sourcing or supply of resources • *Climate change:* changes in the distribution of weather patterns over time • *State of infrastructure:* changes in the physical/ technical structures that support society • *Ecosystems:* changes to communities of living organisms, non-living components, and their organizational constructs
Health	• *Physical health:* changes to the physical state of well-being • *Social health:* changes to the social state of well-being of an individual • *Emotional health:* changes to the emotional state of well-being of an individual	• *Community health:* changes to the health patterns in groups with shared characteristics • *Social networks:* changes to the social structures between stakeholders • *Sense of belonging:* shifts in perceptions and experiences of community belonging	• *Public health:* changes to physical health patterns of a population • *Well-being:* changes to patterns in socio-emotional health of population
Culture	• *Lifestyle & habits:* changes to the mode of living and regular practices • *Education:* changes to the ways knowledge, skills, and abilities are learned and transferred • *Values:* changes to the relative worth or importance of functional, social, and emotional issues • *Sense of identity:* changes to expressions of individuality	• *Organizational structures:* changes to the ways activities are allocated, coordinated, and managed within a group • *Organizational interactions:* changes to ways groups relate with each other • *Collective knowledge*: changes to the shared intelligence emerging from group/domain efforts • *Shared beliefs:* changes to shared group assumptions and values	• *Policy/government:* shifts in principles, protocols, or rules set by societal governance to guide decisions and actions • *Demographics:* changes to statistical patterns in a population over time • *Body of knowledge:* changes to sets of collective knowledge in/across domains • *Cultural norms:* shifts in patterns socially accepted /unaccepted norms

Many links exist between these areas of significance as impact benefits trickle down or up across levels of reach. For instance, an innovation that provides new knowledge for a group can impact individuals' socio-emotional well-being. In addition, although the net cumulative impact of innovation is positive, this impact can also include some negative effects; for example, the introduction of an innovation might provide broad societal benefits, while simultaneously making a specific set of jobs, firms/businesses, or a value chain obsolete in an economic system.

Lastly, *paradigm change* conveys the degree to which an innovation alters the *worldview* of implicit or explicit rules that guide current thought and action in a particular domain. This change reshapes the interpretation of the worldview and the assumptions and habits that one may routinely employ and be unaware of, due to being rooted in tradition. Regardless of the domain of application, some innovations help establish new paradigms while others rely on existing paradigms, and researchers have identified different types of paradigm changes (e.g., Perez, 2003, 2009; Kuhn, 1962; Arthur, 2007, 2009; Dosi, 1982; Christensen and Rosenbloom, 1995). For example, in science, Kuhn (1962) argues that scientific revolutions often start when a prior scientific paradigm is reshaped. In technology, Dosi (1982) emphasizes that paradigm changes stem from the interplay of scientific, economic, institutional, and technological variables, while Arthur (2007, 2009) emphasizes that radical invention rests on redefining the paradigms upon which dominant designs are founded. In economics, Perez (2003, 2009) highlights that paradigm changes are techno-economic in nature and are often triggered by technological revolutions. Effectively, innovations can either trigger a change in worldview or exploit a current working worldview and each of these perspectives has implications for the pursuit of innovation.

Whether in business, science, engineering, or government, these measures of impact – namely reach, significance, and paradigm change – can help differentiate innovations.

The following section describes these differences for what are herein defined as breakthroughs, enabling innovations, and progressive innovations.

4.3 Classifying Innovations by their Impact

A new way to frame innovations is herein developed based on their reach, significance, and paradigm change, putting forward the terms *enabling* and *progressive* to create a taxonomy of innovation impact (see Figure 4.4). On the scale of impact, "breakthroughs" are discoveries or inventions that may be precursors to innovations with different significance and reach of impact, yet they are not considered innovations in and of themselves due to their lack of application in practice (Solis and Sinfield, 2014). The term defined herein as "enabling innovations" describes innovations that exploit a fundamentally new or different paradigm, with broad reach across individuals, groups and society, and comprehensive significance in multiple areas of economics, environment, health, and culture. The combination of these impact dimensions often results in the impact cascade shown in Figure 4.4. In contrast, the term "progressive innovations" refers to innovations that also facilitate impact in many of the aforementioned areas (i.e., economics, environment, health and culture) yet with narrow reach, select significance and within an established paradigm (although minor paradigm variations are possible). As a result, progressive innovations do not often have the ability to generate a cascade of impact benefits commensurate with the cascade of enabling innovations.

The differences between these forms of innovations are herein exemplified and contextualized in Table 4.2, which synthesizes the breakthroughs, enabling innovation, progressive innovations, and impact dimensions for the set of historical cases analyzed in this dissertation. This synthesis highlights that both of these fundamental forms of innovation are necessary to achieve impact and that breakthroughs, enabling innovations, and progressive innovations can be linked in a model of innovation over time. In this study, these links are synthesized in what is herein termed the "enabling innovation model." The following section describes such a model using historical case evidence to exemplify and contextualize its key stages and characteristics.

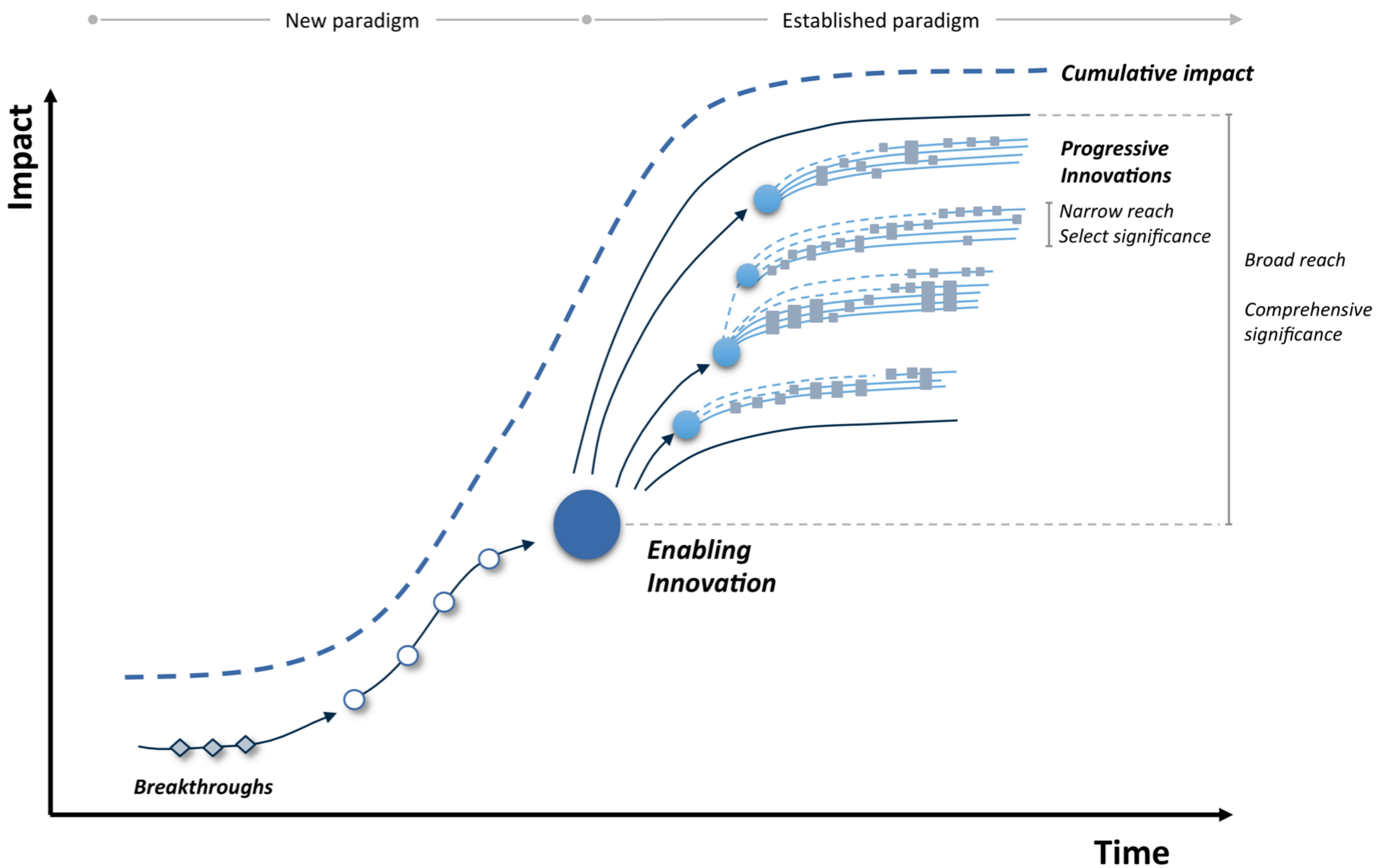


Figure 4.4 Classifying Innovations by their Impact (Solis and Sinfield, 2015)

Table 4.2 Historical Examples of the Enabling Innovation Model

Paradigm Change	Breakthrough(s)	Enabling Innovation	Progressive Innovations[1]	Reach and Significance[1]
From studying and characterizing the properties of light to manipulating and applying light for a variety of purposes	• Discovery of the possibilities for the manipulation of light by stimulated emission of radiation • Analogy to the maser • Origins in microwave spectroscopy	Lasers	• Instrumentation • Surveying equipment • Lasik surgery • Remote sensing (LIDAR) • Fiber optics • Target tracking • Etching	• Increases in health through surgical precision • Increases in productivity • Creation of new firms • Investment in new technologies • Creation of new knowledge • Changes to communications equipment • Increases in productivity due to manufacturing changes • Increases in defense capabilities due to military equipment
Manipulation of energy in the electromagnetic spectrum beyond visible light; shift to scientific medicine	• Work by Maxwell, Faraday, Henry, and Ampere on electricity, light, and magnetism • Experimental work with Crookes tubes • Work on cathode rays (electrons)	X-ray equipment	• Radiographs • CT scanning • Radiotherapy • X-ray crystallography • Astronomy applications • Airport security equipment • Truck scanners • Fine art x-ray equipment	• Investment in new technologies • Advances in individual, group, and societal health • Advances in security and livability of spaces and facilities • Creation of new firms • Advances in astronomy • Improvement in socio-emotional health due to the more sophisticated, non-invasive, and accurate health assessments • Changes to culture and values in terms of personal space and privacy • Changes to laws and policies to accept x-rays as legal evidence • Creation of new medical specialty (radiography) • Changes to the medical value chain

[1]Not exhaustive due to the relatively large cumulative impact of enabling innovations

Table 4.2 Continued

Paradigm Change	Breakthrough(s)	Enabling Innovation	Progressive Innovations[1]	Reach and Significance[1]
Changes to the fundamental ways by which society conducts navigation, time-keeping, and tracking activities	• Doppler effect • Radar • Triangulation analytical techniques • Signal processing	GPS	• Military applications • Navigation applications • Hiking/ backpacking applications • Surveying applications • Logistics and supply chain management • Smartphone applications	• Investment in new technologies • Creation of new firms • Changes to value chains • Changes to culture and value • Improvements in productivity • Improvements in trade and output • Improvements in efficiency • Changes to facilities and spaces • Changes lifestyle and habits • Changes to connectivity • Legal changes • Changes to the body of knowledge • Advances in science and engineering • Advances in socio-emotional well-being
Changing notions of pain as a normal part of life to proactive pain management in acute circumstances	• Studies of gases • Studies on nitrous oxide • Studies of ether • Studies by Lavoisier on carbon dioxide and oxygen	Use of first forms of anesthesia	• Airway anesthesia • Local anesthetics • Intravenous anesthetics • Endotracheal anesthesia • Intubation techniques • Anesthetic machines • Anesthesia equipment	• Reduction in surgical death rates • Creation of a new profession • Creation of new equipment • Creation of new services • Investment in anesthesia-based firms • Improvement in socio-emotional well-being • Changes to laws and regulations • Improvements in individual health • Improvements in group health • Improvements in public health • Creation of new surgical techniques • Changes to medical spaces and facilities • Changes to cultural norms and values regarding pain • Changes to the medical body of knowledge • Changes to demographics

Table 4.2 Continued

Paradigm Change	Breakthrough(s)	Enabling Innovation	Progressive Innovations[1]	Reach and Significance[1]
From the study of radiation and electromagnetic waves to the proactive use of radio energy for detection, identification, and quantification of various phenomena	• Scientific work by Hertz, Maxwell on electromagnetism • Invention of radar by Hülsmeyer	Radar	• Microwaves • RFID • Civil aviation radar • Marine navigation radar • Radar guns • Doppler radar • Lidar • Medical applications • Remote sensing • Military grade radar	• Increased security • Increased productivity • Changes to value chains • Creation of new firms • Changes to infrastructure (e.g., radar networks) • Changes to the way the weather is predicted • Increased social and emotional health • Changes to physical health • Changes to the way objects are detected and located
From hygiene not being a critical part of medical care and infection being considered a critical part of healing to proactive management of infection	• A. van Leeuwenhoek studies of bacteria • Pasteur's theory of germ disease • Pasteurization • Lister's connection between Pasteur's work on fermentation and wound sepsis • Lister's studies of carbolic acid and its use to treat sewage • Publication of Lister's studies in The Lancet, a medical journal • Koch's postulates	Antisepsis and infection control	• New antiseptic methods in medicine • New antiseptic chemicals • Use of disinfectants in food production • Use of disinfectants in industrials and manufacturing • Use of disinfectants in water treatment	• New surgical procedures; decreased barriers to surgical complexity • New companies • New chemicals • Changes to healthcare habits • Changes to disease control methods • Improvements to physical health and mortality rates • Improvements to socio-emotional health • Ability to control environmental cleanliness

Table 4.2 Continued

Paradigm Change	**Breakthrough(s)**	**Enabling Innovation**	**Progressive Innovations**[1]	**Reach and Significance**[1]
From individual, customized approaches, to recognition that all chemical processes share key steps. Helped establish chemical engineering as a discipline, and raised the status and attractiveness of chemical research and chemical manufacturing to new levels by enabling the pursuit of scale in these endeavors	Conceptual change in the way of thinking about seemingly unique and different chemical operations	Unit operations	Industrial processes related to: • Fluid flow • Heat transfer • Mass transfer • Thermodynamics • Mechanical processes • Material manufacturing Applications across a broad array of industrial processes (e.g., petroleum refining, chemical manufacturing, food process engineering)	• Changes to industries such as chemicals, petroleum refining, rubber, leather, coal, food-processing, sugar refining, explosives, ceramics, glass, paper, cement, and metallurgy • Laid the foundation for consulting firms • New investments in technology • Changes to value chains • Socio-emotional impacts as a byproduct of industrial advance • Changes to lifestyle and habits as an indirect byproduct of industrial advance
Altered worldviews in banking that led to the creation of banking services to the poor, who were previously thought of as unbankable, and helped rethink notions of development and poverty	Conceptual change in banking practices	Microfinance	• New lending forms • New banking structures and processes such as group micro-loans and community meetings to motivate repayment • New credit assessments • New international development approaches	• New firms • Increases to income levels • Improved measures of physical health such as nutrition • Improved measures socio-emotional health (e.g., security and empowerment)

Table 4.2 Continued

Paradigm Change	**Breakthrough(s)**	**Enabling Innovation**	**Progressive Innovations**[1]	**Reach and Significance**[1]
Change in the way resources, services, ideas, or content are sourced: from a single or limited number of sources to a relatively large number of contributors	Isolated crowdsourcing attempts embedded throughout history (e.g., Oxford English Dictionary's call for volunteers to make contributions and identify all words in the English language in the 1800's)	Crowdsourcing	• Crowdsourcing • Crowdfunding • Citizen science • Collective intelligence • Knowledge discovery and problem solving competitions • Stock archives • Sharing platforms • Crowdsharing	• Investments in technology • Creation of new businesses/firms (e.g., funding platforms) • Changes to value chains • Improvements in efficiency (e.g., crowdsourcing problem-solving activities) • Improvements to productivity • Increases in trade/output • Changes to physical health (e.g., health data sharing platforms) • Changes to socio-emotional health • Changes to lifestyle and habits (e.g., citizen science fostering amateur astronomers) • Changes in connectivity • Changes in resource availability • Changes in social networks • Changes to the nature of work • Changes to income due to new business and revenue models

4.4 The Enabling Innovation Model

Evaluation of the trajectory of enabling innovations based on changes in reach, significance, and paradigm over time calls attention to considerable variations across three major stages of innovation impact, namely: *the breakthrough stage* (which encompasses the processes of discovery and invention), *the enabling window* (which focuses on driving generational enablers towards becoming enabling innovations), and *the progressive cascade* (which represents cascading adoption in multiple contexts of society through platform and progressive innovations). Each of these stages, shown in Figure 4.5, has a unique set of characteristics, challenges and characteristics. As such, distinct strategies can (and should) be employed to address the challenges and exploit the opportunities that typically emerge at each stage. In addition, these stages are iterative and nonlinear, since, for instance, breakthrough discoveries or inventions might be needed throughout the trajectories towards enabling and progressive innovations. As an example, the laws of thermodynamics were derived through study of the operations of steam engines (Dudley, 2013). Collectively, and although it is recognized that all forms of innovation are valuable, this framing of innovation highlights that enabling innovations are the foundation of disproportionately higher impact than any other innovation form.

The breakthrough stage, enabling window stage, and progressive cascade are discussed in depth throughout the following sections. For each stage, the set of historical cases is examined at the cross-case level to highlight an underlying set characteristics, challenges, and opportunities, followed by an in-depth examination of select case histories that exemplify and provide context to such characteristics. Each stage discussion concludes with a synthesis of patterns and insights that emerge from this analysis.

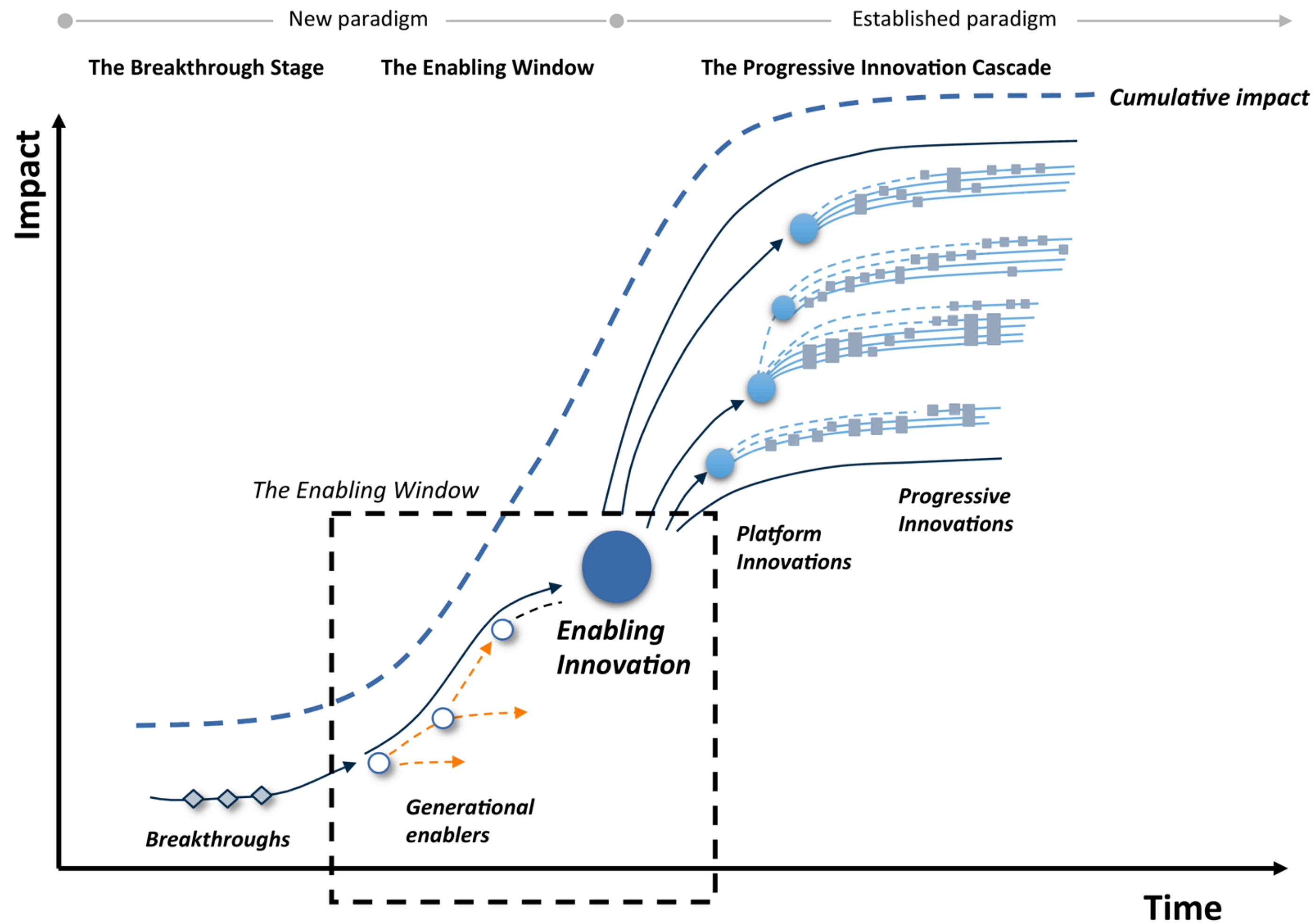


Figure 4.5 The Enabling Innovation Model

4.4.1 The Breakthrough Stage

The process of driving significant impact almost always starts with breakthroughs, which are herein defined as discoveries or inventions that represent step changes in paradigms with relatively no impact on business and society due to their lack of application. In this framing, shown in Figure 4.6, breakthroughs are not considered innovations, because of their lack of application, but represent the type of advance that is often pursued to address complex challenges given the opportunities they represent to change existing paradigms. Analysis of the set of cases, summarized in Table 4.3, reveals a set of patterns and insights underlying the breakthroughs that eventually led to an enabling innovation.

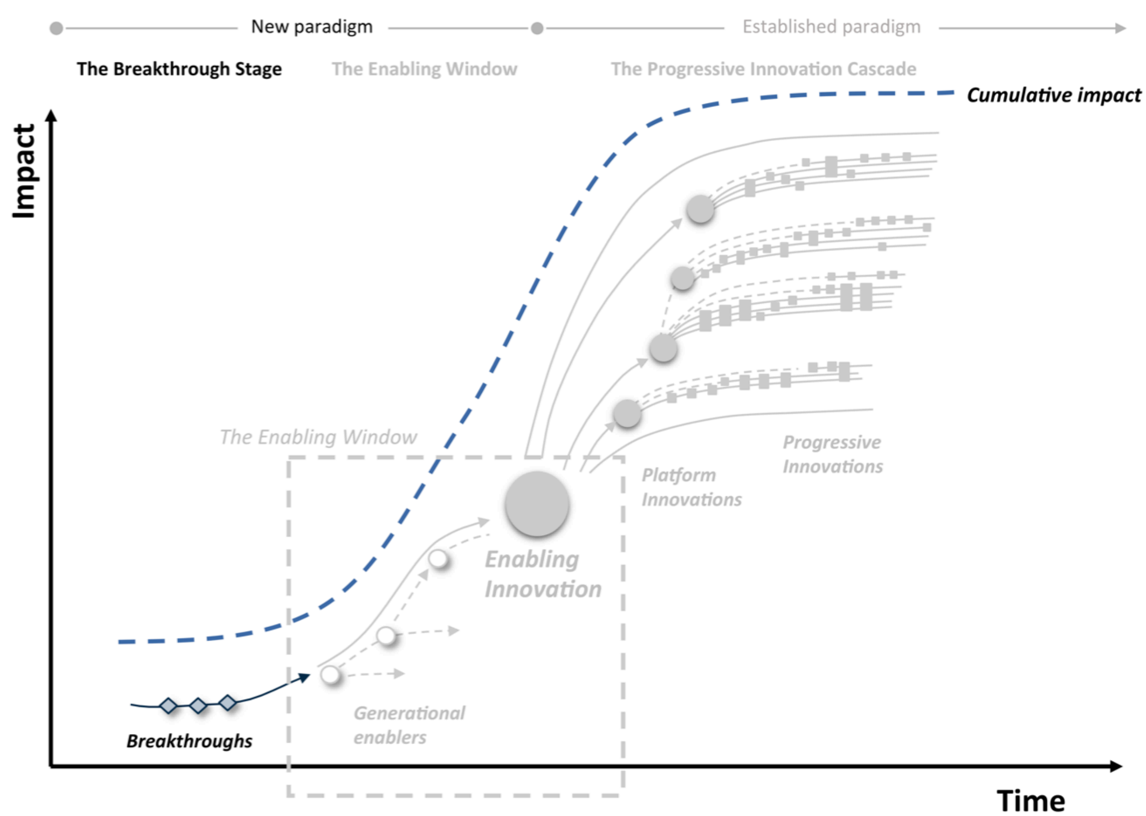


Figure 4.6 The Breakthrough Stage

Table 4.3 Summary of the Breakthrough Stage for the Cases Analyzed

Case	Breakthroughs	Example fields involved	Example barriers/challenges	Estimated time span
Lasers	• Discovery of the possibilities for the manipulation of light by stimulated emission of radiation • Analogy to the maser	• Photonics and theories of light • Electromagnetism • Optics • Atomic models • Spectroscopy • Quantum mechanics	• Characterization of the nature of light and its fundamental properties • Understanding of the mechanisms to manipulate electromagnetic radiation at relatively small wavelengths • Translation of the maser resonant cavity principles to an "optical maser"	• Work in basic physics from 1500 -1950s (approximately) • Invention of the laser in 1960
X-ray equipment	• Work by Maxwell, Faraday, Henry, and Ampere on electricity, light, and magnetism • Experimental work with Crookes tubes • Work on cathode rays (electrons)	• Electromagnetism • Atomic models • Optics and luminescence • Photography and image processing	• Characterizing the nature and source of X-rays • Understanding the mechanisms to generate X-rays • Identifying the materials that allow (or not allow) X-rays to go through	• Work in basic physics from 1500-1895 (approximately) • Discovery of X-rays in 1895
GPS	• Doppler effect application to navigation problem • Radar • Triangulation analytical techniques • Signal processing	• Electromagnetisms and electromagnetic radiation • Orbital mechanics • Signal processing	• Methods to calculate the orbital path of each satellite • Data broadcasting and data processing by receivers • Methods to correct data due to atmospheric (ionospheric) distortions of Doppler shifts	• Launch of Russian satellite Sputnik (1957) • The Transit system is made operational (1968)

Table 4.3 Continued

Case	**Breakthroughs**	**Example fields involved**	**Example barriers/challenges**	**Estimated time span**
Use of first forms of anesthesia	• Studies of gases • Studies on nitrous oxide • Studies of ether • Studies by Lavoisier on carbon dioxide and oxygen	• Chemistry and chemical manufacturing • Physiology • Clinical practice	• Selection of the type of ether to be employed as an anesthetic • Dosage calculation • Medical device employed to administer early anesthetics	• Study of gas properties (1500-1800) • First anesthetic demonstration (1846)
Radar	• Scientific work by Hertz, Maxwell on electromagnetism • Tesla suggests the use of electromagnetic waves to determine the relative position, speed, and course of a moving object • Invention of radar by Hülsmeyer	• Electromagnetism • Radio waves and radio wave transmission • Signal processing	• Use of electromagnetic radiation to detect and locate reflecting objects • Emission and reflection of pulsed radiation • Methods for wave time of flight processing • Methods to understand the direction of radio pulses	• Study of electromagnetic waves (1500-1900) • Invention of one of the first operating radar devices (1904)
Antisepsis and infection control	• Leewenhoek's studies of bacteria • Pasteur's germ theory of disease • Lister's connection between Pasteur's work on fermentation and wound sepsis • Lister's studies of carbolic acid and its use to treat sewages • Publication of Lister's studies in The Lancet, a medical journal • Koch's postulates	• Pasteurization • Fermentation and putrefaction • Germs and bacteria • Chemicals and chemical manufacturing • Clinical practice • Physiology	• Identifying the agents (germs and bacteria) that caused certain diseases and wound-related infections instead of coldness, air, or oxygen • Identifying a chemical agent and its concentration that can eliminate germs and bacteria without damaging tissue • Devising antiseptic methods and evaluating their effectiveness	• Studies of air as an agent of disease (500 BC – 1800 AD) • Pasteur's germ theory of disease and pasteurization (1858) • Lister's publications on antisepsis (1867)

Table 4.3 Continued

Case	**Breakthroughs**	**Example fields involved**	**Example barriers/challenges**	**Estimated time span**
Unit operations[1]	Conceptual change in the way of thinking about seemingly unique and different chemical operations	• Chemical engineering • Manufacturing • Chemistry	• Division of chemical engineering processes into classes (e.g., heating, fluid flow, mechanical, thermodynamic) and categories (combination, separation, reaction)	• First courses in chemical engineering (1888) • Introduction of the concept of unit operations (1910)
Microfinance[1]	Conceptual change in banking practices to make the poor bankable	• Banking • Entrepreneurship • Economic development ecosystems and value chains • Sociological study of poverty	• Identifying sources of poverty and famine • Identifying communities in need • Raising capital to lend • Establishing lending processes for people without collateral and without the ability to read or write • Monitoring and controlling loans	• 1960s-1970s
Crowdsourcing[1]	Isolated crowdsourcing attempts embedded throughout history (e.g., Oxford English Dictionary's call for volunteers to make contributions and identify all words in the English language in the 1800's)	• Problem-solving • Science • Finance	• Structuring programs and enticing users to participate • Establishing control mechanisms for the crowdsourced activities • Defining boundaries and ownership of byproducts	• 2000-present

1. For conceptual breakthroughs such as unit operations, microfinance, and crowdsourcing historical documentation is much less available than for physical inventions

Analysis of the cases in Table 4.3 reveals a set of common underlying characteristics. Breakthroughs can be theoretical/conceptual and/or experimental/inventive. They are highly transdiciplinary, often connect seemingly unrelated fields that share a characteristic pattern in their lack of application/impact, and open up entire new fields of study. Breakthroughs are often pursued through research endeavors, but can also stem from conceptual change (i.e., defined by Vosniadou [1999] as a change in mental models or personal theories constructed to comprehend phenomena). When stemming from research, breakthroughs can be the result of basic research (i.e., searching for fundamental understanding), use-inspired research (i.e., searching for fundamental understanding with an approach that is inspired by or applicable to real world problems), or applied research (i.e., seeking specific solutions to targeted problems by applying known fundamental results), which Stokes (1997) synthesized as the "Pasteur's Quadrant" model. When stemming from conceptual change, a constantly evolving working hypothesis often drives the breakthroughs.

Two breakthrough case histories from the technological domain – lasers and GPS – are herein described to contextualize these insights. In the history of the laser, theoretical breakthroughs, particularly theories of light amplification had their origins, for example, in the work of Niels Bohr, Max Planck and Albert Einstein. The work of these scientists focused on understanding how molecules and atoms absorb and emit light (or any type of electromagnetic radiation) driven by the paradigm change that quantum mechanics represented compared to classical mechanics (Townes, 1999; Gross and Herrman, 2007; Hecht, 2010; Bertolotti, 1999). More specifically, Einstein "was the fist to recognize clearly, from basic thermodynamics, that if photons can be absorbed by atoms and lift them to higher energy states, then it is necessary that light can also force an atom to give up its energy and drop down to a lower level. One photon hits the atom, and two come out. When this happens, the emitted photon takes off in precisely the same direction as the light that stimulated the energy losses, with the two waves exactly in step (or in the same 'phase'). The net result is called stimulated emission and results in coherent amplification" (Townes, 1999, p. 13).

Yet experimentally, the laser had its origins in microwave spectroscopy and the realization of the maser (microwave amplification by stimulated emission of radiation) and an early vision of what would eventually become atomic clocks (Hecth, 2010). Based on his work in microwave spectroscopy and his overarching goal of working at wavelengths much shorter than microwaves, Charles Townes suggested that "stimulated emission at microwave frequencies would oscillate in a resonant cavity thus producing a coherent output" (Hecht, 2010). This insight was used to build the first maser by directing excited ammonia molecules into a resonant cavity (Hecht, 2010; Gross and Herrman, 2007). With time, this work indeed led to the first means to track time at the molecular and (later) atomic levels as well as a number of additional applications for which time keeping is critical (Townes, 1999). After work in the field made masers operational, and due to his desire to work at even shorter wavelengths, Townes realized the possibility to build an "optical maser," which would eventually be called the laser and launched the race to build the first device (Bertolotti, 1999).

In like manner, the breakthrough for global positioning systems (GPS) dates back to the Cold War era, the launch of Russian satellite Sputnik, and the work by Johns Hopkins scientists William Guier and George Weiffenbach. Shortly after the launch of Sputnik, these physicists decided to attempt to receive the signals emitted by the satellite while passing near their laboratory (Bray, 2014). Using a radio receiver tuned to 20 MHZ and 2 feet of wire as an antenna, the scientists generated signals as Sputnik passed near them and decided to record and time stamp them. Using this data and the Doppler effect as a basis for their calculations, later that afternoon, Guier and Weiffenbach were able to infer the satellite's orbit from their data (Guier and Weiffenbach, 1998; Alexandrow, 2008). As described by Guier and Weiffenbach (1998, p. 15): "Within weeks, we were spending almost all of our time "on the problem." We did some homework and established the definitions for typical near-Earth satellite orbital elements using published literature…George had set up a way to digitize the Doppler signals… Bill was desperately trying to establish the values for the orbit parameters." Over the next few weeks, the scientists refined their analytical methods and tracking device with the help of other members of the Johns Hopkins Advanced Physics Laboratory (APL) research team. These refinements included establishing definitions for typical near-Earth orbital elements, size and positioning of the antenna, and data reduction techniques, which led to the (informal) team being able to predict Sputnik's orbit and location. As a result, in a matter of weeks they were able to infer the satellite's orbit and predict the time of appearance of signals, which helped confirm inferences on the satellite's orbit.

The breakthrough for GPS then came from flipping the satellite tracking problem around. As recalled by Guier and Weiffenbach themselves (1998, p. 16): "Frank McClure, also from Johns Hopkins, called us to his office and asked us to close the door. He asked us if anything new suggested that we had exaggerated our claim that we could find an approximate orbit from a single pass of Doppler data. When we replied that nothing had really changed, [he] asked if we could invert the solution, i.e., determine the station position while assuming the orbit is known." Preliminary analyses by the APL team determined the feasibility of this request, which stemmed from the desire of the Navy to locate submarines.

The aforementioned examples, namely lasers and GPS, illustrate scientific/technological breakthroughs; however, not all breakthroughs need to be associated with science and technology and instead may entail a change in conceptual thinking as the main driver behind the breakthrough, as shown in the following case histories. Crowdsourcing, for example, stems from a change in worldview that shifts the way a human task is sourced, from a single or a few sources to leveraging the power of a larger group of sources. The earliest documented example of crowdsourcing is the Oxford English Dictionary's attempt to map every single word in the English language in the 1800s, for which it called for submissions from the general population. Similarly, modern microfinance efforts began when, for example, Joseph Blatchford in Venezuela in the 1960s, and Muhammad Yunus in Bangladesh in the 1970s, realized that the banking practices of the era made the poor "unbankable," despite their desire to pursue entrepreneurial endeavors (Robinson, 2001). Even in the technological domain a breakthrough that stems from a change in conceptual thinking can drive substantial knowledge advances and move a field forward. In the field of chemical engineering for example, the concept of unit operations draws together the common features of industrial processes that once were thought to be unique for each single chemical byproduct. In Arthur D. Little's words the concept entails the notion that: "any chemical process, on whatever scale conducted, may be resolved into a coordinated series of what may be termed 'unit actions,' such as pulverizing, mixing, heating, roasting, absorbing, condensing, lixiviating, precipitating, crystallizing, filtering, dissolving, electrolyzing, and so on. The number of these basic unit operations is not very large and relatively few of them are involved in any particular process" (Little, 1913; Helpman, 1998; Flavell-While, 2011, p.55). Similarly, the finite element method has changed the way many structural elements in multiple applications are analyzed, from airplanes, to buildings, cars, rockets, and boats.

These cases exemplify the nature of breakthroughs, their development in niche communities, often in disparate fields, and their focused reach and significance at the breakthrough stage due to the lack of broad application. Collectively, examination of the breakthrough stage for the cases in Tables 4.2 and 4.3 highlights an emerging set of patterns for this stage of the model:

- *Breakthroughs, whether technological or non-technological, set up a paradigm change to be exploited.* The aforementioned cases positioned breakthroughs as opportunities to transition into a new paradigm that drove change and impact. X-rays and lasers, for instance, set the stage for an era of manipulation of light and electromagnetic radiation. Unit operations positioned chemical processes as a small number of common operations and reduced the apparent complexity of chemical manufacturing. Breakthroughs in anesthesia set the stage for an era of pain management. Although easy to spot in hindsight, these paradigm changes are difficult to articulate when looking forward, due to being in disparate, often niche communities who use language in different ways, making the use of pattern recognition and precise language to articulate/describe these patterns/trends seemingly important.

- *Because of their lack of application, the byproduct of breakthroughs is typically knowledge (even if in the form of a conceptual hypothesis).* Regardless of being theoretical/conceptual or inventive, the byproduct of breakthroughs is knowledge. Whether knowledge regarding the fact that the people living below the poverty line (in any given context) are unbankable by current practices, as in the case of microfinance, or knowledge regarding theories and inventions for the use of electromagnetic radiation, physics principles, or numerical methods to locate and track objects on/around Earth, as in the case of GPS, the breakthrough stage is characterized as a stage of knowledge creation. Although knowledge is also generated in all other stages of the enabling innovation process, in the breakthrough stage, this knowledge provides weak signals for a change in paradigm that could potentially be exploited, as opposed to solving specific subproblems within a working paradigm.

- *Breakthroughs are chained sequences of knowledge-generating events.* Although many of the aforementioned historical breakthroughs seem to have "aha!" turning points, many preceding and subsequent steps in the knowledge generation process were just as critical as the realization of a seemingly key insight. For instance, the conceptual realization of the maser, which preceded the laser and set the foundation for the practices of stimulated emission of radiation, involved advances in millimeter electromagnetic radiation, thermodynamics, quantum physics, molecular physics, especially with ammonia molecules, molecular beam systems, and resonators. As an example, generating millimeter waves in a maser was at first assumed to require a very small resonant cavity, only a millimeter in size in an era where such precision was not yet achievable, able to cope with large amounts of heat. These resonant cavity size assumptions and heat amounts stemmed from the second law of thermodynamics, and over the course of several weeks Townes (1999) explored implications in varying the components of his millimeter wave system with respect to size and heat. In this time period, he discarded the idea of very small (millimeter sized) resonators and decided to emulate nature in larger size resonators. The second law of thermodynamics, however, seemed to imply that to build a larger resonator would require an extraordinary amount of heat to reach the millimeter wave region of the electromagnetic spectrum. This challenge in turn implied thinking of "a way to twist nature a bit" (Townes, 1999, p. 56), and was overcome by conceptualizing molecular systems as independent, where each system would have need to be in thermal equilibrium, but not all interacting molecular systems needed to be in equilibrium. By having collections of entirely excited molecules, the density of excited atoms or molecules would increase, which would lead to signals getting stronger as radiation waves picked up more photons along the way. Eventually, these chains of insights led to the conceptual design of the maser device (before even attempting to build it) and exemplifies the sequence of knowledge generating episodes that encompass a single breakthrough.

- *Time spans for the application of knowledge generated by a breakthrough have large variances.* The first documented discoveries of the soporific effects of ether date back to the 1500s, which went unused until the breakthrough studies of Joseph Priestley in 1772 (Sykes and Bunker, 2007; Shephard, 2009). This time span implies that approximately two centuries passed before Priestley made a connection between the soporific effects of these gases on the human body and the possibilities of employing such gases to proactively manage pain. In contrast, the breakthroughs generated during the discovery and invention of GPS techniques were carried out in a matter of a few weeks. As such, time spans for the application of breakthroughs that add links to a knowledge chain have large variances. The variance in these time spans often depends on stakeholders' ability make knowledge connections – which highlights an opportunity to be more proactive – as discussed in depth in Chapter 5 of this dissertation.

- *Many potential paths can lead to breakthrough, knowledge-generating episodes and these paths often jump across counterintuitive contexts.* Selecting which path to take and predicting to where such a path will lead is difficult. Some of the most suited paths might be in counterintuitive contexts outside the fields in which prior chain links of breakthrough were conceived. As such, discipline-specific pursuits likely contribute to the formation of silos, which hinder the creation of connections between these meaningful patterns of information. Examples of these links include the connections between microwave spectroscopy and the laser, the connection of the study of the properties of gases in science and anesthesia; the connections of the study of satellite orbital trajectories, the Doppler effect, electromagnetic radiation, and GPS; and the common features across seemingly unique chemical processes and the organizing principle of unit operations. Chapter 5 discusses strategies to overcome this challenge, which seems to commonly affect the breakthrough and enabling window stages.

- *Serendipity and chance seldom play a role as critical as the systematic approaches of the stakeholders driving the breakthrough*. The laser and GPS for instance, are the byproduct of systematic, goal-oriented pursuits; yet even in seemingly serendipitous discoveries, such as x-rays, employing a systematic approach to discovery and invention seems key. X-rays, are said to have been discovered while inaugural physics Nobel prize winner Wilhelm Röntgen was studying cathode rays (later called electrons) using Crookes tubes (a device commonly used in

> scientific experiments of the era) (Kevles, 1997). One night, Röntgen noticed an unexpected glow in a fluorescent screen in his lab when the cathode ray tube was turned on. After noticing such a phenomenon, and consistent with his approach to science, Röntgen proceeded to examine the rays methodically over the course of several weeks, experimenting with everything available in his lab, including photographic plates. He noticed that bones and lead stopped the rays, that the rays would leave an impression in photographic plates, and that such rays could not be deflected by magnets like cathode rays or refracted by prisms like visible light. Röntgen named these rays X-rays, since "X" was the letter that represented the unknown. He published his discovery in late 1885 and, within a month, news of the discovery had gained considerable attention from the global press. After the announcement, others claimed to have noticed the rays/glow before (Kevles, 1997), but Röntgen was granted credit for noticing and methodically studying a phenomenon that his peers had overlooked – which was more important than serendipity in and of itself.

The realization of breakthrough discoveries and inventions in and of themselves is, however, not enough to drive an idea towards broad, enabling impact. Instead, many additional issues must be addressed to create a path from breakthroughs to enabling innovations and transform sequences of knowledge generating episodes into solutions that generate impact cascades in ecosystems.

4.4.2 The Enabling Window

The transitional period between breakthrough discoveries or inventions and enabling innovations, shown in Figure 4.7, is herein termed the "enabling window." In this period, the issues associated with employing a breakthrough in practical applications are addressed by facilitating the development of benefits and capabilities for application and impact across contexts – one of the hallmark characteristics of an enabling innovation (discussed in detail in Section 4.5 of this chapter).

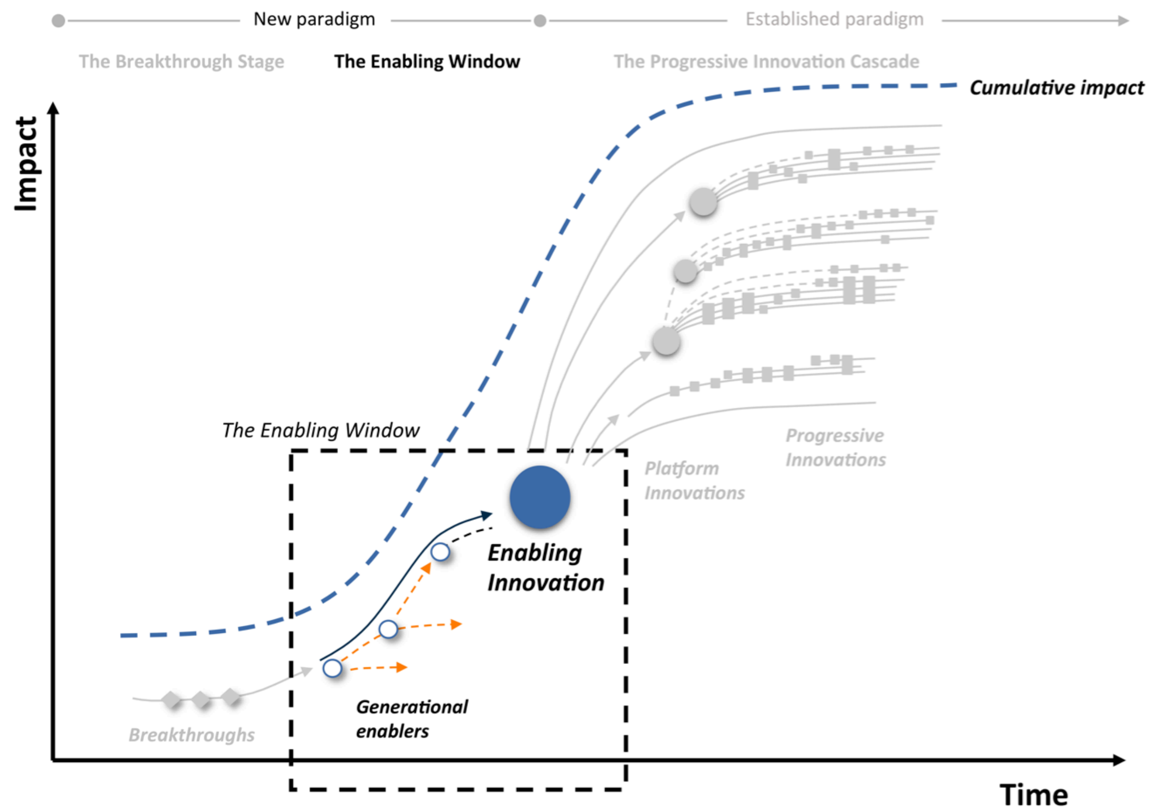


Figure 4.7 The Enabling Window

Navigating the enabling window and the subproblems associated with breakthroughs often depends upon *generational enablers*, i.e., "lily pads" that address these subproblems and serve as stepping-stones to the grander, more significant goal of an enabling innovation. Such subproblems can be the result of technical, economic, sociological, and/or psychological challenges that act as barriers for the broad application and impact of an enabling innovation. Examples of enabling window challenges include matching generational enablers with (both accepted and counterintuitive) application contexts, garnering resources and retaining interest in a concept, addressing systemic and infrastructural issues, changing deeply embedded habits and/or cultural norms, and identifying how performance advances could open up new applications.

Analysis of the enabling window stage for the cases in Table 4.4 reveals two distinct paths to achieving a vision of an enabling innovation: a single-track, "moon shot and trickle-down" approach and a multi-context, "enabling lily pads" approach (see Figure 4.8). Both paths are driven by a vision of an enabling innovation yet are fundamentally different in their approach to unfolding performance and impact across contexts.

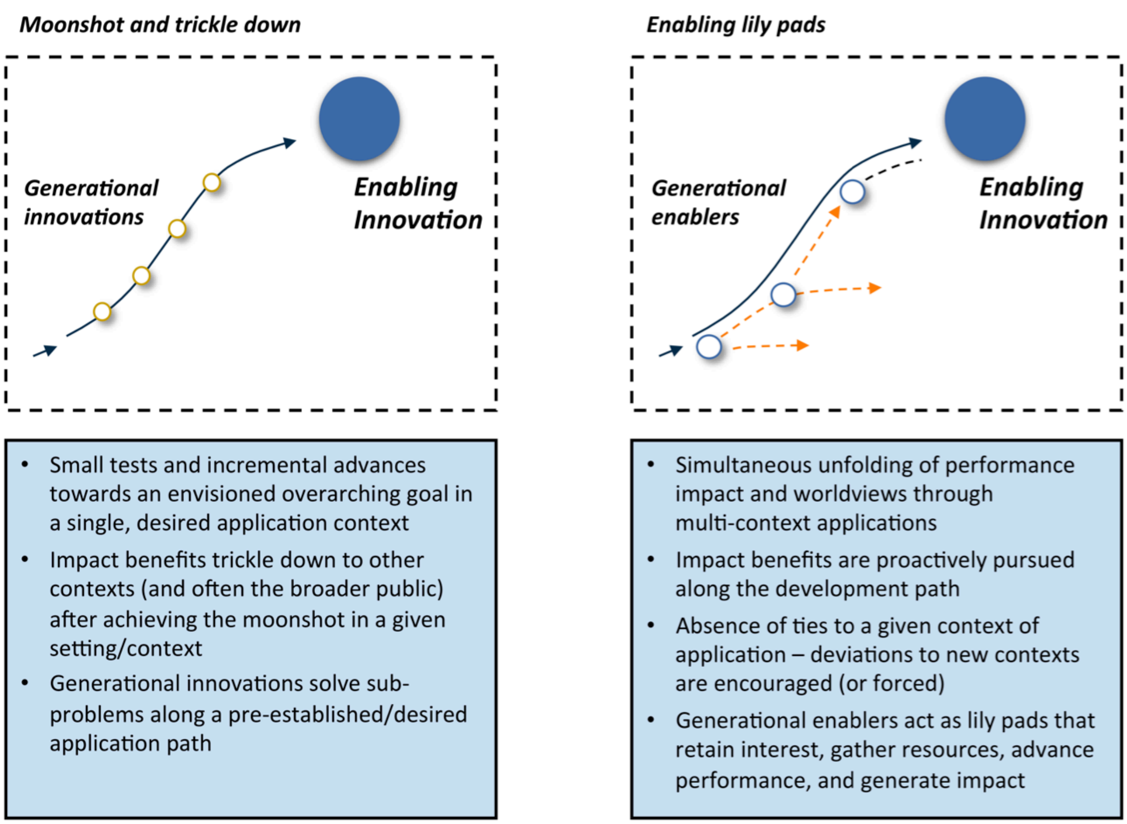


Figure 4.8 Contrasting Moonshot and Lily Pad Enabling Window Paths

In the "moonshot and trickle down" approach (hereafter referred to as "moonshot"), barriers are often addressed in a particular sequences as resources become available and in many instances artificially tied to a single context or single use case – likely due to an underlying assumption that addressing barriers hindering the adoption of breakthroughs is an inherently lengthy and evolutionary process. Once success is achieved in a given context, impact benefits are assumed to trickle-down to other societal areas. The history of radar is a prime example of this approach, radar advances during World War II focused on military applications, and non-military applications such as meteorological applications and the microwave were only pursued post World War II. In this approach, *generational innovations* (which address "generational" problems in subsystems associated associated with an innovation) (see Gatignon et al., 2012) can be artificially hindered by pursuit in a single context or desired use (i.e., in cases where progress is slow or "enabling activity" never occurs). Generational innovations in the moonshot path herein thus represent small tests in pursuit of the grander goal/vision for an enabling innovation.

In contrast, in the "enabling lily pads" approach, broad performance, impact and worldviews are simultaneously unfolded by pursuing different applications in multiple contexts. In the cases analyzed herein this multi-context unfolding happened reactively and implicitly (i.e., historical enabling window barriers "forced" such disciplinary/context transitions). However, enabling window barriers can potentially be addressed more rapidly, with greater availability of resources (and perhaps lower risk) by proactively seeking contexts in which the application of the current state of the breakthrough is viable. In such an approach, *generational enablers* (i.e., lily pads) may temporarily stray from the originally intended goal and/or envisioned context of application. Yet these lily pad pursuits represent impact-generating applications that often provide the transition for a breakthrough to move from theory to practice and, in so doing, to facilitate increases in performance, versatility, and impact towards a grander goal/vision. Historical cases of enabling innovation, such as lasers, X-rays, and anesthesia, hint at this approach.

Table 4.4 The Enabling Window Period for Sample Cases

Case	Applications envisioned in the breakthrough stage	Simultaneous unfolding in the enabling window of:			Enabling window pattern
		Performance advances[2]	**Applications and impact**[2]	**Worldview**[2]	
Lasers	• Amplification of light • Communications • Probing matter for basic research • Concentrating light for industry, chemistry, and medicine	• Laser beam power • Variants in laser architecture (e.g., CO2, red light, pulsed vs. continuous lasers) • Combination of lasers with other technologies (e.g., optical fiber)	• First laser surgical procedures to remove tissue in medicine • Range-finding in the military and astronautics • Weapon guiding in the military • Electrical resistance calibration in thin films • Spectroscopy and other research techniques in science • Rotational gyroscopes in airplanes •	Unfolding perspectives of the manipulation of light to address a variety of problems with new levels of performance (e.g., sensitivity, accuracy/ precision, speed)	Enabling lily pads
X-ray equipment	• Medical applications (e.g., diagnosis, surgery)	• Coolidge tube which replaced platinum filaments with tungsten thus generating clearer images • X-ray collimation techniques to eliminate unfocused rays and improve resolution • Lack of adoption by medical practitioners, establishing radiology as a field of study	• Entertainment • Dentistry and dental diagnosis • Forensics and personal identification • Medical applications	Unfolding perspectives of the ability to see through the human body and its technical, economic, systems (with regards to the healthcare ecosystem) and socio-emotional implications (especially in regards to privacy)	Enabling lily pads

[2] Not exhaustive

Table 4.4 Continued

Case	Applications envisioned in the breakthrough stage	Simultaneous unfolding in the enabling window of:			Enabling window pattern
		Performance advances[2]	Applications and impact[2]	Worldview[3]	
GPS	Two systems originally envisioned (by the Navy and the Air Force): • Locating ballistic missile submarines and other ships (Navy Transit GPS) • Dual-use (military and civilian) GPS system (Air Force), for example: - Coast guard ship tracking - Civilian ship tracking - FAA landing instruments - Missile tracking and guiding	• Transition from 2D measurements (Transit) to 3D measurements (Navstar GPS) • Pinpointing accurately the position of satellites • Providing all weather service • Comparing time between receiver and synchronized satellites accounting for the theory of relativity • Enabling GPS use in cell phones • Addressing FCC regulatory challenges	Military and civilian uses (in separate systems), for example (not exhaustive): • Airplane navigation • Coast guard ship tracking • FAA landing instruments • Civilian ship tracking • Missile tracking and guiding • Backpacking, hunting, and hiking	Unfolding worldviews on new ways to navigate the world, track time, and track objects	Enabling lily pads
Radar	• Aircraft and ship detection • Military target location	• Higher power outputs • Increased sensitivity • Improved timing and signal processing	• Military aircraft and ship detection • Military target location	Unfolding perspectives on the proactive use of radiation for detection, identification, and quantification of various phenomena	Moon shot and trickle down

[3] Not exhaustive

Table 4.4 Continued

Case	Applications envisioned in the breakthrough stage	Simultaneous unfolding in the enabling window of:			Enabling window pattern
		Performance advances[2]	**Applications and impact[2]**	**Worldview[4]**	
Use of first forms of anesthesia	Medical applications	• Acceptance of anesthesia by the medical community and society in general • Development of practices and procedures • Establishing anesthesiology as a field of study	• Entertainment and recreation in shows/exhibitions • Dentistry in tooth extraction and root canals • Medicine in surgery	Developing notions of pain as an area of life that can be managed in acute circumstances	Enabling lily pads
Antisepsis and infection control	Medical applications	• Selecting antiseptic chemical and dosage • Establishing antiseptic methodologies • Gaining buy-in from the medical community	Medical applications	Emerging perspectives of hygiene and infection control being a critical part of healing to proactive management of infection	Moon shot and trickle down
Unit operations[1]	• Chemical manufacturing • Chemical engineering education	• Developing qualitative and quantitative unit operations content • Adoption by the chemical manufacturing community	• Broad array of chemical manufacturing circumstances (e.g., petroleum, industrial chemicals, paints) • Chemical engineering education	Possibility of systematizing chemical processes and production (instead of each process being unique). Emerging notions of chemical engineering as a discipline and nascent views of chemical research and chemical manufacturing as profitable and rewarding endeavors	Enabling lily pads

[4] Not exhaustive

Table 4.4 Continued

Case	Applications envisioned in the breakthrough stage	Simultaneous unfolding in the enabling window of:			Enabling window pattern
		Performance advances[2]	Applications and impact[2]	Worldview[5]	
Microfinance[1]	Financing for the unbankable	• Lack of banking structures for target sectors of the population • Lack of processes for microfinance • Incompatibility of banking practices with microfinance	• Three-share farms in which farmers, land owners and financiers collaborated in agricultural efforts • Informal financing for the poor • Institutionalized financing methods for the poor	New worldviews in banking that led to the creation of banking services to the poor, who were previously thought of as unbankable; evolving perspectives of poverty and development	Enabling lily pads
Crowdsourcing[1]	Obtaining services, ideas, or content by a large group of people	• Creation of crowdsourcing processes • Establishment of governance mechanisms and product ownership • Development of crowdsourcing-related technology • Encouragement of stakeholder participation	• Corporate problem solving • Funding for charities • Funding for artists • Online crowdsourced encyclopedias	New perspectives on the channels to obtain resources, services, ideas, or content are sourced: from a single or limited number of sources to a relatively large number of contributors	Enabling lily pads

[5] Not exhaustive

These two approaches – moonshot and enabling lily pads – are represented in Figures 4.9 and 4.10. Figure 4.9 contrasts the trickle down approach, which might encounter barriers or face slow progress with the possibility of embracing opportunities for early trial in contexts that may be considered temporary deviations from the original goal/vision for the enabling innovation. Pursuit of lily pads in early trial contexts generates opportunities for early impact, retain/foster interest in an innovation, and facilitate advances in desired performance.

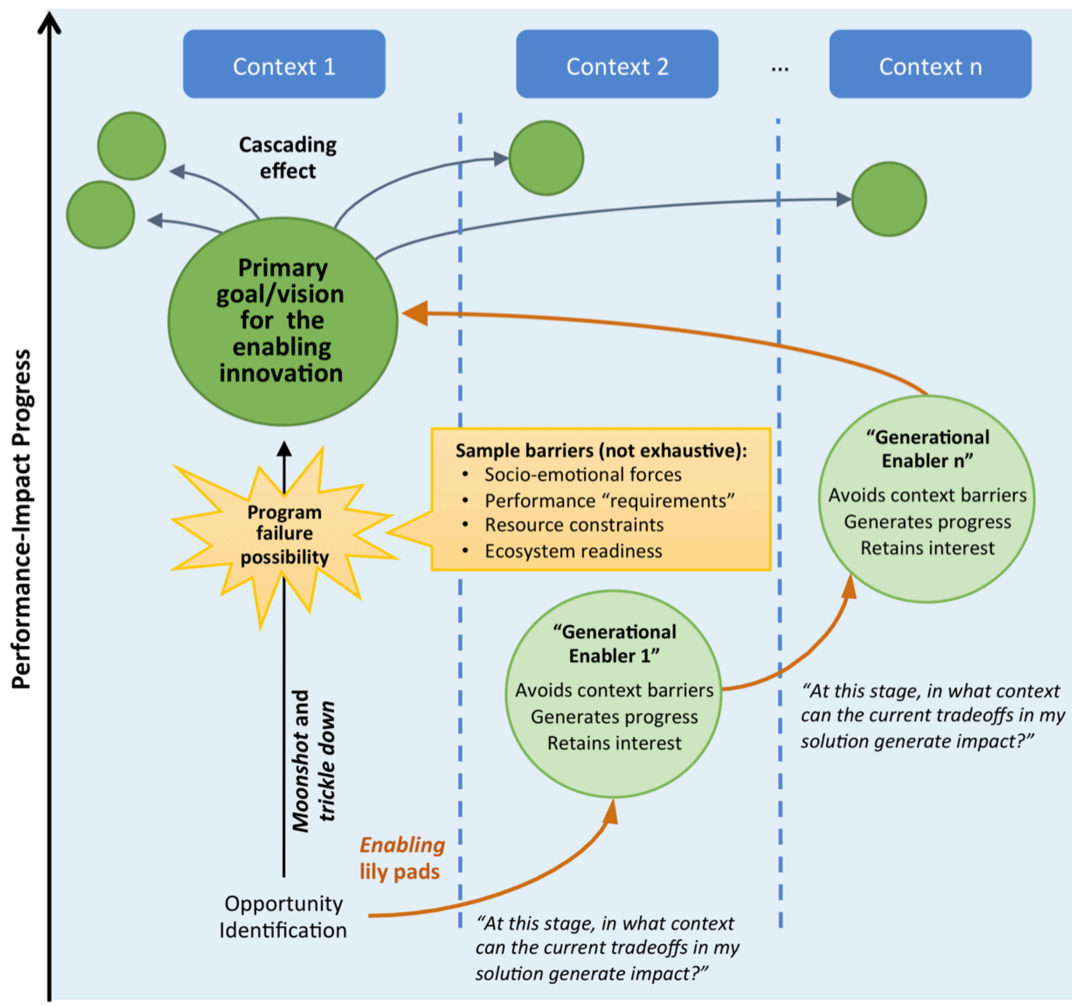


Figure 4.9 Moonshot and Lily Pad Pathways to Unfolding Performance and Impact

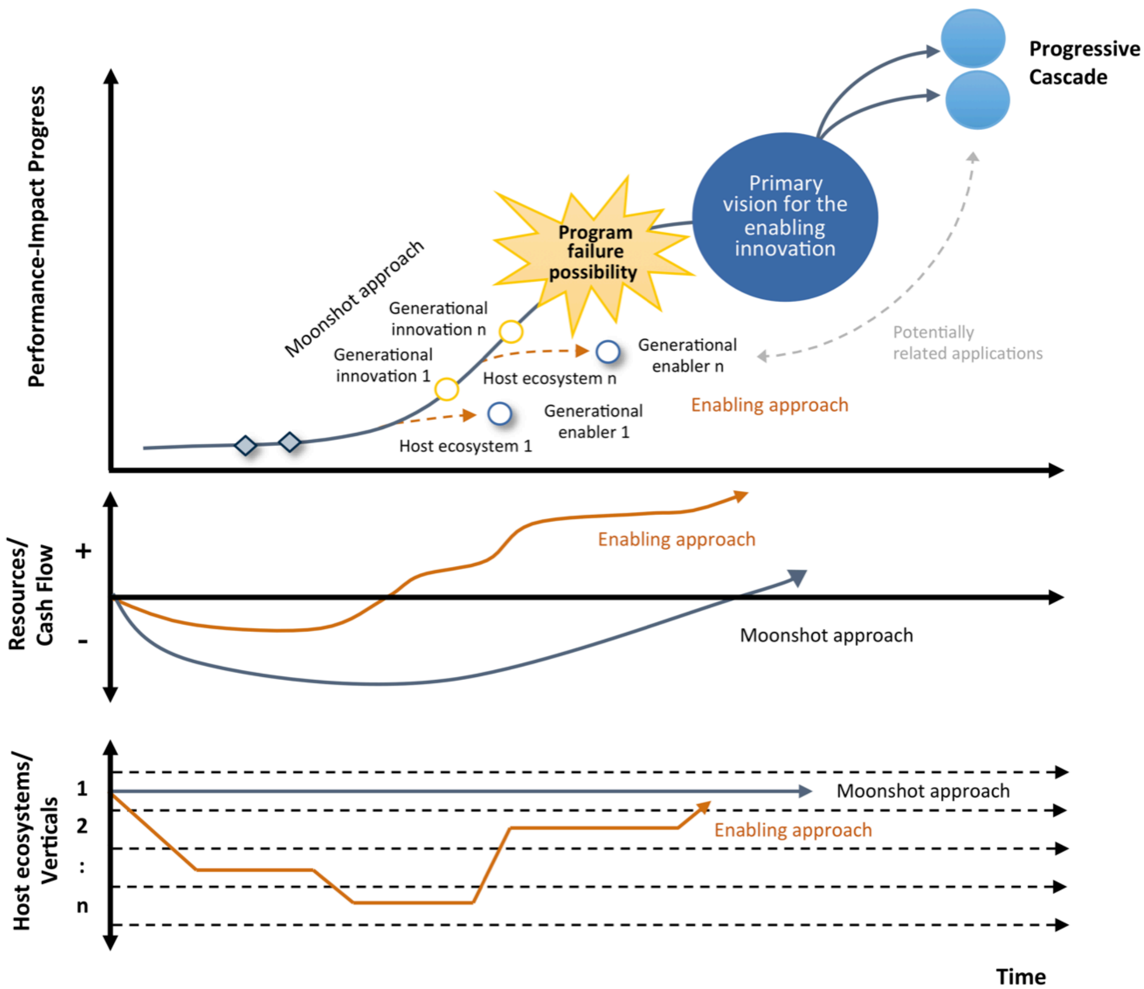


Figure 4.10 Two Paths for the Enabling Window and their Implications

Figure 4.10 hypothesizes the implications of these two approaches to unfolding performance and impact over time. The enabling lily pad approach to generational enablers is herein hypothesized to gather resources (and likely interest) for a concept more rapidly than the moonshot and trickle down approach to generational innovations. This hypothesis is grounded on the diverse set of application contexts (or host ecosystems) for this approach, and the possibility of matching solution capabilities with contexts where a solution can more rapidly advance performance and generate impact. The cases analyzed in this study that encountered barriers to application and impact in a given ecosystems (e.g., X-rays, anesthesia, lasers), for instance, in medicine, often found additional host ecosystems in which their current state of benefits and tradeoffs matched a desired profile in the ecosystem. Lasers, for example, found applications in medicine, the military, space exploration, aviation, manufacturing, and scientific pursuits, which both generated impact and advanced the performance of the innovation. In contrast, the trickle down approach tends to fixate on a single application space, in some cases artificially and in others due to non-negotiable circumstances, which might lead to slow progress due to barriers that might need to be overcome (but that might be absent in other contexts). A prime example is radar, which although likely due to circumstances of the era (World War II), focused generational innovation efforts for a single context (military-related), and additional applications (e.g., meteorology, range finding, microwave-related applications) were pursued after this military-focused time period. Hypothetically, the enabling lily pad approach could have focused on developing the aforementioned additional applications (e.g., microwave) in the generational enabler stage (thus the hypothetical relationship between generational enablers and progressive innovations in the cascade in Figure 4.10)

The enabling approach to the pursuit of lily pads or generational enablers is a primary focus of this work (and the foundation for the enabling thinking framework), and is thus herein described in more depth in the context of two cases – anesthesia and X-rays. (A synthesis of additional enabling lily pad cases can be found in the aforementioned Table 4.4.) Following these case histories, a collection of patterns for the enabling window that can be inferred from the analysis of all cases in the sample is provided.

4.4.2.1 The Enabling Window History of Anesthesia

Promising ideas are often difficult to implement in practice largely due to worldviews. In the case of anesthesia, even with documented efforts in which several scientists noted the pain relieving effects of nitrous oxide gas, the medical community continued operating without anesthetics for a relatively long period of time. Humphry Davy, a young chemist who at the time was carrying out experiments with nitrous oxide, noticed that inhaling a few breaths of the gas relieved the pain caused by a gum infection and produced irrational peals of laughter, which he proceeded to document in 1800 (Davy, 1800). Davy suggested the use of nitrous oxide in surgery, but was largely ignored by the medical community, and surgeons continued to operate without anesthetics for almost 50 years. A few advocated for the change, such as Henry Hickman, who tried to disseminate his idea of using anesthetics in surgery, but passed away before achieving success in his efforts (Sykes and Bunker, 2007; Shephard, 2009).

In the enabling window, however, additional contexts of application can often serve as lily pads to an overarching goal. Despite the many discoveries and suggestions for use in the medical/surgical field, the recreational use of laughing gas, as nitrous oxide became known, and its use in the field of dentistry acted as generational enablers. Throughout the 1820s and 1830s, entrepreneurs organized public and private demonstrations of the effects of laughing gas, which was often sold as a recreational drug (Sykes and Bunker, 2007). In 1844, during one such demonstration, Gardner Colton showed the effects of nitrous oxide and, Horace Wells, a dentist in the audience, noticed that a subject had hurt himself during the inhalation but felt no pain, and consequently arranged a private demonstration with Colton to understand the effects of the gas. Wells had been experiencing pain on a wisdom tooth and asked to experiment with the gas while this tooth was extracted and realized the value of the use of (nitrous oxide) gas for tooth extraction, proclaiming “a new era in tooth-pulling” (Sykes and Bunker, 2007, p. 9; Duncum, 1947). Wells learned from Colton how to prepare the gas for tooth removal applications and started using the technique. A year later, in 1845, Wells was invited to demonstrate his experiment in the Massachusetts General Hospital, but at the moment of the demonstration his experiment failed due to lack of proper anesthetizing (Davison, 1965).

Delays in documentation highlight the importance of quickly and strategically disseminating efforts regarding generational enablers to foster adoption. In the case of anesthesia, other dentists also pursued its use and led generational enablers in the then nascent anesthetic field but failed to provide documentation that disseminated new insights to the medical community. William Clarke, for example, claimed to have used ether as anesthetic in 1842 for tooth extraction, and Crawford Williamson Long claimed to have used ether for a surgical procedure in 1842 although he did not document his cases until 1849 (Sykes and Bunker, 2007; Shephard, 2009).

Because of this delay in documenting/disseminating, the use of ether by William Thomas Green Morton in 1846 is generally regarded as the first documented, successful public administration of anesthesia, which helped convince the medical profession that anesthesia could be used in surgery (Sykes and Bunker, 2007). Morton was searching for a pain relieving drug that could be used in dentistry. In his search, he ran across Charles T. Jackson, a graduate from the Harvard Medical School, with expertise in chemistry, geology and mineralogy. Jackson alerted Morton of the possible use of ether in purified form (rather than the commercially available impure form) of the time (Sykes and Bunker, 2007; Shephard, 2009). This advice triggered numerous legal disputes over the discovery of purified ether as an anesthetic between Morton and Jackson. However, what is relevant to this dissertation is that this change in chemical can be considered a lily pad (generational enabler) in and of itself.

Anesthetic advances in the field of dentistry such as the use of pure ether (and impact in the health of dental patients) generated new opportunities for adoption in the medical field (the initial and likely overarching vision of scientists that originally suggested the use of anesthetics in medicine). Morton was aware of Wells' and other prior failures in using nitrous oxide in surgery and thus sought opportunities to demonstrate the use of diethyl ether in dentistry as recommended by Jackson. On September of 1846, Morton was granted an opportunity to demonstrate the use of anesthesia in tooth extraction (Keys, 1945), which had a successful outcome and for which the Boston Journal reported (Sykes and Bunker, 2007, p. 12): "Last evening, as we were informed by a gentleman who witnessed the operation, an ulcerated tooth was extracted from the mouth of an individual, without giving him the slightest pain. He was put into a kind of sleep, by inhaling a preparation, the effects of which lasted about three-quarters of a minute, just long enough to extract the tooth."

Henry Jacob Bigelow, a surgeon at the Massachusetts General Hospital heard of Morton's tooth extraction demonstration, and decided to invite him to demonstrate its use in surgery at the hospital. On October 1846, Professor John Warren performed the first surgery with the use of anesthesia, to extract a neck tumor. The device (see a replica in Figure 4.9) was supplied by Morton and used Jackson's suggested form of ether. The success of the surgery made the final connection for the use of anesthesia in the medical/surgical field and generated national recognition for Dr. Morton (Sykes and Bunker, 2007). Forces of resistance still remained, mostly due to changes in worldviews, for example, with some patients and doctors considering it a "needless luxury" and clergymen criticizing its use (Gawande, 2013). Yet anesthesia rapidly spread after this historical success, and many additional, progressive advances followed in the form of platforms, such as local, regional, intra venous, and airway anesthetics.

Figure 4.11 Replica of first inhaler used in a surgical demonstration (NIH, 2012)

In summary, the path of anesthesia through what is herein termed the *enabling window* seems to have been originally envisioned for medical applications, but medical practices and beliefs of the era made dentistry a more suitable candidate for its first-use after a long period of time in which "laughing gas" was simply used as a recreational drug. After advances in the dental community, anesthetics garnered interest in medicine and enabled multiple cascading impact advances throughout history. These "jumps" across ecosystems, summarized in Figure 4.12 for the case of anesthesia, highlight an example of a possible path between breakthroughs and an enabling innovation – and even if for anesthesia such jumps occurred unintentionally, there remains a latent an opportunity for their intentional pursuit.

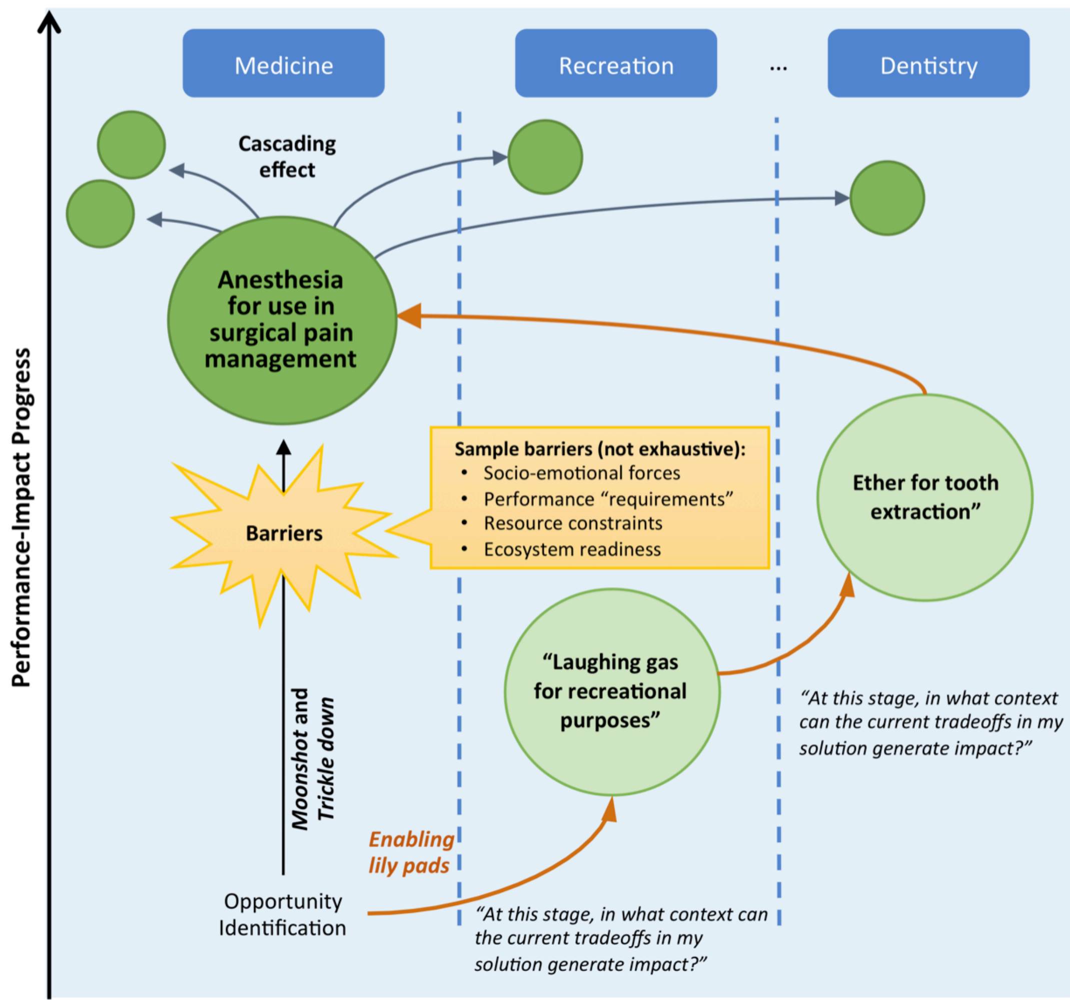


Figure 4.12 Anesthesia Enabling Window

4.4.2.2 The Enabling Window History of X-rays

In another example of generational enablers and their jumps across ecosystems, after the breakthrough discovery of x-rays and the fundamental mechanisms to generate such rays, applications were rapidly developed within weeks of Röntgen's announcement of the discovery. Examples of such applications included X-ray slot machines to examine your own bones in hotels and boutiques, X-ray demonstrations for entertainment purposes in department stores, and X-ray photographs for curious people (Howell, 1995; Francl, 2010). As examples, "[i]n New York, Bloomindale's brought in customers with demonstrations conducted by Herbert Hawks, a Columbia University senior who did research for his physics professor, Michael Pupin. In Paris, M. Dufayel, the owner of his own chain of department stores, alternated public demonstrations of an X-ray machine with demonstrations of the Lumiere brothers' new moving pictures" (Kevles, 1997, p. 24). Yet once the novelty of the device faded and some health dangers, particularly skin burns were noticed, efforts focused on early applications, here considered generational enablers, for scientific and medical purposes (Kevles, 1997). These pursuits involved the search for applications and new designs with different combinations of materials, tube shapes, protective devices, methods to improve signal-to-noise ratios, and advances in knowledge regarding the nature of X-rays and X-ray devices, which highlighted the broad scope for improvement in devices dedicated to the manipulation of X-rays.

Among the first to pursue practical X-ray applications were Thomas Edison and his team, who built a medical device called the fluoroscope – which provides an example of the technical efforts that generational enablers typically involve. Edison focused on two features of Röntgen's device, namely, the tube and the substance that made fluorescent screens glow (Fuchs, 1947), as described by Kevles (1997, p.34):

> *"First there was the tube itself. By using thinner glass than an ordinary Crookes tube, he produced a tube that allowed more X-rays through faster; and he replaced the platinum wires inside the tube with electrodes made of*

> *aluminum disks. Next, there was the question of the aluminum screen and what made it glow. Edison directed his assistants to test the substances at the top of his chemical storage wall and work their way down to find something that would reflect a sharper image than barium platinocynanide. His assistants systematically explored over eight thousand different chemicals; they painted coin-sized dabs of each onto thirty-six test circles on a cardboard square. The substances were graded according to the way they fluoresced when X-rayed. The search led to calcium tungstate. Edison turned the discovery to a nearby manufacturer for marketing as a 'fluoroscope' (he coined the term)."*

In addition, Edison focused on the entire medical device ecosystem while developing the fluoroscope, using contract manufacturers and marketing events at galas to disseminate his team's device. Because of this involvement and given his prestige as one of the most famous inventors of the era, Edison's fluoroscope efforts helped to considerably increase the attention that X-rays were receiving.

Many other medical applications followed suit and advanced knowledge regarding X-rays and X-ray devices, yet none were able to achieve mass adoption of these devices (Kevles, 1997) due to issues rooted in the medical working paradigm of the era. A few surgeons and physicians started to use the device to get "radiographs" of broken bones, and for detection purposes – including uses of the device to locate bullets in two U.S. presidential shooting incidents. An MIT doctor with a degree in chemistry, Francis H. Williams, started using X-rays to explore human chests for signs of tuberculosis as well as to diagnose pneumonia, emphysema and to find kidney stones (del Regato, 1983). Military physicians used X-rays to locate bullets in soldiers and military medicine was the medical subfield that more broadly accepted X-rays in the first decade after their discovery (Kevles, 1997). Combined with antisepsis and anesthetics, X-rays continued to push surgery to the top of the medical hierarchy of treatments. In addition, X-rays reinforced efforts of some doctors to push a "scientific medicine" paradigm, which emphasized pattern recognition and technology as tools of diagnosis, and contrasted the medical paradigm of the day of diseases being unique to each patient (Pasveer, 1989) – a dichotomy that was reconciled with the advent of genetics in the 20th century and its link to some inherent diseases such as the inability to process sugar or alcohols due to specific genes (Kevles, 1997). These practical applications of X-rays hint at the signals of impact that were a result of the generational enablers in the trajectory to broad reach, high significance and paradigm change.

Many barriers significantly slowed down the adoption trajectory of X-rays in the medical field despite the many attempts at generational enablers and the pursuit of faster adoption. Among the technical barriers, early medical applications of X-rays required long exposure times (over an hour in some cases), which helped highlight the first noticeable hints of health dangers due to overexposure to radiation. These dangers were noticed through skin burns, and X-rays were highly debated as acceptable evidence in malpractice legal cases as well as other law practices, which also influenced the rate at which X-rays were adopted and improved.

Prior to systemic adoption by the medical community, in another example of the lily pads across contexts/ecosystems that characterize historical enabling innovations, adoption of X-rays came from dentistry, a field in which the performance-impact tradeoffs were more acceptable (Kevles, 1997). X-rays of teeth needed considerably shorter exposure times than other parts of the body and, because of this, dentistry was less sensitive to the barriers for broad application compared to medicine. Among the first uses of X-rays in this arena included advocating for root canal surgery rather than indiscriminate extraction of teeth, tooth decay monitoring, pediatric dentistry, and the then nascent specialty of orthodontics. By late 1896, one year after Roentgen's discovery, dentists routinely X-rayed their patients (Brecher and Brecher, 1969), which suggests that dentistry was a path of lower resistance given the match between benefits/capabilities of the technology and the needs of the profession.

The increase in the use of X-rays by dentists was followed by the use of X-ray records as a means for security and forensic applications. One of the first applications of X-rays to identify the deceased occurred in France in 1987, when an exhibition hall caught on fire and people were identified by bone fractures or dental features; and one of the first applications of X-rays to security happened in Paris when customs inspectors used fluoroscopes to examine packages (Kevles, 1997). These applications sparked interest in the technology in domains beyond medicine and dentistry.

Performance advances over time facilitated the application of X-rays in the medical community and beyond. More specifically, generational enablers such as the Coolidge tube and the processes to collimate X-rays reduced the exposure time needed for medical applications to only a few minutes for the thicker parts of the body (compared to up to two hours in earlier versions of X-rays) and X-rays re-gained interest from the medical field. Coolidge tubes replaced Crookes tubes as the mechanism to generate a vacuum, and were developed by using ductile tungsten instead of platinum in a tube with more vacuum (Brecher and Brecher, 1969). Because of Coolidge tubes, X-ray devices had fewer residues in tube walls as Tungsten filaments has a higher melting point and produced less vapor than platinum filaments used in prior generations of the device, and thus produced clearer pictures. Almost at the same time, the ray collimation process was invented (Kevles, 1997). In this process, two metal grids were inserted, one between the patient and the tube and one between the patient and the photographic plate, to reduce the number of unfocused rays reaching the photographic plate, thus improving the resolution of X-ray devices.

Other advances that facilitated X-ray use medicine were not related to technical progress but to the evolving working paradigm. Often times, barriers to generational enablers (or generational innovations in the moonshot path) are deeply rooted in a working paradigm beliefs/cultural norms and the power-influence dynamics of ecosystems. In the case of X-rays, personal protective equipment (PPE) would have helped mitigate the health dangers due to overexposure to radiation, and some inventors developed this equipment. For example, the Friedlander suit, a lead-lined whole body suit named after its inventor Robert Friedlander, which was one of the first X-ray PPE of the era, was not widely adopted because some physicians had the widespread belief that X-rays were indeed benign and resisted the adoption of protective equipment. Because during this period of time "[t]echnological progress was largely doctor driven… Manufacturers raced to satisfy their demands. And when the doctors did not think it worth spending money on a product – such as lead shielding to limit excess radiation from spilling onto patients, technicians and themselves –these products, like Friedlander's suit, disappeared from the marketplace." (Kevles, 1997, p.57). In addition, power struggles between physicians and X-ray technicians also slowed down adoption in the medical landscape. Physicians and X-ray technicians (many of them scientists and engineers) disputed control and use of X-rays in both clinical and research settings. Ultimately, physicians prevented technicians from participating in the medical X-ray community without physician credentials. Struggles remained within the physician group, however, especially between those that viewed X-rays as a tool for diagnosis and those who considered X-rays as a tool for treatment. These power struggles in the medical community were gradually resolved, by consolidating X-ray use for medical diagnosis and by the slow establishment of the field of radiology. Overall, key barriers to X-ray adoption in medicine related to either/or the technology in and of itself, paradigms in the practice of medicine and legal issues regarding malpractice, or medical stakeholder power-influence ecosystem dynamics.

In summary, the trajectory of x-rays through the enabling window seems to have been envisioned for medical applications, but multiple barriers such as the power-influence dynamics of doctors and x-ray technicians, beliefs about the benign vs. damaging nature of x-rays, and the performance limitations of early x-ray machines may have made dentistry a more suited candidate for the first broad use of the technology, followed by brief applications in the identification and security spaces. Performance advances in such as the Coolidge tube and ray collimation techniques facilitated use in the medical field, the original envisioned application context. These transitions across contexts, summarized in Figure 4.13, again highlight an example of the path between a breakthrough and an enabling innovation.

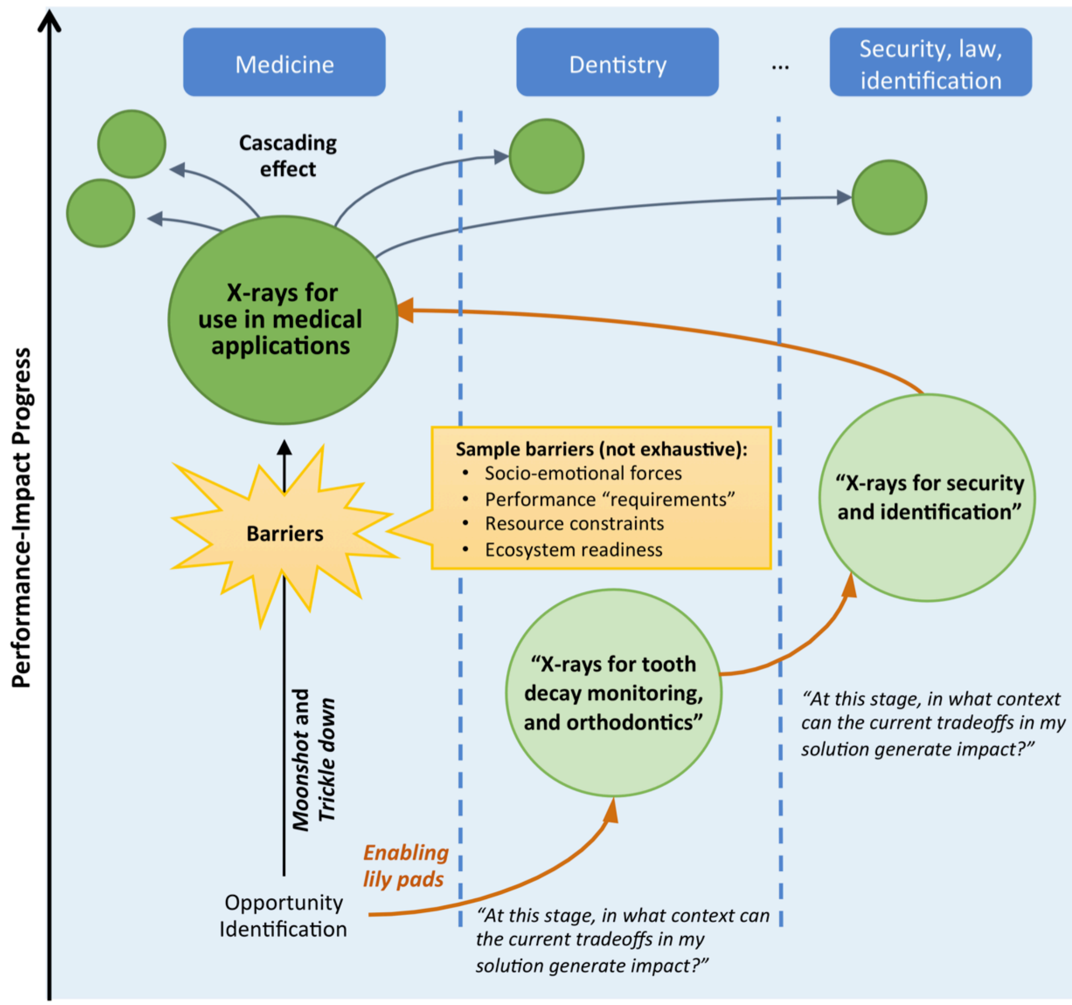


Figure 4.13 X-rays Enabling Window

4.4.2.3 *Patterns in the Enabling Window*

From the analysis of the cases in the sample, a set of patterns emerge for the enabling window, which can be summarized as follows:

- *Deviations from the envisioned ecosystem of application of a breakthrough seem to be the norm in the enabling window.* Many may consider the process of addressing issues associated with breakthrough discoveries and inventions to be lengthy and serendipitous, and may seek to pursue these issues in a particular sequence in a given context/vertical as resources become available. However, as shown in the aforementioned cases many of the sub-problems perceived as barriers to a breakthrough are context specific and often artificially tied to a single use case. In contrast, these sub-problems can potentially be addressed more rapidly and with greater availability of resources by seeking seemingly counterintuitive contexts for which the current embodiment of the breakthrough is an immediately viable solution. These trial applications, or generational enablers, may stray from the originally intended goal, but often provide the transition for a breakthrough to move from theory to practice by serving as lily pads, and, in so doing, to increase in performance, versatility, and impact. Anesthesia and X-rays took deviations to dentistry before applications in medicine (and beyond in the case of X-rays), laser applications were pursued in an array of contexts due to the broad interest in the technology, and crowdsourcing jumped from language applications, to photographic image stocks, to problem solving platforms.

- *Immediate large-scale applications can be nonobvious/ambiguous and/or difficult to achieve.* X-rays, for instance, were pursued in medicine and encountered challenges due to the long exposure times required to generate an X-ray image. Because of this, dentistry, which required less exposure time due to the lower density of teeth compared to bones was the first field to broadly apply X-rays (Kevles, 1997). This difficulty in envisioning and achieving these applications immediately following a breakthrough suggests a need to look broadly for application opportunity spaces for solutions in the enabling window without losing track of an intended goal/vision.

- *Performance improvements open up new application spaces.* New application spaces often become feasible when performance advances are achieved. In the case of X-rays, when the Coolidge tube, and ray collimation processes were invented, new application spaces opened up in the fields of medicine, and security. Similarly, the development of radar networks facilitated the meteorological use of radar for weather prediction, and advances in signal availability and receiver weight/size opened up handheld applications in GPS.

- *Types of barriers in the enabling window can be perceptual or factual and include systemic, technical, economic, sociological and psychological issues*. In the case of anesthesia, for example, clergy of the day assumed that pain was a normal part of life and some viewed the discovery as contradictory to natural and spiritual laws of life and/or as a needless luxury (Sykes and Bunker, 2007). Similarly, antisepsis required a change of habits and cultural norms in physicians (Gawande, 2013). With regard to performance requirements, GPS found early uses in application that did not "require" the ability to determine a location on demand (Bray, 2014). In other cases, the ecosystem might not be ready for adoption due to many forces being at play, in the case of X-rays, for instance, concerns emerged regarding the possibility of X-ray glasses and what the discovery meant in terms of cultural norms regarding privacy and personal space, the complexities of the medico-legal landscape, the power disputes of physicians and x-ray technicians, and the technological performance of devices (Kevles, 1997). In summary, these technical, economic, systemic, sociological, and/or psychological forces can be real or perceived (i.e., stemming from a flawed paradigm/worldview) and can stall progress in navigating the enabling window if not proactively managed.

- *The novelty of breakthroughs can spark significant interest in groups and create artificial ties to contexts of application, yet when novelty fades and barriers that stall progress emerge, solution-ecosystem alignment governs progress.* For example, shortly after the announcement of Röntgen's discovery of X-rays, machines were installed in boutiques, department stores, and demonstrations were given as a form of entertainment (Kevler, 1997; Francl, 2010), but once the dangers of this type of radiation were noticed this novelty faded. Interest in medicine emerged but barriers stalled progress. Dentistry was an ecosystem more aligned to X-ray solutions of the era. Similarly, after invention of the first laser, Theodore Maiman (its inventor), was questioned about potential applications and named five potential ones: "1) increased communication channels, 2) true amplification of light, 3) probing matter for basic research, 4) high power beams for space communications, and 4) concentrating light for industry, chemistry and medicine" (Hecht, 2010); yet, when probed if the laser as a weapon, Maiman admitted he could not rule them out and the Los Angeles Herald tagged the discovery as "L.A. man discovers science-fiction death ray." (Hecht, 2005, pp.191-192; Hecht, 2010). Yet, lasers were pursued in medicine, industry, space exploration and to guide weapons (rather than as a weapon) as laser advances aligned with host ecosystems. In both of these cases (as well as in other cases such as GPS) the novelty and attention from the public seemed to fade, and although helpful to raise awareness, performance advances and achieving broader impact seem to have relied heavily on matching current solution capabilities with the characteristics of host ecosystems/application spaces, thus creating lily pads toward the enabling innovation.

- *Flexibility to embrace emerging (rather than deliberate) applications (even if not originally envisioned) can accelerate performance-impact progress.* When pre-determined conceptions of intended use are removed and instead possibilities for application are broadly conceived, the potential and speed for impact seem to accelerate. The laser, for example, is an enabling innovation that sparked enough interest to almost immediately drive efforts (and impact) for a diverse portfolio of applications – with a relatively short enabling window. It could even be argued that the enabling window for the laser was proactively pursued as a portfolio of lily pads, which accelerated its development. In their first decade of existence, many improvements to the functionality of lasers that came through variations in architecture and performance-context matches for such variations. In this period, the pursuit of applications in contexts that embraced the tradeoffs of the then early-stage device facilitated its use across a broad spectrum of problems that the laser was envisioned to solve. As an example, shortly after Maiman's demonstration of the ruby laser in 1960, IBM's Thomas J. Watson Research Center demonstrated an uranium four-stage solid state laser, followed thereafter by the first Helium-Neon (HeNe) continuous wave laser. In 1961, one year after the first laser demonstration, commercial companies (e.g., Trion Instruments, Perkin-Elmer, and Spectra Physics) started to appear. More laser variants were demonstrated in laboratories, such as neodymium glass (Nd) and ytrrium aluminum garnet (YAG), gallium-arsenide (GAAs), gallium-arsenide-phosphide (GaAsP) (red-light) (the basis of CD/DVD devices) lasers. Other variants continued to appear, such as CO_2 lasers (broadly used in cutting and surgery), dye lasers, chemical lasers, Nd-YAD lasers (used in Lasik and skin surgery), and a few years later in the early 1970's, excimer lasers, quantum well lasers (conceptually developed), and semiconductor lasers. Alternatives to continuous pulsing also appeared within five years of the first laser demonstration. Q-switching, also known as "giant pulse formation," which allows the production of light pulses with extremely high (e.g., gigawatt) peak power, was demonstrated in 1962. This laser variant facilitated uses of the invention in applications that demanded high energy, such as laser-based industrial cutting. Further, mode-locking (in 1963) and phase-locking (in 1965), which were critical foundations for advances that were to come in telecommunications. These improvements highlight the importance of embracing the emerging features/aspects of solutions and in proactively pursuing the broader (and also emerging) set of impact spaces that are often possible with an enabling innovation. Compared to the laser, other enabling innovations (e.g., radar) were pursued in a relatively slower manner due to deliberate plans in envisioned application spaces.

In summary, many may consider the process of addressing issues associated with the enabling window to be lengthy and serendipitous, and may seek to address these issues in a particular sequence as resources become available. However, the aforementioned cases suggest that many of the sub-problems perceived as barriers to a breakthrough are context specific, often artificially tied to a single use case, and addressed through generational innovations. In contrast, these sub-problems can potentially be addressed more rapidly, with greater availability of resources, and perhaps with lower risk, by seeking contexts for which the current embodiment of the breakthrough is actually a relatively viable solution. These *lily pads* or *generational enablers* may stray from the originally intended goal, but often serve as lily pads for a breakthrough to transition from theory to broad practice and consequently help drive advances in performance, versatility, and impact.

4.4.3 The Progressive Cascade

In the enabling innovation model, once a set of benefits and capabilities for application across contexts has been achieved and worldviews have been relatively established, an innovation transitions out of the enabling window into a stage of true enabling innovation, as shown in Figure 4.14. In this stage, an innovation is primed to drive a characteristic pattern of cascading impact across many economic, environmental, health, and cultural elements. This impact is generated by solving families of problems across multiple circumstances of use or need in ways that current working paradigms are unable, thereby triggering a cascading effect that constitutes a foundation for business growth and societal advance,. As an example, consider the laser. In and of itself, the laser has spawned new companies and related jobs rapidly after the invention of the device, redefined numerous medical procedures, enhanced our ability to measure distance, to communicate, and to sense the world around us, and altered the way popular culture interprets the future (Solis and Sinfield, 2014, 2015).

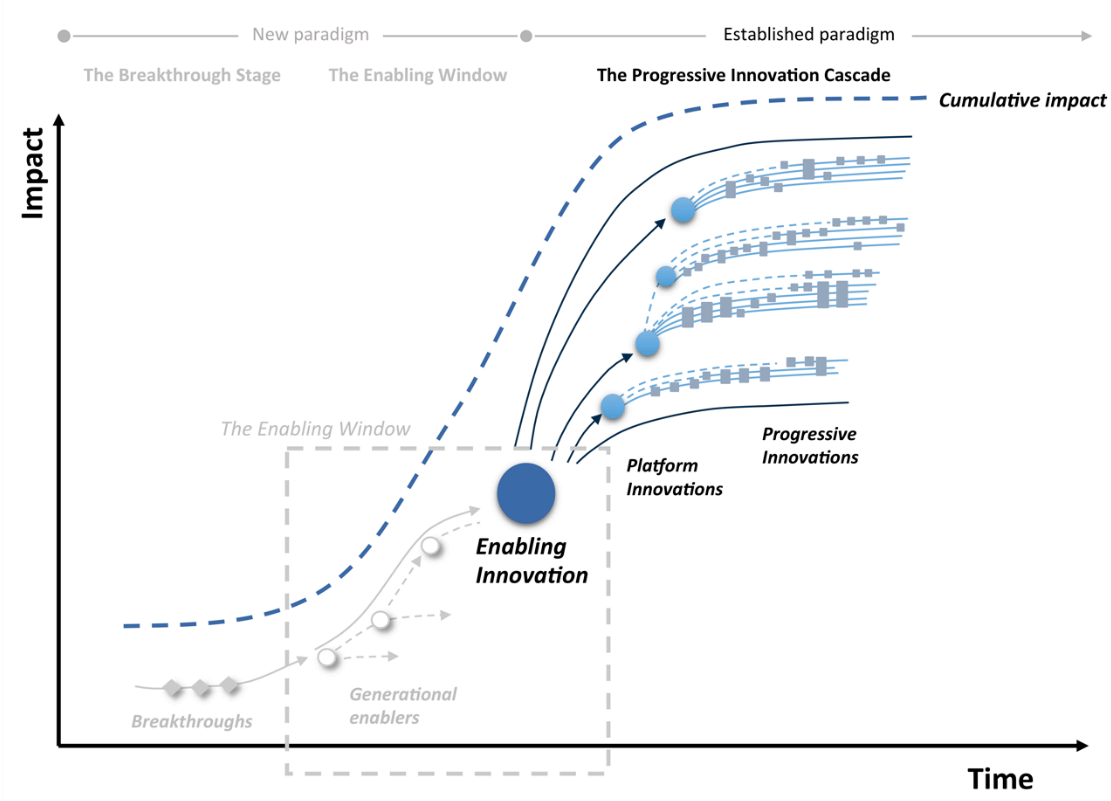


Figure 4.14 The Progressive Cascade

In the progressive cascade, enabling innovations begin to create platform innovations – the application of an enabling innovation in new or combinatorially different solutions to a *meta-problem* (or family of problems). Platform innovations are the first byproduct of the cascading effects of an enabling innovation, because they create a path for a stream of progressive innovations to happen. X-ray machines, for instance, rapidly found platforms across scientific discovery, airport security, medical imaging, industrial radiography, industrial and medical computerized tomography, and astronomy. In these applications, X-rays address meta-problems, such as seeing through objects for diagnosis, scanning, and detection purposes. Similarly, lasers are now used in applications spaces such as electronic data communication, sensing, science, security, counterfeit detection, cutting, welding, etching, and surgery. Through these applications, lasers address meta-problems, such as transferring information, detecting, identifying, and quantifying select aspects of objects and/or substances, and cutting/etching through specific materials. Platform innovations in turn create a path for progressive innovation activity to happen. These innovations exploit a working paradigm (or minor variations of a paradigm) using a broad array of approaches. Such approaches can include (but are not limited to) innovation strategies such as "disruptive innovation" (Christensen, 1997; Christensen and Raynor, 2003; Anthony et al., 2008), and design strategies such as human centered design (Kelley and Littman, 2001; IDEO, 2011). Other approaches include implementation principles such as "the lean startup" (Ries, 2011), and proactive value chain reconfigurations through the pursuit of integrated and modular innovation (Christensen et al., 2004). To date, new progressive applications of the cases analyzed in this work continue to emerge, thus augmenting the long lasting, cumulative impact of enabling innovations. The key characteristic in progressive innovation activity is the tie to a single context of application or a specific pursuit. Ride-sharing for example, solves a specific problem (crowdsourcing transportation) compared to the general (and conceptual) enabling innovation (crowdsourcing activities). Likewise, Lasik, focuses on laser applications for vision correction and new innovations in Lasik technology fall under the progressive domain. For instance, the use of lasers in eye surgery, the technological advances in eye surgery equipment, and the variations in business model that have accompanied such an innovation have historically driven progress across select economic, environment, health, and cultural impact elements centered around addressing vision problems.

This view of the stages of the enabling innovation model suggests that many of the ways currently used to describe innovation fall under the umbrella of "progressive innovations" which drive focused change and impact in only a select number of applications. Whether the type of change is incremental, radical, modular, interdependent, or even disruptive, the characteristic impact of a progressive innovation is limited to a specific problem or family of problems. It is exactly this narrow impact that limits the long term growth prospects of these forms of innovation and why they are a necessary, but insufficient, aspect of an innovation portfolio.

This dissertation does not claim that enabling innovations are more important/valuable than progressive innovations. Both forms of innovation are complementary and a necessary component of society's innovation activity. The enabling innovation model, however, can help one understand whether an innovation is in the breakthrough stage, in the enabling window, or whether it is a platform or progressive innovation in the progressive cascade. The model also highlights the importance of decomposing innovations to understand the underlying enabling innovation that might be underneath, or whether there is potential to amplify the impact of an enabling innovation that is being narrowly pursued as a platform innovation (instead of embracing the possibilities of the enabling window). Effectively, the enabling innovation model is a "meta-idea," which Romer (2007) defines as an idea that helps develop and transmit other ideas – a meta idea regarding innovations that positively impact society in the context of this work, for which specific strategies and behaviors are discussed in Chapter 5 of this dissertation.

4.5 Identifying Enabling Innovations

With this model trajectory of innovation impact in mind, a question arises regarding the characteristic patterns that can help identify/screen enabling innovations and clearly differentiate them from progressive innovations, particularly before they develop. At the core of enabling innovations are patterns that can be organized according to their *impact cascade*, *worldview change*, *affected ecosystems*, *solution architectures*, *problem categories*, and *headroom*, as shown in Figure 4.15.

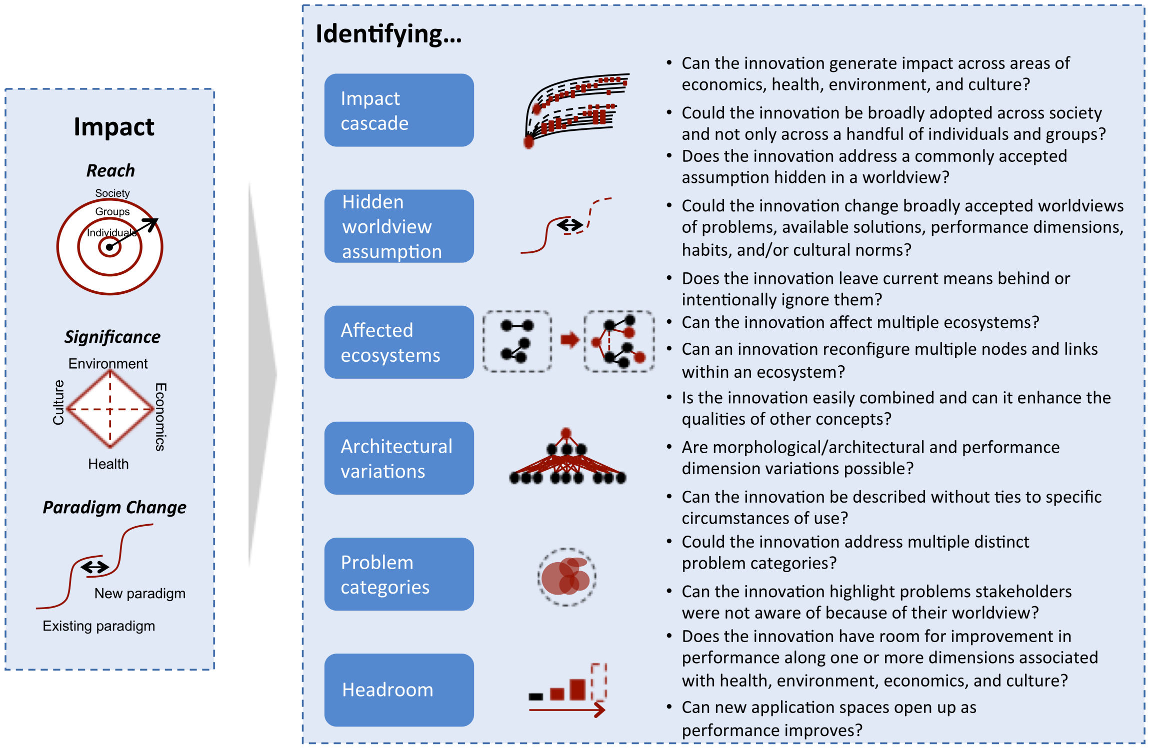


Figure 4.15 Identifying Enabling Innovations

These characteristics integrate many features discussed in disparate schools of thought (reviewed in Chapter 2 of this dissertation). For example, terms such as "generic purpose technologies" (Helpman, 1998) and "enabling technologies" (DARPA, 2010) are used to describe technologies (and potentially concepts) that are complementary to other ideas (thus facilitating many solution architectures). Yet these terms fail to explicitly acknowledge other components of what are herein identified as the characteristics of an enabling innovation such as an impact cascade, worldview change and/or separate affected problems, solutions, and ecosystems. Consistent with the discussion in Chapter 2 – which discussed what an innovation is (and what it is not) – in this work, the language *enabling innovation* is preferred (over technology) because the patterns in solutions meet both characteristics of an innovation: 1) a new or different idea used in practice, and 2) impact. In addition, a purely technological explanation of the introduction of solutions to society (such as GPTs) would in fact ignore many conceptual ideas that are non-technical that could still be considered enabling innovations.

Figure 4.15 also provides key questions to proactively identify enabling innovations. These characteristics and key questions were generated from the synthesis of insights that stem from the enabling innovation model and the cases used to develop such a model. Each of these characteristics and examples that stem from historical case evidence are discussed in the following sections.

4.5.1 Impact Cascade

The fundamental basis for the enabling innovation model is a classification of innovations based on their impact dimensions (i.e., reach, significance, and paradigm change), and of these impact dimensions, the cascade that stems from the reach and significance of enabling innovations is discussed herein. Compared to progressive innovations, the impact cascade that stems from enabling innovations can be identified by answering questions such as:

- Can the innovation generate impact across areas of economics, health, environment, and culture?
- Could the innovation be broadly adopted across society and not only across a handful of individuals and groups?

The enabling innovation cases in Table 4.2 display these patterns in impact outcomes. GPS, for example, has been the source of new firms, improved productivity, has changed the way people understand their environment and the changes that occur within it, has improved measures of emotional health by being able to track goods or avoid the feeling of being lost, and has changed society's navigation habits and culture. In like manner, anesthesia has driven the creation of a new profession, new equipment and drug development firms, improved the economy and affected demographics by improving population health, and has changed cultural norms regarding surgery and healthcare. Predicting these cascading outcomes at the breakthrough stage for future innovations might seem difficult, but understanding the impact potential of an idea without anchors to the current status of a breakthrough can help separate ideas that are truly enabling from those that are progressive.

In contrast, progressive ideas tend to have impact across select elements of significance (economics, environment, health, culture), or reach only a select number of individuals, groups, or societal segments, effectively lacking a cascading effect. A new GPS feature, for instance, incorporating user-generated feedback into a civilian navigation system has only select impact compared to GPS as an enabling idea. In like manner, a new anesthetic method might have focused reach compared to the broader reach of anesthesia as a concept.

As such, if a vision for a cascade (i.e., significant impact and for broad reach) can be created then a concept is more likely to have enabling innovation potential. This vision may be constrained by an idea's current capabilities/performance, which calls for creating visions that are long term, with performance improvement scenarios, and with impact opportunities opening up in cascading ways.

4.5.2 Hidden Worldview Assumption

Also in the impact/outcome spectrum, ideas that are enabling will drive a change in worldview, compared to those that are progressive, which will exploit a working paradigm. A new worldview can likely be identified by answering questions such as:

- Does the innovation address a commonly accepted assumption hidden in a worldview?

- Could the innovation change worldviews of problems, available solutions, performance dimensions, habits, and/or cultural norms?
- Does the innovation leave current means behind or intentionally ignore them?

The historical cases in Table 4.2 also display a change in paradigm. In the case of antisepsis, for instance, historical perceptions of causes of fermentation, putrefaction, and infection in medicine changed from an emphasis on physical properties of an environment (i.e., coldness), to constituent parts of the environment (i.e., oxygen), to foreign elements, before the "germ theory of disease" paradigm was established, as shown in Figure 4.16. Also in the medical field, prior to anesthesia, the solution space in surgery valued/demanded rapid interventions to minimize pain, and the introduction of anesthetics caused a shift to value precision and accuracy as solution space parameters. "It would take a little while for surgeons to discover that the use of anesthesia allowed them time to be meticulous" (Gawande, 2012, p. 1718) As such, surgical skill was likely defined in terms of speed while post anesthesia surgical skill emphasized technique, precision, and accuracy. In another example, lasers re-defined performance expectations across a set of problem spaces such as medicine, manufacturing, and electronics by increasing the precision and accuracy of processes in these fields by several orders of magnitude. Both of these innovations also led to changes in socio-emotional aspects of society, such as the frequency with which surgeries are commonplace in the medical arena and changes to habits in medical procedures, or changes to habits in retail in the case of the laser with the use of barcode scanners or manufacturing with the use of precise cutting.

In contrast, progressive innovations tend to exploit a working paradigm, which implies that current thinking/worldviews, conceptions of problem and solution spaces, and cultural norms and habits are used to shape ideas with innovative potential. Chi and Hausman (2003) hypothesize that the process of fundamental discovery requires re-conceptualizing ontological/fundamental categories. For example, once the "germ theory of disease" paradigm and the use of antiseptic methods were established, finding new techniques (e.g., sterilizing surgical instruments) or equipment (e.g., using sterilized rubber gloves) can be considered a byproduct of exploring an emerging (or working) paradigm.

FERMENTATION AND PUTREFACTION DUE TO THE ATMOSPHERIC AIR.

1. *To Physical Properties.*
COLDNESS.
(500 B. C.-1780 A. D.

2. *To Constituent Parts.*
OXYGEN.
(1780-1876 A. D.)

3. *To Foreign Elements.* (1836 A.D.)
- *Inorganic Substances.*
- *Organic Substances.* GERMS (Conjecture,) (1680 A. D.)
  - *To Spontaneous Generation.* (500 B. C.= 1858 A. D.)
  - *To Pre-existing Germs.* (1861 A. D.)

Figure 4.16 Historical perspectives of fermentation and putrefaction (Clark, 1907)

If a concept has potential to replace or re-define a working paradigm by altering worldviews, then it is likely to have enabling innovation potential. Understanding whether an enabling innovation is driving a change in paradigm or exploiting an established paradigm, however, requires the ability to see a paradigm and create language that paints a picture of these often implicit worldviews.

4.5.3 Affected Ecosystems

Enabling ideas also differ from progressive ideas in the ecosystems in which they can play a role and their effects on the configuration of such ecosystems (or impact spaces). Identifying enabling innovations by their ecosystems implies answering questions such as:

- Can the innovation play a role and affect multiple ecosystems?
- Can an innovation reconfigure multiple nodes and links within an ecosystem?

Most enabling innovation cases that this dissertation focuses on affect multiple contexts/verticals. Radar, for instance, is employed in air and marine navigation, meteorology, object detection and location, speed measurement, and geology, which represent different verticals and ecosystems. Similarly, unit operations affect chemical processes that range from food production to chemical manufacturing. The number of nodes (i.e., the components) or clusters of nodes each of these innovations affects in an ecosystem also varies in quantity. Radar, as an enabling innovation, had to rely on advances in fundamental technology, numerical methods, and the development of a network of radar antennas. A new form of a radar gun or a new type of laser architecture would likely be focused in the number of spaces and ecosystem points it affects.

If the envisioned complexity of the ecosystem change is relatively high, then a concept is more likely to have enabling potential, compared to the ecosystem change required to pursue a progressive innovation. If an innovation only focuses on a select number of ecosystems or ecosystem nodes and links with a single specific ecosystem then it is more likely to be in the progressive domain.

4.5.4 Solution Architectures

Enabling innovations have larger variability in solution configurations compared to progressive innovations. This variability can be detected by answering questions such as:

- Is the innovation easily combined and can it enhance the qualities of other concepts?
- Are morphological/architectural and performance dimension variations possible?
- Can the innovation be described without ties to specific circumstances of use?

If a promising concept can be combined with other ideas for applications across ecosystems then such a concept or a component of a concept is more likely to be in the enabling domain. For instance, lasers can be combined with radar to generate lidar, or with glass to facilitate optical fiber communication, crowdsourcing with microfinance to generate crowdfunding, and X-rays can be combined with computational methods to generate computed tomography (CT) scanning. The result of these combinations are often platform or progressive innovations; yet, if unpacked/ broken down, these platform progressive innovations reveal their enabling components. When the number of idea combination possibilities grows (i.e., the idea space expands) geometrically, identifying ideas for combinations that are likely to succeed becomes difficult (Weitzman, 1998; Brynjolfsson and McAfee, 2014) – which is one of the key challenges of the enabling window. Further, the combinatorial nature of enabling innovations is not only between technical/ technological ideas/concepts, as these innovations are also able to be combined with nontechnical ideas, for example, with new business models, conceptual/categorical structuring schemes, or other types of conceptual ideas.

Similarly, if a concept is highly complementary to other ideas then such a concept (or a component of such a concept) is more likely to be enabling than progressive. However, this complementarity is not often evident, especially when the enabling innovation is artificially tied to a single use or context of application or when seeming performance barriers limit one's ability to imagine applications and combinations. For instance, X-rays and anesthesia were pursued in medicine, yet dentistry was the first field to adopt them. In contrast, lasers were envisioned without preconceived ties to uses and paradigms, and as result were combined with a relatively large number of additional ideas across a broad array of contexts.

Beyond combinations across solutions, if many morphological variations are possible within a solution a concept is more likely to have enabling potential, compared to the morphological variation possibilities of progressive innovations. Lasers can be, for instance, gas, chemical or solid-state, and within the gas lasers, one may find, for example, argon, or CO_2 lasers. Similarly, many fields are composed of unit operations (e.g., petroleum, food processing).

In addition, if a concept can be described without ties to specific circumstances of use (i.e., can be described in generalized, non-context specific ways) it is more likely to be in the enabling realm, since platform and progressive innovations are often tied to specific contexts. For example, “a laser may be used to perform surgery on an eye, but what it is actually doing is ablating material in a precise fashion” (Sinfield, 2005, p. 10). Even if an idea is envisioned for a specific application, its enabling component can be distilled by breaking such an idea down into layers of fundamental building blocks with no tie to a specific context.

4.5.5 Problem Categories

From a problem variants perspective, enabling innovations can address problem categories (i.e., “meta-problems” or families of problems) across circumstances of use or need. In contrast, progressive innovations typically focus on a meta-problem, or a single specific problem within such meta-problems. Questions to identify this aspect of enabling innovations could include:

- Could the innovation address multiple distinct problem categories/families?
- Can the innovation highlight problems stakeholders were not aware of because of their worldview?

If a concept focuses on a specific family of related problems then it is likely to be in the progressive domain. If a concept has potential to address several distinct problem categories then it is more likely to be in the enabling domain. Crowdsourcing, for instance, has addressed corporate problem-solving challenges, financing for the development world, and scientific challenges such as protein folding, all of which are unique challenges. Similarly, the concept of unit operations has been applied to families of chemical processes, lasers have been applied to measurement, industrial applications, science, and object location. X-rays have solved problems in science, medicine, dentistry, and security. In contrast, Lasik, for instance solves problems with vision correction, X-ray crystallography solves specific problems in science.

Similarly, if the innovation highlights problems stakeholders were not aware of because of their worldview, a concept is more likely to be in the enabling domain, compared to established problem categories in the progressive domain. In the case of anesthesia, the problem category of precise and accurate surgical procedures was not defined at the moment of its introduction, since such an innovation was introduced at a time in which speed was a key performance dimension of the problem space. In GPS, many analytical challenges that came along with this innovation that involved geodesic and orbital computations and precise, multi-satellite time stamping were ill-defined before the vision for such a device was created. When an enabling idea is envisioned, however, these ill-defined problem spaces become more tangible and unanticipated challenges associated with the enabling idea emerge.

4.5.6 Headroom

Enabling innovations are also characterized by their scope for improvement, answering questions such as:

- Does the innovation have room for improvement along or more performance dimensions associated with health, environment, economics, and culture?
- Can new application spaces open up as performance improves?

If a concept has headroom for improvement that could eventually lead to new application spaces and an impact cascade, then it is more likely to be in the enabling realm. In the study of generic/general purpose technologies for instance, Lipsey et al. (1998) make a similar inference by arguing that GPTs are characterized by a wide scope for improvement and elaboration. X-rays, for instance, were not broadly applied in medical applications immediately due to the long exposure times required in early conceptions of the device. Similarly, early GPS receivers could only get a signal every several hours which limited it's potential uses, and some laser applications such as fiber optics depended upon breakthroughs both within and outside the laser domain. Yet, performance improvement roadmaps could have facilitated a vision of how broader, large-scale application spaces that were not obvious at first could have opened up with such improvements.

4.6 Chapter Summary

This chapter focused on the enabling innovation model. Because this model classifies innovations by their impact, dimensions of impact (i.e., reach, significance, and paradigm change) were first characterized. The chapter then provided a new classification of innovations, using the terms enabling and progressive to differentiate between two fundamentally different forms of innovation based on their impact patterns. A model that describes the development of enabling innovations over time was then discussed, using historical case evidence to posit the existence of three distinct impact stages: breakthrough, enabling window, and progressive cascade. Each of these stages was then analyzed in depth, outlining key patterns that characterize each stage. Special emphasis was placed on describing two paths for the enabling window: moonshot and enabling lily pads. The chapter concluded with a discussion of possible ways to identify enabling innovations, providing a set of key questions that can be used for their identification and proactive shaping. The following chapter characterizes a framework to realize enabling innovations called "the enabling thinking framework."

CHAPTER 5. THE ENABLING THINKING FRAMEWORK

5.1 Introduction

While the impact of historical innovations that can be considered enabling, as outlined in Chapter 4, may seem obvious, in hindsight, the need and desire to realize enabling innovations that address society's grand challenges triggers the question: *what patterns of thought and action facilitate the systematic pursuit of enabling innovations?* Each stage of the enabling innovation model, namely the breakthrough stage, the enabling window, and the progressive innovation cascade, will require a different set of patterns of thought and action because of their distinct characteristics. However, this dissertation focuses specifically on the enabling window and its boundaries/transitions from the breakthrough stage, and to the progressive cascade – because in this stage in particular there is an often ignored opportunity to make early decisions that shape the future impact of an innovation and influence its timing and potential for success. In addition, the focus on the enabling window complements the innovation literature's focus on what is herein termed the progressive cascade.

This chapter identifies patterns, behaviors, and their relationships when the goal of design activities is to achieve enabling innovation and its characteristic impact pattern. In this research, the phrase *design pattern* refers to a collection of design behaviors and habits of mind (Crismond and Adams, 2012), and *design behavior* refers to the combinations of individual instances/elements of work (Peeters et al., 2007). Even though the enabling thinking framework is comprised of patterns and behaviors, a behaviorist (see Greeno et al., 1999) perspective for the practice and learning of such behaviors is not advocated.

Instead, as described throughout the chapter, many of such behaviors simultaneously call attention to one's own thinking (i.e., cognition/metacognition), actions (i.e., practices/behaviors), and contextual awareness (i.e., situated cognition).

It is important to highlight that the emphasis of this work is on the collection of behaviors that taken together enhance the potential to achieve enabling innovation. Prior research has studied individual design behaviors, such as analogical reasoning (e.g., Ahmed and Christensen, 2009; Ball et al., 2009; Moreno et al., 2013), or subsets of the behaviors described herein (e.g., Dyer et al., 2008). However, the development of a framework that identifies a collection of patterns and behaviors to innovate intentionally, with a specific level of impact, and that is tied to an end-to-end design process model is unique because of the explicit links between (design) approach and (innovation) outcome that are created. As such, the aim of the framework is to "see and organize the space" of innovation behaviors rather than to provide extensive detail of individual behaviors or subsets of behaviors or to zero in on the performance of specific performance task participants (because no individual is likely to display all innovation behaviors but specific insights from each individual can inform the framework).

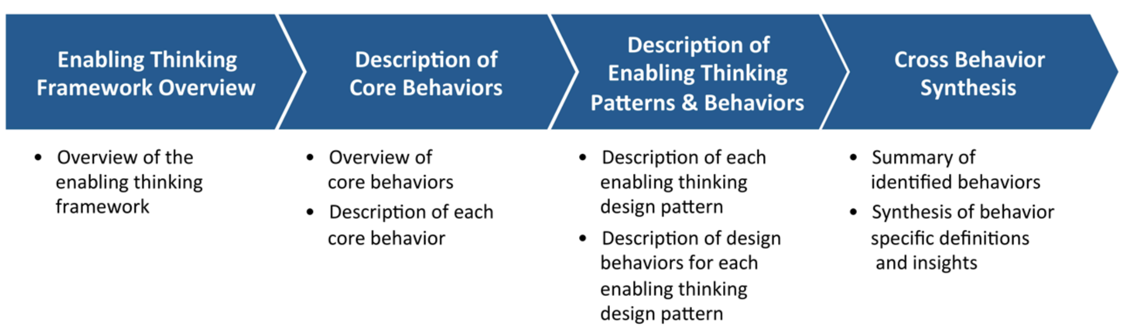


Figure 5.1 Enabling Thinking Chapter Overview

This chapter is organized as shown in Figure 5.1. The chapter begins with an overview of the framework. Then, patterns and behaviors in the framework are described, triangulating evidence from the different methodological approaches described in Chapter 3, i.e., scholarship of integration, historical case research, and verbal protocol analysis of performance tasks, which suggests their existence. Particular emphasis is placed at the beginning of the framework description on characterizing a set of behaviors that are relevant to multiple patterns of thought and action, and are thus considered as "*core*" to the pursuit of enabling innovations. After the description of the core behaviors, for each stage of the design process, a pattern to design for enabling innovation is described and contrasted with *beginner* and *informed* design patterns (described in Chapter 3), followed by a description of its corresponding behaviors. A cross behavior synthesis summarizes all behaviors defined in the study and highlights a set of hypothesized principles/insights for each behavior developed from the study's approaches. The chapter concludes with a summary of the chapter's insights as a means to transition to Chapter 6, where a broader synthesis of findings/insights and the collective implications from Chapters 2, 4, and 5 of this work are provided.

5.2 A Framework to Design for Enabling Innovations

A rich body of work has synthesized the differences between beginner and informed designers, as summarized in Figure 5.2, which groups design process stages into envision, shape, and pursue clusters. This conception of the design process – consisting of the stages of problem definition, information gathering, generation of alternatives, analysis, evaluation and selection, communication, and implementation (Atman et al., 1999, 2007; Adams et al., 2003) – is used as an anchor and organizing framework for such patterns and behaviors and is expanded upon in this work. For each stage of the design process, as well as for two additional stages identified as critical to enabling innovation in this study, i.e., defining a vision and path definition, specific innovation patterns and behaviors with the end goal of achieving enabling innovation are described. Defining a vision herein refers to creating a vision of the outcome of design activities and is herein considered critical to achieving a specific rather than generic type of desired outcome. Path definition refers to designing the implementation of ideas shaped throughout the design process, i.e., creating a set of intended actions to translate ideas into reality, thus creating an intermediate step between the evaluation, selection, and communication of a design/innovation solution and its actual implementation in practice. The framework aims to represent the nonlinear and highly iterative process to design for enabling innovation, with no specific start or end point.

The enabling thinking framework adds to the beginner-informed design school of thought by identifying patterns that are specific to designing for enabling innovation (see Figure 5.3). Patterns unique to the enabling innovation model are identified and described for each design process stage in the enabling thinking framework. The envisioning stage focuses on crafting a strategy for the enabling innovation that provides a guide/roadmap for the innovation efforts. The problem definition stage departs from framing problems to framing flaws in a paradigm, specifically by structuring the ambiguity in paradigms, questioning structured perspectives of a paradigm, and spotting opportunities hidden in paradigm flaws. The gathering information stage departs from researching information considered "relevant" to a given problem, to proactively researching technical, economic, systems, sociological, and psychological forces because all of these issues will influence the success of enabling innovation efforts. The generating alternatives stage departs from generating ideas fluently to proactively broadening idea spaces by connecting generalized first principles. The modeling and analysis stage departs from modeling deep system features to ensuring that a host ecosystem is addressed. The evaluation and selection stage departs from a focus on solution tradeoffs, to an emphasis on matching solutions to application contexts that generate early trial and impact. The communication stage emphasizes the role of persuasion in facilitating acceptance or use of an enabling innovation and its associated paradigm change. The path definition stage generates an implementation plan based on emergent strategy principles with the unique goal of simultaneously unfolding performance, impact, and worldview/paradigm change in the enabling window. Finally, the implementation stage aims to deploy the designed emergent strategy to build an enabling concept. Although variations of these patterns might be applicable to other forms of strategically desired innovation outcomes, the ones herein presented were identified/conceived specifically with the enabling innovation model in mind.

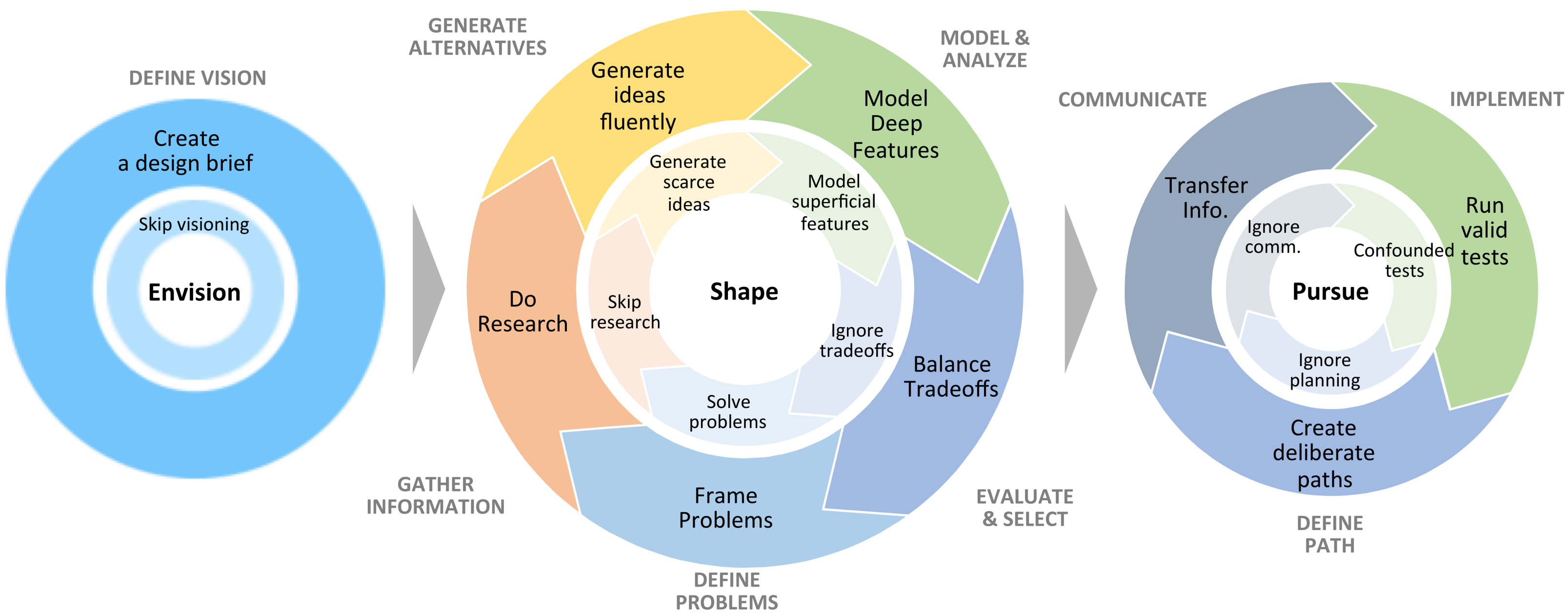


Figure 5.2 Anchor Design Process of the Enabling Thinking Framework

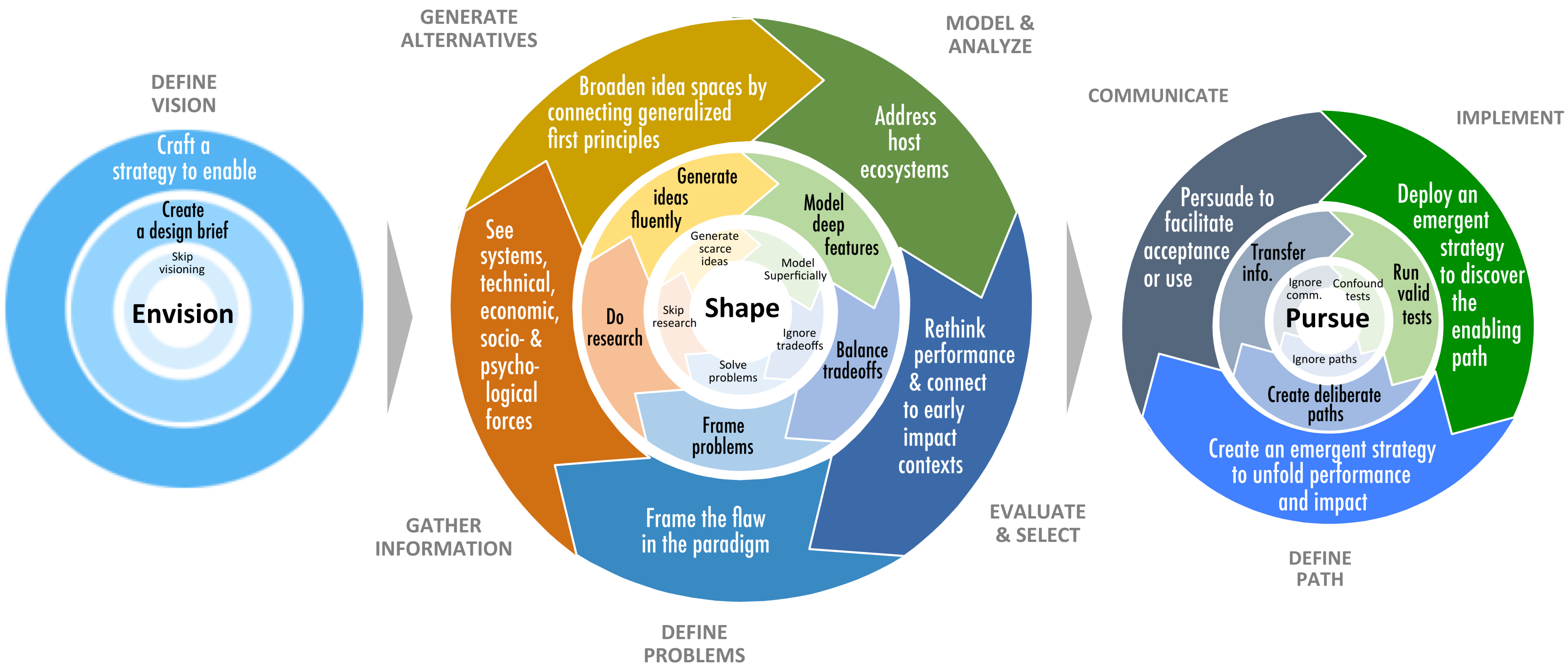


Figure 5.3 Design Patterns in the Enabling Thinking Framework

Further, each of these patterns to design for enabling innovation can be decomposed into actionable behaviors, which will be described in the following sections. Figure 5.4, Figure 5.5, and Figure 5.6 show the breakdown of these enabling innovation design patterns into actionable behaviors for the *shape*, *envision*, and *pursue* design process stage clusters, and Figure 5.7 provides a perspective of the overall enabling thinking framework.

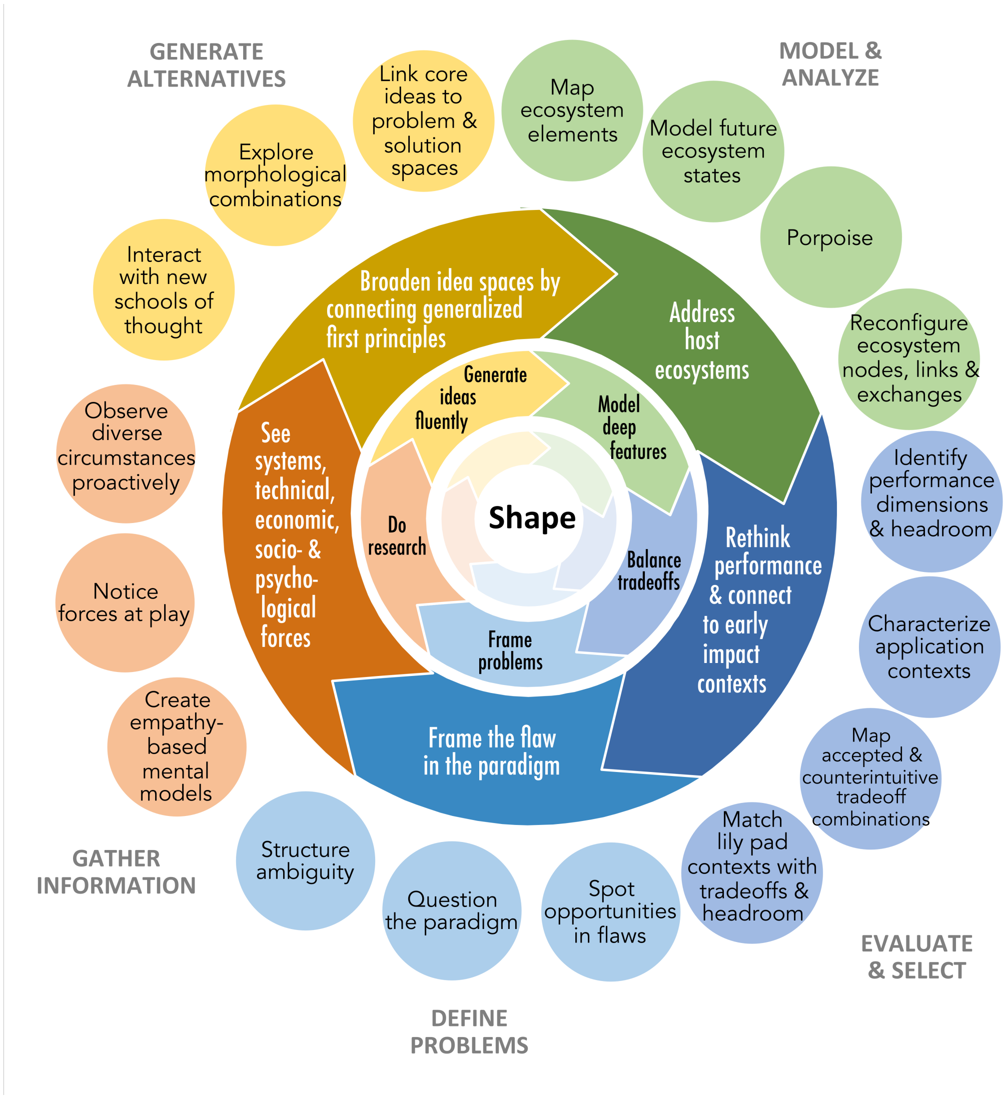


Figure 5.4 Behaviors to Shape Enabling Innovations

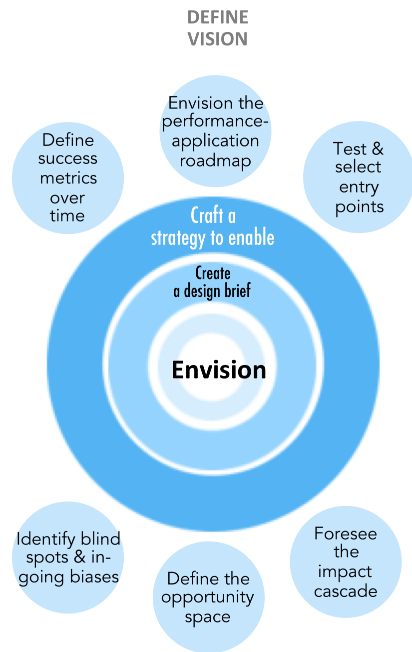


Figure 5.5 Behaviors to Envision Enabling Innovations

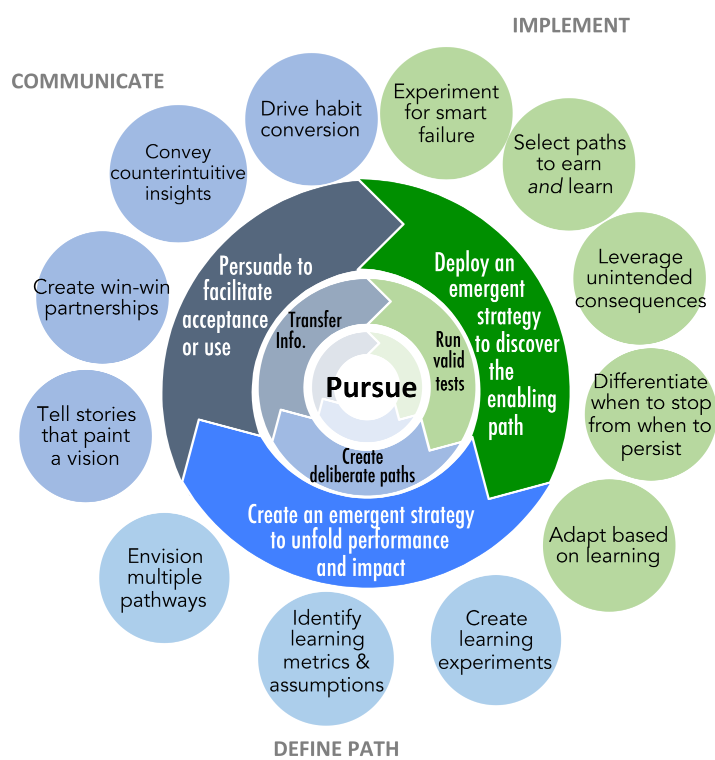


Figure 5.6 Behaviors to Pursue Enabling Innovations

The following sections further describe these patterns and characterize the behaviors that comprise the enabling thinking framework. A set of behaviors identified as "core" because, as described in the following sections, such behaviors are seemingly foundational/critical to effectively employing the patterns and behaviors to design for enabling innovation are at the heart of the framework. Then, for each design process stage, a pattern specific to the enabling innovation model is presented. For each pattern, underlying enabling innovation behaviors are described using evidence from the methodological approaches employed to develop the framework. All relevant behaviors to a pattern are summarized in a table in each section and a synthesis of insights and implications regarding these patterns and behaviors is provided in Chapter 6.

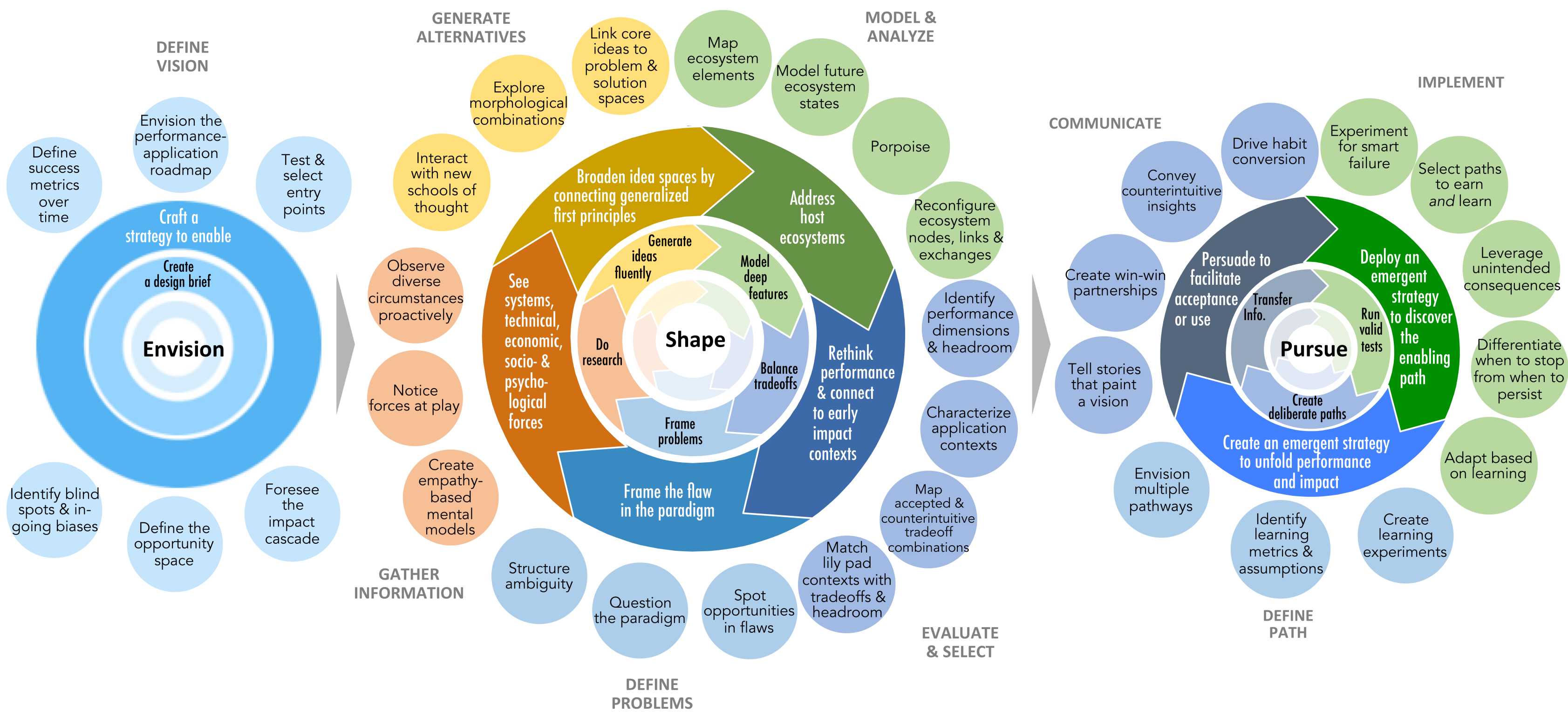


Figure 5.7 The Enabling Thinking Framework

5.3 Core Behaviors

The description of the enabling thinking framework begins with a focus on a set of "core" behaviors, which facilitate the recognition and labeling/naming of patterns related to enabling innovations (see Figure 5.8). These behaviors are labeled as "core" because the analyses described herein suggest that such behaviors are relevant across various stages of the design process (see Figure 5.9). The foundational nature of these behaviors suggests that failing to employ them (or subsets of them) might not lead to the same insights as if these core behaviors were methodically employed.

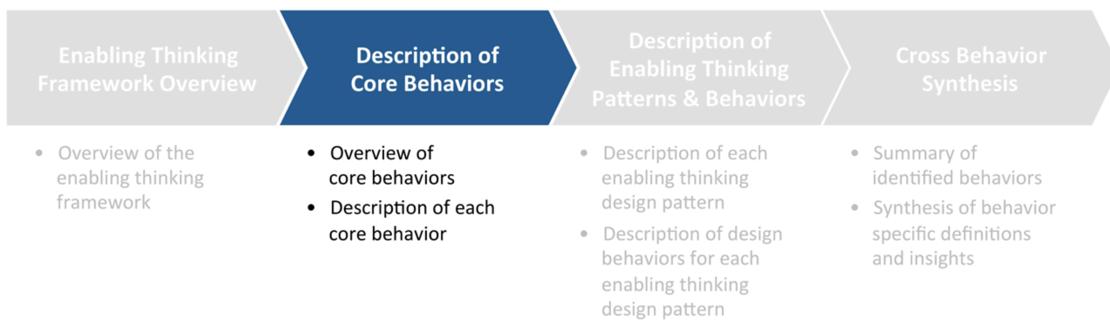


Figure 5.8 Overview of Core Behaviors Chapter Section

This set of "core" behaviors, (shown in Figure 5.10), was identified from the analysis of common themes underlying the actions/principles that seem to govern the behaviors identified for each design process stage (i.e., from problem definition to implementation). (See Table 5.1 for a matrix that qualitatively shows the relevance of the behaviors for each stage of the design process.) The relevance of the core behaviors to the enabling innovation patterns and behaviors will be described throughout the chapter. As an example, the behavior of *diverging-structuring-converging*, which refers to ensuring that one diverges before converging and that one structures/categorizes the results of the diverging process before converging to assess the exhaustiveness/ comprehensiveness of an idea space, can be employed in identifying problems, generating alternatives, analyzing systems, and/or evaluating and selecting solutions.

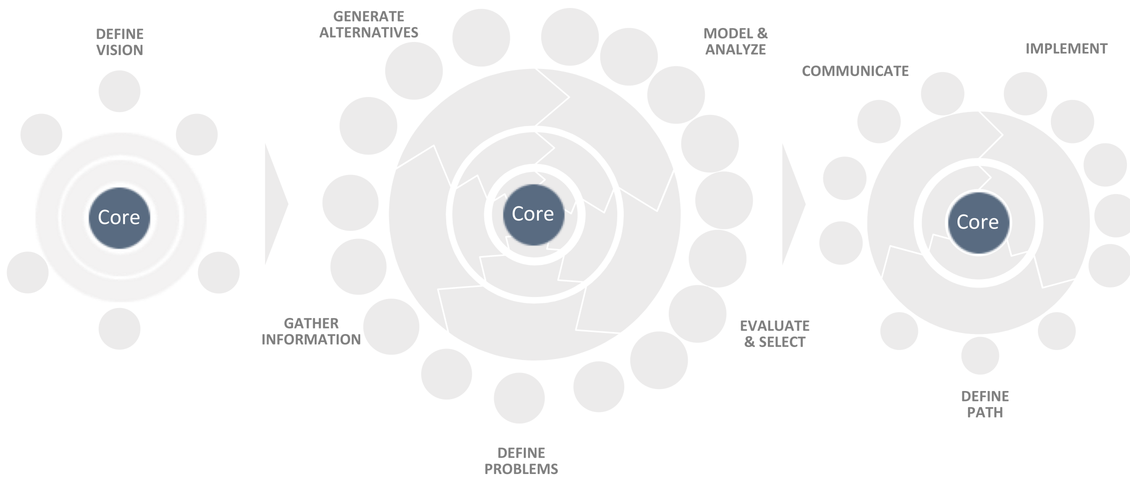


Figure 5.9 Positioning of Core Behaviors in the Enabling Thinking Framework

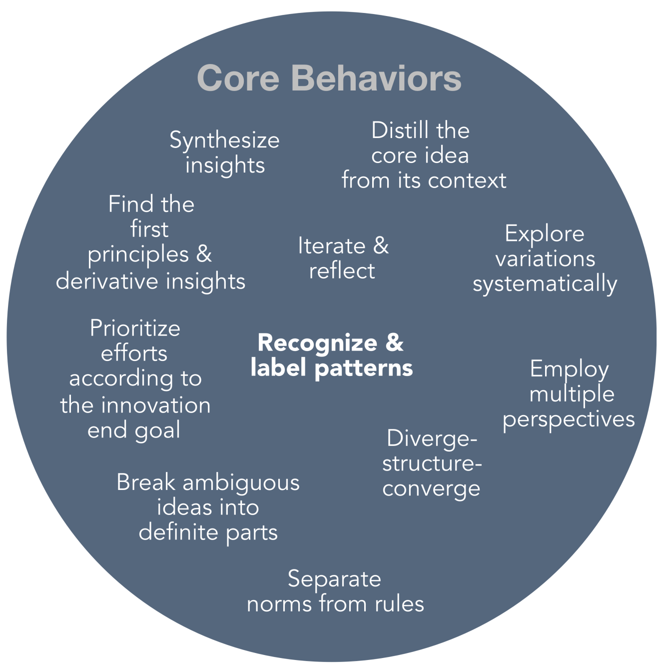


Figure 5.10 Core Behaviors to Design for Enabling Innovation

It is likely important to acknowledge that these core behaviors may also be applicable to generic notions of design activities such as the "informed design" school of thought (thus their separation from the set of behaviors that are tailored to the characteristics of the enabling innovation model). There are many perspectives of design processes, and Atman et al.'s (1999) design process model and Crismond and Adams' (2012) perspective of "informed design" are selected herein as anchors due to their comprehensiveness.

Table 5.2 summarizes the "core" behaviors and the following sections describe each core behavior, highlighting its uniqueness and broad patterns of use. Examples from each of the research approaches are interpolated throughout these descriptions. Effectively, for each core behavior, a definition, a link to enabling innovation, and links to additional/multiple patterns and behaviors are described, triangulating evidence from the methodological approaches to illustrate their existence and relevance. The following sections thus create the foundation of a language that can be used to describe these core behaviors (rather than explore the use of these behaviors in depth). In the sections that provide descriptions of stage-specific patterns and behaviors, however, the use of these core behaviors will be highlighted (rather than their simple description), emphasizing their specific applications across design process stages.

Table 5.1 Relevance of Core Behaviors to Enabling Innovation Patterns

	Craft a strategy for the enabling innovation	Frame the flaw in the paradigm	See technical, economic, systemic, sociological, and psychological forces	Broaden idea-spaces by connecting generalized first-principles	Address host ecosystems holistically	Rethink performance and connect to early impact contexts	Persuade to facilitate acceptance or use	Create an emergent strategy to unfold performance, and impact	Deploy an emergent strategy to discover the enabling path
Recognize and label patterns	●	●	●	●	●	●	●	●	●
Prioritize based on an innovation end goal	●	◑	◑	●	◑	●	●	●	●
Break ambiguous ideas into definite parts	●	●	●	◑	●	●	○	●	○
Separate norms from rules	●	●	◑	◑	●	●	◑	◑	●
Diverge-structure-converge	●	●	●	●	●	●	○	●	○
Employ multiple perspectives	●	◑	●	◑	◑	●	●	○	●
Explore variations sytematically	●	◑	◑	●	●	●	◑	◑	●
Distill the core idea from its context	●	●	◑	●	●	●	○	○	○
Find the first principles and derivative insights	◑	●	◑	●	●	●	○	○	○
Synthesize insights	●	◑	●	◑	◑	◑	●	●	●
Iterate and reflect	●	●	●	●	●	●	●	●	●

Legend

○ Not relevant

◑ Relevant

● Very relevant

Table 5.2 Core Behaviors to Design for Enabling Innovation

Behavior	**Definition**	**Link to Enabling Innovation**
Recognize and label patterns	Assigning a label to a given input stimulus value	Innovation is at a state of pattern recognition in which new ideas likely match prior and novel innovation archetypes
Prioritize based on an innovation end goal	Ordering a list by its measure of importance and its relevance to achieving a specific type of innovation	The strategic pursuit of innovation is defined by critical choices that drive the novelty and impact of an idea
Break ambiguous ideas into definite parts	Breaking down a seemingly ambiguous idea/construct into its constituent components	Breaking ambiguous ideas into more specific parts can help illuminate possible actions related to the innovation
Separate negotiable norms from non-negotiable rules	Separating norms that have been embedded in problems and solutions due to historical precedent from non-negotiable rules which can seldom be altered	Often barriers and opportunities for innovation are hidden in norms that are the result of historical precedent that could be broken in the pursuit of novelty and impact
Diverge-structure-converge	Iteratively generating an array of ideas, structuring them, assessing gaps in sets of ideas, and converging to a solution when appropriate	Idea spaces need to not only be different/novel and satisfice after the generation of a few ideas, but should also need to ensure that all possibilities have been considered before converging
Employ multiple perspectives	Viewing a situation from technical, economic, sociological, and psychological perspectives and selecting what is worth observing	Introducing innovations into an ecosystem call for a thorough examination of issues of a technical, economic, sociological, and psychological issues, effectively calling for multiple perspectives
Explore variations systematically	Exploring variations proactively in the search for ideas and information	Stakeholders naturally gravitate to their usual idea/alternative search process based on their prior knowledge and experience, which calls for proactively ensuring that other, less considered, variations are systematically examined
Distill the core idea from its context	Detaching context-specific language from descriptions of challenges to facilitate connections and understanding across disciplines	Possibilities for the transfer of ideas across diverse problem and solution spaces are often missed due to context-related aspects of an idea, which can be proactively removed
Find first principles and derivative insights	Conducting explorations at different levels of analysis, often at second or third order cause-effect levels to gain novel insights	Barriers and opportunities to innovation are often hidden in second or third order cause-effect relationships that reveal principles or ideas toward new insights
Synthesize insights	Integrating new dimensions of understanding to form a whole greater than the parts	The many issues surrounding an innovation need to be synthesized concisely and effectively for persuasion
Iterate and reflect	Utilizing strategies multiple times as needed and in any order, tracking such strategies and thinking while working	Given its inherent uncertainty, innovation is a highly iterative process that must undergo multiple iterations with a reflective practitioner mindset

5.3.1 Recognizing and Labeling Patterns

At the center of core behaviors, the enabling innovation model, and the framework of patterns and behaviors, is the ability to recognize and label/articulate patterns – particularly those related to innovation. Pattern recognition is herein defined as labeling an input stimulus value based on prior knowledge or information, i.e., “the classification of stimuli into mutually exclusive categories” (Reed, 1972, p. 382).

Theories of pattern recognition discuss “bottom-up” and “top-down” pattern matching approaches (Margolis, 1987; Reed, 2012), and it is herein posited that one can also employ these approaches to identify patterns that drive innovation success. Effectively, many of the “components” of innovation models, such as the enabling innovation model described herein, or the disruptive innovation model, can be used to drive bottom up or top down analyses of ideas. Disruption, as conceived by Christensen (1997), for example, has a pre-determined set of features/patterns. These patterns include an incumbent losing its market position to a disruptor, partly due to an offering with simpler, cheaper, more accessible, or more convenient solution moving up in market position after exploiting the asymmetry of motivation of a stakeholder (Anthony et al., 2008). In like manner, the enabling innovation model described in this dissertation can also be characterized by a set of features/patterns. These patterns include, for example, potential for an impact cascade, many possible combinatorial and morphological variations in problems and solutions, paradigm change, significance across economics, environment, health, and culture, innovation headroom, i.e., potential for use across contexts that emerges with time; and as such, there are many choices that can drive enabling innovation success. Further, each stage of the model – breakthrough stage, enabling window, progressive cascade – has a set of patterns that make success more likely, with each stage likely requiring different combinations of the behaviors described herein to more effectively address/exploit such patterns.

Beyond pattern recognition, labeling patterns (and features of patterns) can help create language that can be used to describe innovations, a language that can (and likely should) be employed among stakeholders working on an idea – which Anthony et al. (2008) make a call for in the business/corporate domain. Crowdsourcing, for example, has been historically employed for many centuries, as described in Chapter 4 of this dissertation. However, the recognition of this problem-solving approach was formalized in 2006 when the pattern was labeled thus giving stakeholders a language to describe such an approach.

Many of the “core” behaviors and design stage-specific behaviors described in this framework facilitate the recognition of innovation patterns (across the many innovation variants). As examples, *breaking down ambiguous ideas into tangible parts* is analogous to pattern recognition methods based on pattern dissection/decomposition. Similarly, *prioritizing ideas according to an innovation end goal* is analogous to the pattern recognition theory which states that recognizing patterns implicitly depends on some features more than others, i.e., a theory of the hierarchy of features in pattern recognition. With this in mind, the behaviors described in the following sections can, if employed proactively, likely help drive pattern recognition of ideas (or features of ideas) with enabling innovative potential.

5.3.2 Breaking Ambiguous Ideas into Definite Parts

Breaking down an idea or a part of an idea that is seemingly ambiguous into a more defined, articulated version of its constituent components helps reduce the ambiguity of an ill-structured space, which is characteristic of the many facets of enabling innovation challenges. Often times a problem is too ambiguous (i.e., ill-defined) or too complex (i.e., with a large “n” and an ambiguous set of connected nodes and links) to be managed without mapping components (Sinfield et al., 2014).

Ambiguous ideas need to be decomposed all along a design challenge, and this behavior, as conceived herein, translates an ill-defined issue into a set of articulated components. Ambiguity can come from many types of ill-defined unknowns, and from a failure to disaggregate these knowledge gaps into manageable and better-articulated parts. For instance, one can disaggregate a problem into its constituent systems involved, system components, stakeholders, and interactions, performance dimensions, or elements of impact. In engineering design, related behaviors are often referred to as functional decomposition (Booth et al., 2013) and backwards design (Burgess, 2012), although such engineering-related behaviors tend have a heavy emphasis on functional/technical issues. Instead, the behavior described herein goes beyond functional/technical issues to encompass other types of issues (economic, sociological, psychological, for instance) while decomposing an ill-defined challenge and articulating/creating language that describes tangible components of such a challenge.

Whether explicitly or implicitly, breaking down ambiguous ideas has played a role in the development of enabling innovations. In their narrative of the early history of GPS, for example, Johns Hopkins physicists Bill Guier and George Weiffenbach illustrate their awareness of the different components of "creating a method to track a satellite from earth based on Doppler shifts" (an ambiguous and ambitious idea at the time of its development):

> *"Within a few days, we were spending almost all of our time on 'the problem.' We did some homework and established the definitions for typical near-Earth satellite orbital elements using published literature from the U.S. effort to launch an artificial satellite during the International Geophysical Year, known by then as the Vanguard program. George had set up a way to digitize the recorded Doppler signals as the recorded WWV broadcast time at which the signal passed through a preset frequency of a high-quality tunable narrow bandpass filter. Bill was desperately trying to establish the values for the orbit parameters in terms of multiple sets of times and distances of closest approach corresponding to multiple passes of the satellite by our antenna at APL… During this time we had lots of help. Some people helped with improving our antenna size and location to get signals closer to*

> *the horizon. Others volunteered to help reduce the data. Several friends checked Bill's algebra and solutions to the elliptic equations of motion. Harry Zink and Henry Elliot became frequent and then regular members of our effort (Guier and Weiffenbach, 1998, p. 15)."*

Similar examples of breaking ideas into tangible parts were observed in the performance task. Don, in his interview debrief, for instance, acknowledged the importance of breaking down and improving the (in his own terms) "concreteness of the problem," stating that the EV challenge is broad, with many moving parts, and likely many underlying problems that the performance task's hypothetical committee was trying to solve:

> *"It's such a broad problem that it's tough to – well, it's potentially tough to generalize – or you're washing out interesting details if you generalize… so one –of the things that I was curious about in the beginning was trying to understand the relationship between EV and the underlying problem that the government is trying to solve. They've got listed here there's economic things. There's energy. There's transportation. There's a lot of different potential things that they could be trying to solve that might lead you to different solutions. So, if it's energy, you might have – you might be able to calculate one benefit. If it's something else, it might be another."*

In another performance task example, Victor decomposed the contexts, types of vehicles, and types of trips in which EVs can play a role, to then think about/analyze each of these contexts separately:

> *"There are three circumstances that I see – and I'm going to try to break this up. And so there's what I would call the urban, suburban, and field. So fundamentally, what I've chosen to do is say, okay, there are personal transportation vehicles. There's heavy transit. And then there's mass transit. And if I look at long transportation, long transportation fits for two basic types of groups, and I'll oversimplify them and call them salesmen and family trips."*

Breaking an ambiguous idea into defined parts is thus likely applicable to many design stages, underscoring the labeling of this behavior as "core." This decomposition activity can occur, for instance, in the study of a problem space, in the development and evaluation of a solution space, in the study of ecosystems/contexts, in understanding the possible impact and/or characteristic dimensions of performance of a solution, or in creating a story that communicates an idea. In an example of a different use of this behavior that differs from the two previous examples provided, Walter, for example, attempted to break down the EV challenge, by creating a list of barriers to be addressed such as range, infrastructure, and cost:

> *"I'm gonna start out by saying it's maybe – current barriers to adoption of the electric vehicles could be cost, could be driving range, and then I'm gonna see if that makes sense – look online just a little bit, just see if those things are maybe barriers. So, see how far electric cars – can travel… There's some of the newer electric cars that are more expensive for the same car than, say, a non-electric car. So, that cost is higher to purchase the car. And then, in the past, I think it is getting better from what I understand, but you don't always have the same kind of range with a car that you might have – you might not be able to go 300 – 400 miles as easily with a charge. The driving range is shorter. And then, I think probably from what I understand of the situation, maybe the biggest challenge is the infrastructure. Right now, there's fueling stations throughout the US. Almost every even small town has at least one fueling station… Some different ideas. So, part of it is just – we have to make sure marketing and education to the consumer."*

5.3.3 Diverging-Structuring-Converging

Many studies highlight the benefits of diverging before converging (e.g., Guilford, 1967, 1971; Pahl et al., 2007; Howard et al., 2008; Lee and Therriault, 2013; Sinfield et al., 2014) in idea generation and others even include diverging and converging as part of their conceptions of design processes (Dubberly, 2004; Beckman and Barry, 2007). Diverging implies being able to generate a broad range of options in response to a given stimulus while converging often involves systematically applying rules or selection criteria to arrive at a single option (Guilford, 1967; Runco, 2010; Lee and Therriault, 2013). These two actions tend to be embedded in every step of a design process, and often go beyond idea generation and brainstorming (Osborne, 1953; Parnes, 1967; de Bono, 1975).

While the diverge-converge process is often highly iterative (going from divergence to convergence and vice versa), in the performance tasks, a select number of participants engaged in an intermediate step that focused on structuring. This exploration of problem and solution spaces also involves diverging and converging in idea generation (Beckman and Barry, 2007; Daly et al., 2012b; Sinfield et al., 2014), yet with a tendency to structure ideas (Minto, 1996; Friga, 2008) in between diverge and converge stages – a behavior herein termed diverge-structure-converge. Effectively, the behavior observed focused on iteratively diverging, structuring, and converging. By creating an organized perspective of ideas considered at any stage of the design process, this intermediate step allowed participants to assess the comprehensiveness of a problem or solution space to then decide if one should continue to diverge to address any identified blind spots, converge, or explore a different area of opportunity as a result of the categorization/structuring process. This diverge-structure-converge behavior/pattern was one of the first steps that, Don, a performance task participant engaged in when exploring the barriers to the adoption of EVs:

> *"So I'm trying to break down the potential barriers to adoption and trying to get some kind of rough categorization and bouncing around kind of as things come up but having a place to slot them, so I can start to see sort of what the structure will be and then likely, after I have an initial list, I'll kind of step back and see a more logical or consistent way to arrange it but, at this point, with having a minimum amount of structure, trying to be as generative as possible."*

This diverge-structure-converge behavior helps regulate the diverge-converge process by testing the exhaustiveness of the idea search space and allows one to consciously ignore rather than unconsciously miss opportunities. The behavior is applicable to a broad array of design stages, for instance, when identifying barriers or elements of a paradigm in a problem definition stage, when ideating a set of solutions in the generation of alternatives, or when identifying possible contexts of application for an idea with enabling potential. Regardless of the design process stage to which this behavior is applied, the underlying theme across the categorization of ideas in between divergence and convergence is that such an intermediate step enables one to assess whether an appropriate next move is to keep diverging or to shift to convergence. Effectively, the benefits of engaging in this behavior are ensuring the expansiveness of an idea space and consciously focusing on opportunity areas that are proactively selected due to being promising rather than simply being "satisficing" (i.e., selecting the first available option that meets a given need or set of needs, as described by Simon, 1996). Performance task participants Mike and Jack, for instance, in their performance task debriefs, described why it is important to not only diverge and converge, but also to structure in the pursuit of expansiveness and focus:

> *"And this isn't exactly very well organized because I have like, funding down there which is not really in the same category as all these others, but then start to think about what are specific ideas within that, and I think it ultimately somehow generated a pretty good list. I think if I had more time, I would go and over time if you're working on this, you'd want to kind-of continue going back to these original lists and be like, "Do I have anything in that category, or do I have anything in this category?" (Mike)*

> *I mean typically – I like to organize my own thoughts, because once you get into the computer, the Web, it's a Web, right, so it tends to divert your thinking quickly. (Jack)*

5.3.4 Prioritizing According to the Innovation End-Goal

In this study, *prioritizing according to the innovation end-goal* refers to ordering a list of issues by each issue's measure of importance and relevance to achieving a specific type of innovation. In the pursuit of innovation, many types of issues need to be prioritized such as (but not limited to) opportunity/focus areas, ideas to pursue, target contexts, critical barriers to address, and implementation steps.

Prioritization with an innovation end goal in mind, whether implicit or explicit, often makes critical choices that can help drive an idea with innovative potential towards success. For example, Anthony et al. (2008) propose a framework for the selection of innovation opportunities based on measures of importance (i.e., how important a need is to an end user), representativeness (i.e., how widely held is a desired need) and satisfaction (how satisfied/unsatisfied users might be with the status quo). In addition, they also highlight the benefits of establishing "goals and bounds" for innovation efforts that can help stakeholders prioritize many types of issues (Anthony et al., 2008). Among these types of issues, the pursuit of business model innovation (Shafer et al., 2005; Johnson et al., 2008; Sinfield et al., 2012) is one that can benefit from defined goals and bounds that help stakeholders prioritize new ideas for such models as "desirable, discussable, and unthinkable" (Sinfield et al., 2013). Similarly, the Defense Advanced Research Projects Agency (DARPA), outlines that the organization has a "dedication to Pasteur's Quadrant" (Dugan and Gabriel, 2013, p. 77) in which all projects must be technically challenging, actionable, multidisciplinary, and far-reaching (Carleton, 2010). Thus, in the context of this dissertation, the behavior of setting priorities is conceptualized as establishing a hierarchy for a given list of issues that aligns with the innovation end-goal.

For the enabling innovation framework in particular, prioritizing according to an innovation end-goal calls for utilizing the dimensions of impact and the impact position of an innovation in the enabling innovation impact curve as organizing guidelines. This prioritization behavior is applicable to many design process stages – from the definition of problems and conceptualizations of a flawed paradigm to the implementation pathways of solutions. Several performance task examples implicitly illustrate this prioritization scheme (because the enabling innovation model has not been yet disseminated, however, the terminology/language described in Chapter 4 of this work is not available to the participants). For example, Ken prioritized focus areas in commuting patterns, trying to identify which area should be prioritized to generate impact within the constraints of the performance task:

> *"So we're going to pick two different commuting patterns. So one is the – two different transportation patterns. One is the commute, and the other one is – what would we call it? General transportation? Driving kids to soccer practice. Road trips. (inaudible). And for the time being, we're going to ignore – we're going to ignore people who drive for a living, so truck drivers, taxis, etcetera, just because I'm not sure I – I'm going to say that – just getting their adoption does not qualify as significant… Because given that – your choice of vehicles by 2018, it doesn't make any sense to focus on long haul trucking, even though potentially, they're a large source of greenhouse gases in a lot of places. So for example, if you're in the State of New York, whatever. Like commuters are great. If you're in the State of Montana, long haul – a lot of long haul trucks pass through your state but don't stop. And they're – they just – you know, they're using (inaudible) to pollute your environment, but they don't fit into the constraints of the problem, so you have to ignore them, because solving long haul trucking doesn't help you drive the electric vehicle adoption of the kinds of electric vehicles specified in this problem solving session. In the same way, like while taxis could have been interesting, because they fit into the kinds of vehicles here, they also don't, in the sense that taxi fleet purchasing happens not – not kind of in a rolling asynchronous basis like people purchase cars. But it happens in large purchases once every seven to eight years, depending on where you are. And likely you've missed your window by 2013. So commercial fleet vehicle purchases, there's too few of them to really think about how to drive significant adoption by then. And B, fleet vehicles generally lag the general market in terms of adopting what's at the latest – at the cutting edge, because of needs around reliability and projectable op-ex costs over the life of that seven to eight years. So there were valid reasons why I picked the markets that I did, and they were based on knowing that the solution was likely not the – it wasn't the easiest place to look, I guess, or it was obviously not a good place to look, in those two cases."*

For enabling innovations, prioritization criteria will likely need to take into consideration the position within the impact curve. Effectively, breakthroughs, generational enablers, enabling innovations, platform innovations, and progressive innovations constitute different end goals in terms of reach, significance and paradigm change, and will likely drive a change in the prioritization of choices. As an illustration, Nicole, in her performance task de-prioritized two of the three available types of electric vehicles, based on the potential for impact in the timeframe specified in the performance task and the paradigm change (in consumer habits) that would need to happen for each type of vehicle:

> *"Interested in pushing two or three, type two or type three [vehicles] and they want success measured by significantly increasing the EV population. It feels like we're allowed type one because that's just not really of interested to the committee and also I'm not sure it really serves as a good stepping stone to other types of EV's because it just feels like it's no better stepping stone to the type two EV then a regular car is because it doesn't introduce any new anxiety, it doesn't solve anything new, it doesn't change any habit, it's just a gas car but with traditional fuel powered. So that's why I would deprioritize looking at how to redrive adoption of number one because it just doesn't feel like it's important to them currently and it - Doesn't feel like it's a good foothold to achieving their bigger goals. And I would deprioritize really focusing effort and investment on number three, on the all electric vehicles primarily because it requires such a fundamental change in consumer behavior and in existing infrastructures with no ability to leverage anything that's existing on the behavior side or the infrastructure side that it's hard to envision achieving the goal of increasing EV adoption in five years. Now potentially in ten or fifteen years you can be moving a lot of people to that third type but it's just going to require a lot of investment and a lot of change. So it just seems like a five year goal directing all of our -Resources and efforts against type three. It's just not going to yield the results we want. Now certainly if there are things that we can do that lay the groundwork for significant adoption of the type three products ten years from now, we should make those investments but I don't think we should put all of our eggs in the all electric basket. So that's what I kind of deprioritize looking there. So then that kind of leaves looking at the vehicles that run on electricity so the electric to fuel like the Volt as kind of where I would put the effort to then really gets prioritized getting deeper on the jobs to be done."*

A perspective of innovation based on impact, thus likely can help stakeholders prioritize ideas based on their impact potential, which is critical for the design for enabling innovation framework given their relatively large scope (or potential for scope if artificial ties to disciplinary contexts are removed). Nicole, summarized this philosophy in her debrief:

> *"I think it's pretty similar to my normal approach because instinctively what I do is I just try to break the problem down into lots of smaller problems. And then with something like this where there are so many different potential areas, try to quickly prioritize what's going to get the most [out of the] effort and then kind of go deep on that. I think as we say, the whole diverge/converge thing, I know I probably converge and problem solving much too fast, too quickly because I want to drive to an answer quickly and test it. And then if it that doesn't work or if it doesn't fully address the problem, then kind of expand. I don't like to languish in let's look at everything that's out there and understand everything about everything. No, 90 percent of that is going to be a waste of time, so I want to as quickly as possibly get down to figuring what's the 10 percent valuable stuff?"*

5.3.5 Finding First Principles and Derivative Insights

The behavior of *finding first-principles and derivative insights* calls for conducting explorations at different levels of analysis, often conducting explorations at second or third order levels of analysis in the search for "first-principles" and using such first principles to derive new insights. The notion of a "first-principle" comes from the field of physics education, in which the term is used to denote a problem-solving approach based on fundamental physical laws (i.e., with few to no fitted/empirical parameters) (Stinner, 1989). Researchers have studied differences in first-principles thinking between novice and expert physicists (e.g., Larkin et al., 1980a, 1980b; Chi et al., 1981). Expert and novices typically begin problem representations with different problem categories. Experts typically begin with initially abstract physics first-principles, and novices base their representation and approaches on literal/superficial features of a problem (Chi et al., 1981). For example, Einstein is often assumed to have constantly engaged in thought experiments to arrive to his fundamental first-principles contributions, such as "what does an electromagnetic field look like to an observer riding on a beam of light" to arrive at relativity or the behavior of “gravity in an elevator in space” to arrive to the equivalence principle (Stinner, 1989, p. 602).

Finding opportunities and barriers to innovation can involve this type of reasoning, i.e., conducting explorations at non-superficial levels to search for opportunities and barriers to innovation hidden at a “first-principles” level of analysis. In the context of technological invention, Arthur (2009), makes a similar argument, emphasizing that: “technology always proceeds from some central idea or concept… I will call this the base concept or base principle of the technology,” that “technology consists of building blocks that are technologies, that consist of further building blocks that are technologies” implying recursive patterns and that invention (not innovation) often begins with a “change in base principle” (Arthur, 2009, p. 276-277).

Historically, one can see this search for first-principles in multiple enabling innovations (especially in the breakthrough stage) that led to new cause-effect possibilities and insights. For example, in the history of microfinance, Muhammad Yunus found a first-principles answer – a new financing/banking model – to the question “how can the poor break out of a cycle of poverty?” (Yunus, 1999) by diving deep into the life of Bangladesh farmers, the farming value chain, and the operations of traditional banking organizations. Similarly, in the case of the laser, Charles Townes searched for new physics first-principles – a method to build devices based on the stimulated emission of radiation – in response to the thought experiment of “how can one work at shorter [than centimeter] wavelengths?” (Townes, 1999) by diving deep into underlying physics theories and assumptions such as the influence of thermodynamics and the energy levels of particles. (Note that these “deep dive” explorations seem to be often guided by the behavior of *questioning a paradigm*, a separate behavior which is described further along in this chapter that likely triggers the search for solutions from first principles.)

Because enabling innovations involve a change in paradigm, the search for first-principles calls for explorations at different levels of depth. These explorations consist of explorations at deeper levels of analysis, because status quo norms and/or information are often the third (or higher) order effect of prior assumptions (and thus likely superficial instead of deep) – and the first-principle is often hidden underneath such effects. Finding the first principles therefore involves decomposing a challenge into its systemic components, exploring components using an intuitive understanding (deductive), zooming into components and exploring cause-effect relationships at subsequent levels of analysis until returns diminish, often drilling down to actionable levels of detail. In the performance tasks, for example, participants often started with the status quo of issues related to the adoption of electric vehicles and searched for first-principles that could lead to new insights. In the context of innovation efforts, finding a first principle provides one with the ability to imagine new second or third order effects, building from such a first-principle to arrive at ideas that are different from the status quo. In the performance task, for instance, Victor discussed second or third order effects from the first principle/fact that EV charging stations must be economically viable/sustainable, particularly as EV adoption and EV infrastructure increase:

> *"The recharging stations have got to be metered and paid for. So how would that work? So I'm now looking at metered parking. Yes. I have meters today. My parking expense goes up slightly, because not only do I have a space, but I'm also getting charge benefits. So if an – so if the parking has to – has to make a capital investment that pays out. Okay. By charging for the recharging. All right. So whatever parking facility is, be it private or public, they got a capital investment that has to pay out in order for them to do that. Okay. So that says that I have to have a electrical system, which they all have, but I have to add lines and dual meters. Because I'll have a meter for – or I'll have some form of parking for the space, and then some charge for the car. It's doable. And it must be convenient, because I don't want to have to get out and double plug a car in or do some other wacky stuff all the time. When I go to a parking garage now, I pull in, I take a ticket, I park the car, I get out. Depending upon where the place is, I either pay before or after, using my credit card. You know, so how am I going to – the extra step is going to be an important issue or concern. Because if I forget to plug it in,*

then I still have that same problem, unless I use the backup. Okay? And so that gives me a choice, but it's got to be a pretty convenient plug in, and it has to be enough of them for me to be able to use it. And so this is going to be – so these parking places will have some phased type of offering, because they're not going to do the whole place. They can't ever get it paid back. So there has to be a way that they – that there's enough incentive for them to want to have at least as many chargeable areas as non-chargeable areas, so that they can maximize their return. That's how that's going to work, because otherwise, it won't work. So if there isn't something in the parking facility for them to make money and make it pay out, they'll never do it, or they'll never do enough of them to drive us where we need to do."

Finding the first principles is thus considered herein as a "core" innovation behavior because it can be used to drive ideas in multiple stages of the design process, for instance the systems domain, the problem domain, or the solution domain. For example, Victor focused on finding first principles from a solution perspective, another participant, Rand, in his interview debrief, stated that he would employ this behavior to probe on the EV challenge brief and find the underlying problem that people are trying to solve:

Well, my first thing – thought was the prompt kind-of says we need more EVs, how do we get more EVs. I'd say wait, why do we need more EVs. Whether I disagree or not, I've – I think EV is probably a good thing to have, but I'd still ask that question and really try to get down to the bottom of are EVs even the solution to this problem, and if so, what are the problems that EVs are solving, right? And that would be the first thing I'd do is really try to figure out why. I mean, because essentially the problem says here's a solution, how do we get there, I'd really find that, OK, thanks for the solution, but is that really the solution we want, what's the real problem.

5.3.6 Separating Negotiable Norms from Non-Negotiable Rules

Separating negotiable norms that might have been embedded in problems and solutions due to historical precedent from non-negotiable rules that cannot be altered can lead to new insights throughout the entire design/innovation process. These insights can include new perspectives of problems, information, alternatives, tradeoffs, systems, solutions, and implementation issues. Often times, assumptions are deeply embedded in historical worldviews of these types of issues, without awareness or an explicit rationale for their existence, which can hinder the adoption of ideas with enabling potential. Thus, this behavior calls for making such assumptions explicit, and proactively exploring which assumptions are byproducts of historical norms rather than absolute necessity.

Historical cases of enabling innovation illustrate how negotiable norms were overcome to facilitate the development of enabling innovations. Speed, for example, was an assumed performance dimension of surgery, deeply embedded in the medical paradigm due to historical norm rather than absolute necessity, which slowly changed after the introduction of anesthesia. In the case of microfinance, an assumption about the poor being unbankable prevailed for many centuries according to conventional banking practices, when in reality all that was needed was a new business model. In the case of the laser, and more specifically it's predecessor, the maser, the second law of thermodynamics (a non-negotiable rule) and its application to collections of molecules (a negotiable norm) for stimulated emission were confounded. As stated by its inventor, Charles Townes (Academy of Achievement, 1991):

> *"what was on my mind was that we had a meeting coming up of a group of scientists and engineers who'd been trying to find ways of producing short waves… I'd tried a lot of different techniques… So I went over the things that wouldn't work, why they wouldn't work. And I recognized, well, if it's ever going to work, we're going to have to use molecules. Because molecules already made by nature, very small, they resonate at these high frequencies or short wavelengths, we just somehow have to use those. But of course I'd thought about that before too. And concluded from what's known as the second law of thermodynamics, that if you have a batch of molecules and you heat them up, yes, they will radiate, they will produce these waves, but they won't produce very much, because you heat them up enough so they begin to produce a lot, and then the molecules fall apart. So I dismissed that before, and it wouldn't work. But this time, I thought, well, if it's ever going to work, it has to work that way. You've got to get molecules, but yet it has this problem of the second law of thermodynamics. And it suddenly occurred to me, now wait a minute. One doesn't have to obey the second law of*

thermodynamics. That's when all the molecules are interacting and exchanging energy and so on. We can keep the molecules from interacting, so we can have some molecules with a lot of energy, other molecules with not so much energy, throw away those, and then we've got a collection of molecules with high energy only. And now we use what was Einstein's idea, that always occurs if you have molecules or atoms with excess energy. If a wave comes along that resonates with them, sort of tickles the molecules and resonates with them, they will give up their energy to the wave, and the wave then passes by and picks up some energy. That's called stimulated emission"

In the performance task, many participants identified negotiable norms, i.e., norms that are often assumed as rules across many aspects of the EV challenge. For example, Drew acknowledge the possibility of separating battery from car as a possibility for EV adoption, drawing from a recent business effort to foster adoption:

"So the second one is then the convenience, and convenience says that I have to change this battery, but that's for me as – that's for me equal as it is, for example, going to a fuel station. So if I find a way to replace the batteries, I think that should be possible. There is this guy in Israel, what was his name again? … But the idea he had was quite interesting. But he said, I have to separate battery from car."

This proactive separation of norms and rules can also happen at the ecosystem level. Nicole, for example, identified negotiable norms in the automobile value chain, specifically the assumption regarding the historical role of dealerships:

"Thinking specifically around the distribution model and is there a way to kind of scrap this dealer concept? Because the dealers, it's such an embedded distribution system that has all of its own baggage and own cost structure and people who are used to selling certain fueled vehicles in certain ways that is there a way to change it?"

Often times these assumptions are hidden implicitly in ideas, which reinforces the need to be proactive in explicitly creating an inventory of norms or rules to be challenged by exploring them in more depth (i.e., searching for first-principles). Ken, for example, argued for smaller, more interactive/intelligent (almost autonomous) vehicles, implicitly separating the norm that a human needs to drive a vehicle and that vehicles need to fit "n" number of people:

> *"So I guess if you start at the increased utilization, right, so what does an electric vehicle need to do? It needs to fit that commute pattern properly. It actually needs to increase the efficiency of not just my commute, but everyone's commute. So I need to be able to pack more people into less space, and potentially move them more efficiently. So – and not to go crazy in the future, what that probably means is you need cars that regulate pace as well as cars that are smaller. So from a physical footprint perspective, an electric vehicle needs to enable car to car communications, and it needs to enable – they actually literally need to be smaller and more efficient."*

5.3.7 Distilling the Core Idea from its Context

A key aspect of the enabling innovation model is the creation of an impact cascade, which often stems from an innovation's ability to play a role in multiple contexts, which, in turn, is driven by stakeholders being able to make such connections. One could argue that in many historical innovations, thinking of ideas broadly, i.e., without specific ties to a specific application or context, might drive consideration of a more comprehensive set of possible application spaces and help make more connections within/between such spaces. The laser's initial set of applications, for instance, were described as: "true amplification of light, probing matter for basic research, high power beams for communications, concentrating light for industry, chemistry and medicine" (Hecht, 2010). Thus, envisioning broad areas of application helped stakeholders avoid artificial ties to narrowly defined contexts, and facilitated connections of the invention to a multitude of specific applications, such that, within a year, many new laser applications appeared in physics, medicine, and communications.

With this in mind, distilling the core of an idea from its context implies detaching context-specific language from descriptions of ideas to facilitate connections and understanding across fields, effectively separating core idea from circumstance. Engaging in this behavior can help stakeholders understand the broader potential of ideas, because new ideas often get rapidly associated with a circumstance of use, and such associations are often difficult to remove (i.e., they become deeply embedded, albeit negotiable, negotiable norms). Yet, by removing artificial ties to a circumstance, one can understand their essence, i.e., the “jobs” that ideas truly address. This behavior is at the center of tools such as the generic parts technique (McCaffrey, 2012), which aims to overcome functional fixedness (Duncker, 1945), i.e., the tendency to fixate on the typical use of an object or one of its parts. Sinfield (2005), for instance, suggests a framework for technology assessment in which he calls for going beyond current or expected market applications to understand what technologies really address: “[f]or example, a laser may be used to perform surgery on an eye, but what it is actually doing is ablating material in a precise fashion” (Sinfield, 2005, p. 10).

This behavior is identified as core because separating core ideas from their circumstance can be complementary to many patterns and behaviors in the framework. Flawed paradigms, for example, can stem from associations to context-specific circumstances and identifying such flaws can come from removing such associations. Problem and solution identification can also be re-framed, with opportunities to trigger novel insights, when circumstance-specific details are removed, facilitating, for instance, the generation of analogies between core ideas. Distilling the core of ideas from contexts of application and specific circumstances within such contexts can also complement other “core” behaviors. For example, distilling the core of ideas can facilitate the separation between negotiable norms and non-negotiable rules by helping one examine concepts at a generalized level thus removing ties to a context that might be embedded with negotiable norms.

In the performance task, some participants engaged in this behavior and tried to separate EV adoption from its underlying core goals. Victor exemplified this action while explaining how the number of EVs adopted is a proxy for the reduction of fossil fuel consumption:

> *"So if I'm – so I'm now going to just kind of tease these apart a little bit, because understanding what a soccer mom vehicle needs to look like is where I would then really want to understand. What is the job to be done? Who is this group? How are they really going to use that, and how many miles – you know, is this going to meet our need? Because the issue, as I kind of come back to the task that I'm wrestling with, is we're really trying to reduce our use of fossil fuels. And so the number of vehicles is actually just a measure. An interim measure in an attempt to reduce the miles, reduce fossil fuel. And so the real – my take on this is, is what we're really trying to do – the reason that we want to increase the adoption of electric vehicles is we want to reduce the use of fossil fuels. And so are we using more fuel in commuting or in running around town? And so I need – I would need to go in and do an analysis of what each of those are."*

Similar to Victor's translation of a context-specific problem to a more generic type of problem, Sam also illustrated this behavior when he stated that he perceived the EV challenge as one primarily involving incentives and the reconfiguration of supply chains:

> *It's really quite remarkable. Well, what's going on there? What's going on there are cultural sort of concerns about is this thing as safe as another automobile? You know? If you go look at them, they're actually amazingly simple. I mean, they really are. And again, looking at economic barriers, I study food policy, and I'm interested in how you incentivize fruit and vegetable consumption. Well, a lot of these are the same things. How do you incentivize EV? If I could walk into a store and I could choose between an EV and a non-EV that costs the same amount of money, and one runs $1.00 a gallon, one runs $3.00 a gallon, I know exactly which one I'd buy, as long as it had the range and there was a recharging system… And can you imagine what the oil companies think of home recharging? They're probably scared shitless. You know? Look at the economic loss to the oil companies around gas stations. I mean, if we can all go home and plug in. In my field, we used to have things called travel agents. How many travel agents are left in the world? Very few. They do specialized work around either corporate or group visits or whatever. But it used to be if you wanted to – if you wanted just to get an airplane ticket, you called a travel agent and you paid 20 bucks*

> *extra. We don't do that anymore. Well, you can see the same kind of huge, huge upheaval of change in society with the lack of – the lack of gas stations. What about the change in the supply chain? I mean, Tesla's proposing that we don't have auto dealers anymore.*

Distilling the core of ideas from contexts also helps identify solution components and analogies by making connections between seemingly unrelated ideas. For example, Ken, when describing a hypothetical car that would allow more efficient commutes made an analogy to a map-based application, the underlying idea behind it and how it would apply to EVs:

> *"Do you know what Waze is? So Waze is like a real time mapping service. So Waze is a real time mapping service. It's kind of like Google Maps, but people create their own maps. And what that's enabled the service to do is to understand, by aggregating people's maps, what the best routes are. So there's a – there's also a – there's a data service – communications between cars, but there's also a – also an important analytics piece around increasing efficiency of someone's commute. And this isn't restricted to electric cars, but it's important."*

5.3.8 Employing Multiple Perspectives

Employing multiple perspectives refers to the intentional use of using multiple perspectives to observe a situation. Perspective taking is a cognitive process in which individuals adopt other viewpoints in an attempt to understand new preferences, values, and needs (Parker and Axtell, 2001). Many frameworks throughout the literature advocate for a "multi-perspective" framing that facilitates the discovery of underlying issues in an innovation. Anthony et al. (2008), for example, emphasize the benefits of employing functional, social, and emotional perspectives. Similarly, Kelley and Littman (2005), argue for multiple roles for innovation endeavors, which they call "faces of innovation" (e.g., anthropologist, cross-pollinator, hurdler); while DeBono (1985) calls for "six thinking hats" to be employed in decision-making and creative thinking.

In the enabling innovation framework described herein, five types of perspectives are argued as "core" to any innovation effort: the technical lens, the economic/business lens, the systems lens, the sociological lens, and psychological lens. Each of these lenses has broad ramifications, some of which will be more relevant in a given challenge. Technical issues are those related to a particular subject, art, craft, techniques, and their systems. Economic issues are those related to the processes that govern the production, distribution, and consumption of goods in economic systems. Sociological issues are those related to the development, structure, and functioning of human society and their influence on societal behavior. Psychological issues are those related to the mental states/functions and behaviors of stakeholders.

In enabling innovations, this broad array of issues should be proactively considered because challenges and opportunities for this type of innovation often go beyond technical issues to encompass economic, sociological, and psychological issues. For example, in the history of modern microfinance, Prof. Muhammad Yunus, when developing the concept of the Grameen Bank, one of the first modern microfinance institutions, had to gain insight into these multiple types of issues. Such issues included new loan procedures for villagers who could not read, group/team loans to address transaction costs, community sessions to build trust, mitigate fear of loans and ensure repayment, and addressing gender roles in communities that encouraged women to become part of the bank (Yunus, 1999).

Employing different perspectives implies understanding stakeholders, objectives, and circumstances, systems, problems, and solutions, shifting perspectives proactively (another core behavior) from one area of emphasis to another (i.e., from one type of force to another). Don, for example, understood the different outcomes desired by a diverse set of stakeholders and explored each of them with a different perspective:

> *"Maybe one where people were in urban areas where, A, they're not traveling far. So EVs become attractive because – there's fewer or no issues of range anxiety and the second piece is they probably have more access to charging stations. So, again, just mitigates the range anxiety, which is a historical barrier for EVs. So these are kind of – so this is a segment that's really defined by – so there's a couple of different things mixed in here. So this segment is defined – is high potential because it has a job – like a major job, which is reduce my cost. This [environmentally conscious] one is – because they have lower barriers because of their circumstances. They don't have this barrier of anxiety. There might be another job related to people. It's not necessarily specific use occasion, but it's people who are environmentally conscious and so they have a job of sort of social responsibility or something. Whether that's image or they really care about the environment doesn't particularly matter, I think, at this point."*

With so many possible areas of focus in information gathering activities, there needs to be special consideration of the lenses that are relevant to an innovation challenge. Often times, frameworks (and combinations between frameworks) help understand specific areas of focus and thus some frameworks will naturally be more useful in specific circumstances. Mike, for instance, employed functional, social, and emotional (as described in Anthony et al., 2008) lenses when exploring "barriers to consideration" to the acquisition of an EV (a stage in the "purchasing funnel" marketing framework):

> *"Barriers to consideration, barriers to consideration so I am aware of it but I'm not really buying it. Basically the – your perception is the pros outweigh the cons. Maybe they're – and I – that – the problem is that's bucketing a lot of different things. There might be like, social reasons, there might be functional reasons, there might be emotional reasons. And then if I think about misperceptions, I need to know what the misperceptions are. That's something I could probably help research but I think it's basically that – they're too slow, not powerful, negatives of being a user. So what are the negatives? There might be social, there might be like you're made fun of for using it, there might be too expensive, I mean, relative to like, taking public transport. There might – why else would you not like it? It's just that it's not as good in ways that matter, that seem to matter."*

5.3.9 Exploring Variations Systematically

At the center of many creativity and innovation frameworks is the behavior of systematically exploring variations to uncover new or different ideas. For example, Brynjolfsson and McAfee (2014) call for combinatorial innovations, the ability to combine innovations with other ideas, TRIZ and morphological analysis (1984) call for proactively exploring reconfigurations in ideas, and Adner's (2012) wide lens framework calls for adding, subtracting, or combining elements of ecosystems. Underlying these and other frameworks are systematic explorations to explore new idea combinations, morphological variants, and potential system reconfigurations.

Exploring variations should thus happen systematically (rather than haphazardly) while searching for ways to depart from the status quo and intentionally explore new possibilities. These variations in an idea or information search process can consist of, for example, opposites, intersections, combinations, adjacencies, reconfigurations, reductions, or additions.

Exploring variations systematically is herein defined as a different behavior than *employing multiple perspectives*. Employing multiple perspectives helps one select among the different types of "qualitatively different viewpoints" on a given set of issues. Exploring variations systematically can help one ensure that the search for ideas within such viewpoints is exhaustive by considering multiple types of idea search paths/channels are, and that one is not fixating on one particular category of variation/reconfiguration. Effectively, systematically exploring variations implies becoming aware of the direction of the shift/change that new ideas embody (relative to the status quo) and proactively exploring additional directions (e.g., opposites, intersections, adjacencies, combinations, additions, subtractions) to ensure a comprehensive search throughout relevant idea spaces.

Throughout history, many enabling innovations have been realized through (explicit or implicit) directional variations. As an example, in the history of GPS, a directional change in perspective, specifically by considering exploring the opposite or inverse of a solution, helped Frank McClure, a Johns Hopkins program manager, realize the potential of Johns Hopkins physicists W. Guier and G. Weiffenbach's satellite tracking solution – i.e., tracking an receiver on earth from a satellite in space instead of tracking satellites with receivers on earth.

In the performance tasks, many participants systematically explored variations (e.g., Ken, Victor, Nicole, Don). Ken, for example, proactively systematically explored variations throughout his performance task in which he was considering alternative car sharing business models. These shifts ranged from the way people commute and conduct leisure trips today, to a new car sharing business model according to travel purposes that shifts vehicle acquisitions from a capital expenditure (cap-ex) model, to an opposite operating expenditure (op-ex) model:

> *"Because it doesn't make sense for the Joses to buy giant SUVs all the time, to drive all the time, when they're not going to be driving them all the time in that use case. And at the – on the other end, it really doesn't make sense for Fred to own a car at all. And there has to be a way to create an asset shift where Fred's kind of pay as you go model, which is ideal for him with regards to using the car to run errands, helps make Jose's transition to what is essentially using more the one kind of vehicle – today I'd be owning two cars – more economical for him, which is where you kind of end up with this kind of financial intermediary that gives Jose a car every day of the week… From car manufacturer to financial intermediary/rental company, this cap-ex to op-ex, this is the result of this (inaudible) transfer"*

Similarly, Nicole focused on systematically exploring variations to identify new ideas for dealership systems, articulated their functioning and benefits, and expressed her intent to explore variations in distribution and business models:

> *"Thinking specifically around the distribution model and is there a way to kind of scrap this dealer concept? Because the dealers, it's such an embedded distribution system that has all of its own baggage and own cost structure and people who are used to selling certain fueled vehicles in certain ways that is there a way to change it? And it's tough because there are certainly benefits to the dealer network in the same way that gas stations are everywhere. And if you need one or not you've kind of always known where one is because they advertise so heavily and their signs are all over. So there are certain benefits to it but I wonder if there's a way to not be captive to it? You could potentially have a business model that looks very similar to the current business model; you use the dealers. But are there ways to change that up whether it's through retailing the way Tesla has, which actually could lay the foundations for paving the way for all electric vehicles. Because I'm sure if GM and Ford and the big guys got into retailing, then it wouldn't just be Tesla against the legislative - Legislators, it would be the auto industry against the law makers and it probably would be half the fight that it currently is because of the embedded lobbying of the big auto makers."*

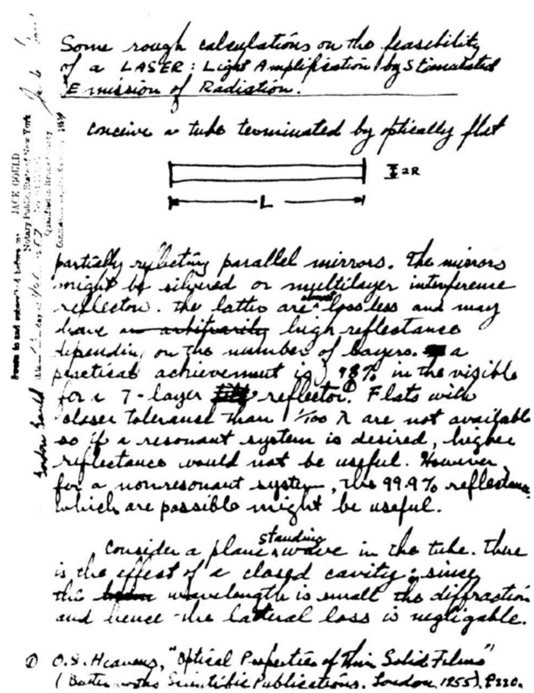
Exploring variations systematically implies conducting explorations even for ideas that might seem counterintuitive. Rand, for example, explored an adjacent idea space from incentivizing consumers directly to incentivizing the media to disseminate EVs (likely, but not explicitly mentioned, in an attempt to change culture):

> *I'm trying – well I'm just trying to think what would be – make more incentive, or make more sense to incentivize, building chargers or building electric cars for companies, because you could incentivize companies with electric cars, you could build chargers or incentivize building chargers, or you could incentivize consumers to buy electric cars, right? So you have kind-of those options, all going off incentives, which as a government, this is the US government. What kind of industry executives?*
> *Administrator: It would – you can make any assumption but probably car manufacturers.*
> *Participant: Car manufacturers, OK. Because it could be something interesting to look at presence of electric cars in media and marketing, because that could be an interesting way to potentially cut costs because it could be cheaper to incentivize people using Teslas in movies or something like that than it would to incentivize people – actually the purchase of a Tesla. I mean, marketing and media, you can sell stuff, so [laughter] and then – but that's – and also I don't know if that's something that's been done before, which I'm going to Google right now [laughter]. US government*

incentivizing with media. Not sure how you'd phrase what I'm looking for. I'm just reading a bunch of articles on governments incentivizing things.

5.3.10 Synthesizing Insights

Synthesizing insights refers to integrating new dimensions of understanding to form a whole greater than the parts, which can happen at multiple points of a design exercise as a way to reflect in action as well as an ending point to concisely summarize ideas. This behavior is described as core because it can take different meanings depending on the context and task at hand. For example, the behavior can imply (but is not limited to) articulating new ideas, taking many parts of an idea to arrive to a new one, analyzing conflicts and opportunities of a new idea, making sure all aspects of a challenge are being considered, summarizing learning from networking or experimentation, or deciding if solutions are applicable.


Some rough calculations on the feasibility of a LASER: Light Amplification by Stimulated Emission of Radiation.

Conceive a tube terminated by optically flat

partially reflecting parallel mirrors. The mirrors might be silvered or multilayer interference reflectors. The latter are almost lossless and may have an arbitrarily high reflectance depending on the number of layers. a practical achievement is 98% in the visible for a 7-layer reflector. Flats with closer tolerance than 1/100 λ are not available so if a resonant system is desired, higher reflectance would not be useful. However for a nonresonant system, the 99.9% reflectance which are possible might be useful.

Consider a plane standing wave in the tube. There is the effect of a closed cavity; since the wavelength is small the diffraction and hence the lateral loss is negligible.

① O.S. Heavens, "Optical Properties of Thin Solid Films" (Butterworths Scientific Publications, London 1955) P.220.

Figure 5.11 Early sketch of a laser resonator (Hecht, 2010, p. 2)

This synthesis of insights played a role in the development of historical enabling innovations. For example, Figure 5.5 shows one of the first known sketches of a laser, by inventor Gordon Gould, from 1957, in which he coined the term "laser" and sketched out a plan to build one using resonator mirrors (Hecht, 2010).

In the performance task, participants often engaged in this behavior. Andrew, for example, constantly synthesized insights often scanning for conflicts and opportunities embedded in his ideas – in the following quotation regarding issues with EV infrastructure and the installation of charging stations in existing gas/fuel stations – and posing questions and/or hypotheses that allowed him to "dive deeper" into the EV challenge:

> *"Like, we talked about – the marketing's out there. You see electric car ads all the time. People understand their options, I think, for electric cars. Plus, I believe if we're gonna stay focused on – I think this is what I want to start off looking at, is this infrastructure, because technology is gonna improve the driving range and reduce the price. That's maybe not anything we have to worry about as much right now. So, this infrastructure to recharge – that's something where we're gonna have to look at. That's nothing for the end consumer to deal with. So, if we're gonna increase the adoption, one potential way would be to have some sort of partner or relationship partner with, say, fueling stations, because that infrastructure's already there. But, I guess the problem with that is: they make their money from people that drive non-hybrids right now. So it might be a conflict of interest if there's a franchise that – let's say – through Shell oil, they may say: you can't recharge electric cars at our fueling station. So that's one potential problem, is that conflict of – just say a conflict of interesting. And then, I think because it's not really feasible to go through and put in, say, new charging stations everywhere, it would be possible. But if you think about how many fueling stations are in the US, and make an assumption that cars – electric cars are going to have to drive – maybe have the same range eventually. Say, around 300 miles per charge, you'd only need about the same amount of charging stations that you would need fueling stations, potentially. So, it makes sense that there's some way to partner with these fueling stations to do that, and that's – it's a conflict of interest, and then we would probably – even if there wasn't a conflict of interest, that would increase costs because someone's*

> *going to have to pay the fueling station to put in the equipment to recharge vehicles. And then someone's gonna have to pay for the electricity. So, it's gonna increase costs to somebody, and maybe we could say probably – you know, electricity costs – to the user of the car, or the car driver. And then, the equipment costs, I don't know yet – who would take care of that. It's probably not feasible to think about right now about partnerships with these large oil energy companies because, again, they make a lot of money from the traditional fuel-powered cars, or even fuel-power hybrids. They still are making money there because they're selling fuel, but with these that are almost strictly electric – like, now, they're not really getting benefit from that. That's gonna hurt them. So, it's gonna be pretty hard to make it – probably the first place that would be good to look is to see: can we partner with all the independent fueling stations, and maybe not the big franchise, the Shell – those kind of places."*

In addition, to exploring conflicts or opportunities, synthesizing insights is herein considered "core" to communication issues and concretely describing elements of a proposed plan/solution. As an example, of another instance of synthesizing insights, at the end of his performance task, Jack synthesized all elements of his EV plan, reflecting upon each of the plan's components along the way:

> *So, one is a deep DOE study, one to two years, to assess power grid across the USA, including last mile wiring. That's Number 1. Number 2 is – pilot program proposal – that's got to be one year – to choose, let's see, the infrastructure, the participating leads – e.g. taxicabs, whatever. Okay? Then there's pilot implementation. So that's years 2 to 4, including media coverage. So 4 is – where would I have it at, end-of-life – end-of-life battery challenge with ten million (inaudible). And then long-term infrastructure plan. Maybe that's the second – so that's the second – or piece of work from the DOE, because I think the government has to run that. So this is DOE work from Years 2 to 3, and execution. So the plan is Years 2 to 3. I mean it's going to take a little time to do this, it's not going to happen overnight. So I think a little planning will go a long way here. And the key there is to align existing efforts with – align existing efforts across competitive boundaries. And then 6 will be implementation of that. That would be Years 3 to 5, so a couple of years of that – if you could actually go a long way once you were serious about it. And then the repair network. I think that would be within the pilot program. So implement new repair guidelines. And then Number 7 is (inaudible) – you know, it's Years 5-plus, and that's tax incentives,*

> *etcetera. And I think that covers – okay. I think I – I mean I obviously would like to type this out to make it more presentable.*

Synthesis activities can also trigger reflective modes of thinking that lead to other/additional insights. For example, Mike synthesized information gathered through his online search, and the started listing other barriers that did not come across through his information gathering process but from related insights triggered from this synthesis activity:

> *"So I think one is – one theme I'm kind-of taking away is that electric cars kind-of suck in various ways, and so it's not so much that people are like – even if the – like it's kind-of like even if the money was equal, there's a lot of people wouldn't want it because it's small, it's ugly, it's unsafe, and I think there's also this notion of that you're like – well that – so that's one problem is to attack the EV cars, unsafe, poor performance – and probably biggest is ugly. Ugly, unsafe, poor performance and was the other one? Aesthetics, safety, expensive, not pleasurable to drive, maintenance costs, max speed, limiting, I'll say. It's limiting in how far it can go, in range. So you're sort-of – you feel kind-of hemmed in, like the fact – like you never actually would want to drive off into the distance, but the fact that you could at any moment is kind-of cool." (Mike)*

5.3.11 Reflecting and Iterating

Iteration is often referred to "as 'another pass,' 'the next version,' or 'starting over.' For it to work well, iteration in design must engage in meaningful learning" (Crismond and Adams, 2012, p. 770). It is herein proposed that this learning often comes from reflective activities.

Thus, iteration and reflection are coupled in the enabling thinking framework described herein. Schön's (1983) alternate theory of being a professional – the reflective practitioner – is critical to any design and innovation endeavor and thus a core behavior to be able to drive enabling innovations. A reflective practitioner goes beyond rational and cognitive knowledge to embrace "knowing in action," for which reflection is critical to practice. A reflective practitioner also "emphasizes problem-setting (in addition to problem-solving) activities, reasons about the problem and solution through experimentation, and fluidly engages in a variety of representations (both inscription representations and language representations to experiment with the problem" (Adams et al., 2003, p. 276). Engaging in reflective practice implies interacting with problem-solution spaces, naming things while framing problems and solutions, generating "moves" towards a solution, and reflecting on the outcomes of such moves. Reflections can happen while designing and problem-solving (called reflection-in-action) or after making a design/problem-solving move (called reflection-on-action) (Schön, 1983). The concept of reflective practice has been broadly studied, for example, Adams et al. (2003) found that studying coupled iterations (which integrate problem and solution decisions) might be one way to directly capture the underlying process by which a designer engages in reflective practice thus establishing a link between reflection and iteration.

The uncertainty that is inherent to innovation challenges, and particularly enabling innovation challenges, which involve a change in paradigm, often implies that the pursuit of such challenges will be highly iterative. Iteration is defined as a "goal-directed cognitive process that is triggered by an information processing activity (i.e., accessing, utilizing, and/or generating) and concludes with a change to a design state (i.e., process, problem, or solution element)" (Adams, 2012). In fact, some researchers (Adams, 2001; Mosborg et al., 2005) argue that design and problem solving *are* iteration.

Iteration can occur spontaneously, as one notices a dilemma or opportunity, strategically, as one plans to revisit an issue, or as part of an overall design approach (Crismond and Adams, 2012) and be an integral part of strategizing, shaping, and pursuing enabling innovations, especially for transforming assumptions into knowledge. Examples of effective iterative behaviors discussed by Adams (2001, 2002) include: 1) more time iterating and more iterations, 2) more time in iterative processes than in a conceptual shift in understanding, 3) more time in iterations triggered by self-monitoring and examining activities, 4) more time iterating within and across conceptual design and problem-setting activities, and 5) a greater awareness of iterative strategies and processes for monitoring detecting, and resolving design failures. For example, while gathering information (an information processing activity), Nicole, in her performance task, changed a design state (thinking about solutions at a city level rather than national), effectively engaging in a design iteration:

> *Nicole: So what I'm thinking now is kind of ricocheting back between these jobs and the business models and this not all people, not all geographies are created the same. Hold on. So there's probably, you think about a national committee composed on government officials. I'm going to assume there are. There's probably national government officials like the Department of Energy folks, but there's also potentially state government officials, maybe even city government officials making that up. Am I allowed to assume that?*
> *Administrator: Yes, yes. You can assume.*
> *Nicole: Alright. So there are government officials from all levels national, state and city and I think there's going to be potentially a tension there as we think about solutions - Because things like subsidies and tax deductions and things like that will have to be, I'd assume, offered on a, I don't know... You'd want to offer those on a national level, but you could further support those through state subsidies, state tax deductions, and even local. Sorry, now I'm starting to shift into what would be a recommendation be.*

In the context of this study, reflection and iteration were embedded in participants approach to the EV challenge. Because this behavior has been broadly studied in design circles, one brief example is provided below. In this example, Kate, after reviewing her ideation criteria listens to the situation's "back talk" (i.e., reflective conversations with a design challenge, as defined by Schön) and realizes her list of ideas is not exhaustive, so she iterated (in her own terms) "ideation activities":

> *"Oh, I was thinking that I want more ideas on my idea list before I prioritize them and make like the more like specific story for the deliverable. So that's what I was thinking. I was thinking like, Hmm, I don't have enough ideas."*

Similarly, Mike engaged in iterative activity throughout his task, especially while gathering information, which helped him make changes to his framing of the problem/ challenge and ideation of solutions:

> *"So attitudes towards electric cars. I think that's an interesting thing. Here's attitudes of electric – of European car drivers toward electric cars… these are all going to just give us familiarity with all the different factors that people are thinking about. It looks like likelihood of buying a car is fairly equal between men and women, slightly higher in women, slightly higher 18 to 30, 40 year olds. So we have women, 18 to 34, no degree, that's interesting. Working status, not working, the not working people want a car. Living area is metro area as opposed to large city, large town or small town or rural area. Public transport service, well served, so that confirms with metro area. Intention to buy a car in the future, next six months, 42 percent. Familiarity with the electric car, very familiar. So the more familiar they are, the more – that makes sense. Car usage, if they use it every day they're more likely to want an electric car, and if they're more – they're more likely to buy it if they are in the car market. In car market, well that makes sense. Distance – max speed. That's a key issue. So you know what I bet it is? It's sort-of this issue of the now versus later. Because basically the now is you've got to pay a higher price now…"*

5.4 Summary of Core Behaviors and Transition to Enabling Thinking Patterns

This section provides a brief mid chapter summary. Overall, the chapter aims to describe a set of patterns and behaviors in what is herein termed the enabling thinking framework. A set of core behaviors that are foundational to enabling innovation activities, but also to other types of design/innovation endeavors were described. These behaviors included: *recognizing and labeling patterns*, *prioritizing according to an innovation end goal*, *breaking ambiguous ideas into defined parts*, *separating negotiable norms from non-negotiable rules*, *diverging-structuring-converging*, *employing multiple perspectives*, *exploring variations systematically*, *distilling core ideas from their context*, *finding first principles and derivative insights*, *synthesizing insights*, and *iterating and reflecting.*

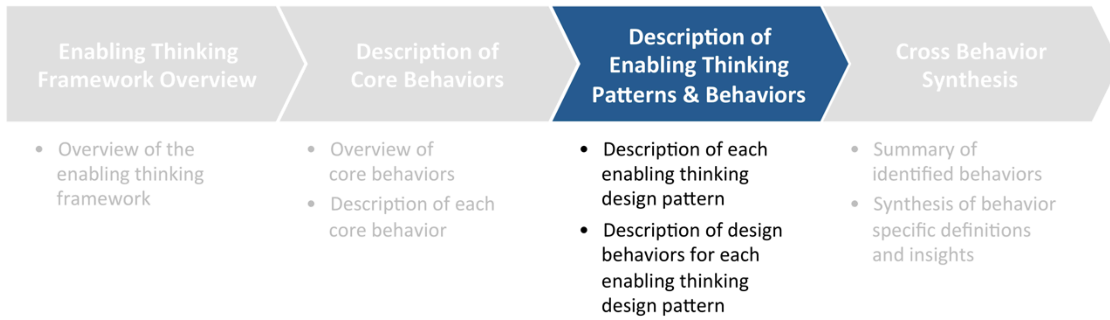


Figure 5.12 Enabling Thinking Patterns and Behaviors Chapter Section Overview

In the following sections, such behaviors are employed to characterize the design patterns and behaviors that are herein considered specific/unique to proactively achieving enabling innovation (see Figure 5.12). The following sections will explore each of the design patterns for enabling innovation (shown in Figure 5.2): *framing the flaw in the paradigm*, *seeing technical, economic, systemic, sociological, and psychological forces*, *broadening idea spaces by connecting generalized first principles*, *addressing host ecosystems holistically*, *rethinking performance and connecting to early impact contexts*, *persuading to facilitate acceptance or use*, *creating an emergent strategy to unfold performance and impact*, and *deploying an emergent strategy to discover the enabling path*. For each pattern, a corresponding set of behaviors is also characterized.

5.5 Framing the Flaw in the Paradigm

In problem definition activities, beginner designers are likely to attempt to *solve problems* prematurely, while informed designers have a tendency to delay decision making and *frame problems* until a challenge is better understood (Crismond and Adams, 2012). Beginner or informed designers may indeed serendipitously identify opportunities for high-impact, enabling innovation; albeit likely due to unintended consequences instead of explicit and proactive, goal-oriented behavior.

The characteristics of the enabling innovation model thus call for a proactive shift in problem definition activities, from framing problems to framing and addressing flawed paradigms that, if exploited, can drive an impact cascade. As described in Chapter 4 of this dissertation, paradigms typically describe the status quo norms that govern the framing of a problem and the nature of commonly employed solutions to drive broad reach and significant impact. Flawed paradigms thus refer to the negotiable yet often latent assumptions governing such norms. It is often in finding opportunities to break the hidden assumptions underlying flawed paradigms, where the spark for many enabling innovations has been ignited across domains such as economics (Perez, 2003), science (Kuhn, 1962), and technology (Dosi, 1982, Arthur, 2009).

Although paradigm changes may seemingly come as a result of time and random events, through the combination of specific problem-framing behaviors one can *structure paradigms to reveal flaws* to proactively attempt to frame opportunities for a paradigm change. While there are many possible approaches to frame a paradigm to reveal flaws, the pattern described herein focuses on behaviors which include systematically *structuring ambiguity*, purposely *questioning a paradigm*, and proactively *spotting opportunities in flaws*, as shown in Figure 5.13. Effectively, a structured perspective of ambiguous idea spaces and asking right questions can facilitate/scaffold the quick understanding/learning required to be able to spot opportunities in paradigm flaws.

Further, core behaviors such as recognizing and labeling patterns, breaking ambiguous ideas down, diverging-structuring-converging, and separating norms from rules take special meaning. Many features/aspects of a paradigm often go unrecognized due to historical precedent, and thus explicitly recognizing and labeling patterns in problem and solution spaces becomes relevant. Often times such patterns are too broad (or even complex) and thus breaking ideas/patterns down into components that are more manageable helps identify flaws and recognize the opportunity for or resulting from a paradigm change. Diverging, structuring, and converging can help ensure the comprehensiveness of the problem and solution space exploration in the search for flaws. Finally, analyzing ideas to separate norms from rules can help zoom in on negotiable norms and systematically explore variations/deviations from these norms to uncover flaws in a paradigm (and possible alternative paradigms).

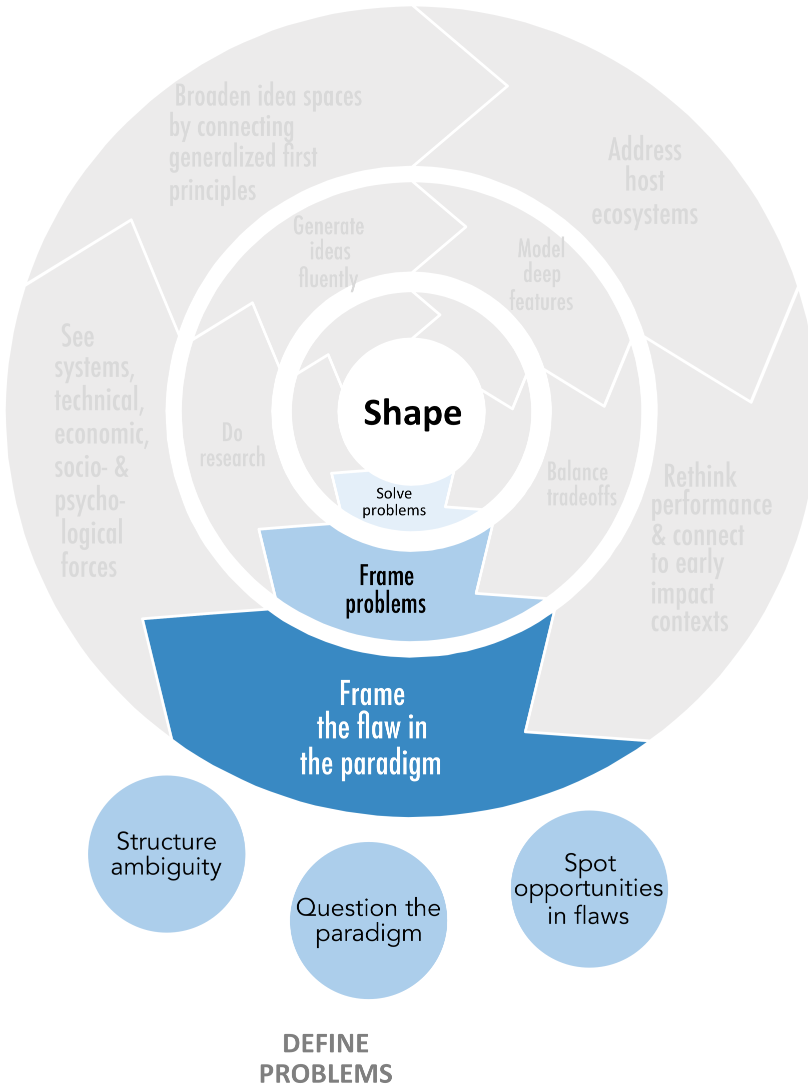


Figure 5.13 Frame the Flaw in the Paradigm

An example from the performance task, particularly from the interview debrief with Susan, one of the participants, helps highlight the importance of searching for flaws in a paradigm. After explaining her approach to the EV challenge, Susan made an analogy to traditional problem framing and problem solving approaches in her discipline:

> *"So I'm trained as a polymer scientist but we try to solve problems in medicine using as much biology as we possibly can. And so we may try to sort of formulate a general problem in medicine and then go read the biology literature focusing on the biological macromolecules because I study polymers and think about what's going on with the biological macromolecules, then once we have an understanding there try to think about how we can mimic those macromolecules using what we know from polymer science and engineering to improve health. And so I try to bring in sort of the medical problem, the biological understanding of what we understand from polymers to come up with a simple approach. So in biology there's some pretty complex macromolecules that we can't just make an ecoli or we can't just make a yeast. They're specific to mammalian systems but we can't harvest them easily from mammalian systems either, and so they're just not easy to make that exact molecule. So understanding there's a flaw there, what can we bring from polymer science to overcome that flaw."*

Figure 5.13 highlights the aforementioned pattern and relevant behaviors, while Table 5.3 summarizes relevant behaviors that are herein defined as specific to framing the flaw in the paradigm. For each behavior, the following sections provide a definition, a link to enabling innovation, links to the core behaviors, and characteristic principles/actions based on evidence from all methodological approaches.

Table 5.3 Behaviors to Frame the Flaw in the Paradigm

Behavior	**Definition**	**Related literature**	**Unique link to enabling innovation**	**Link to framing the flaw in the paradigm**	**Illustrative actions/activities of the behavior**
Structure ambiguity	Providing logic to ambiguous, complex, and ill-structured problem and solution spaces	• Minto (1996) • Vandebosch (2003) • Sinfield et al. (2014) • Miyake and Norman (1979)	Enabling innovations often participate in multiple complex systems with a relatively high number of nodes and links that are ill-defined (which eventually translate to reach and impact), and structured perspectives of ambiguity can help one provide logic to ill-defined paradigms	Creating a mutually exclusive and collectively exhaustive perspective of problem and solution spaces can help highlight gaps in logic (paradigm flaws) or unaddressed areas in which a paradigm flaw might be hidden	• Creating an issue tree or influence diagram that provides structure to an ambiguous problem or solution space • Defining and naming categories of ambiguous ideas • Employing a framework that helps capture all aspects of a complex problem-solution space
Question the paradigm	Asking "why" and "what if" questions that reveal a paradigm's hidden assumptions	• Graesser et al. (1996) • Ottero and Graesser (2001) • Dyer et al. (2008) • Sitkin et al. (2011)	Many schools of thought call for asking root-cause questions to innovate, but few (to the author's best knowledge) explicitly focus on questioning fundamental paradigm assumptions when high-impact is a desired result	"What if" questions help unearth hidden assumptions that shape current paradigms and the opportunities to drive a change in paradigm	• Asking questions about current norms or aspects of the working paradigm • Wondering why things are done in a certain way in a given context • Asking "why" and "what if" to unearth new paradigm possibilities
Spot opportunities in flaws	Recognizing opportunities in flawed yet latent assumptions that underpin paradigms	• Solis and Sinfield (2014) • Garcia et al. (2012) • Short et al. (2009) • Dutta and Crossan (2005) • Adner and Levinthal (2008) • McCaffrey & Krishnamurty (2014)	While the notion of opportunity is common entrepreneurial contexts, finding opportunities to innovate with enabling impact (reach, significance, paradigm change) by searching for hidden paradigm flaws is unique	Opportunity recognition approaches can help reveal flaws in paradigms as target problems in design activities, and translate such flaws into enabling opportunities	• Searching for anomalies/ gaps within an idea space • Interpreting/explaining insights that might seem to be anomalies/flaws • Integrating/articulating hidden assumptions in a synthesis activity

5.5.1 Structuring Ambiguity

Structured perspectives of ambiguity can help frame flaws in paradigms for enabling innovation challenges. To achieve these perspectives, the behavior of *structuring ambiguity* is herein defined as shaping a seemingly ambiguous, unknowable, and uncontrollable problem space (e.g., Minto, 1996; Vandenbosch, 2003; Friga, 2008), to create a logic-based, high-level perspective of the status quo and potential knowledge gaps (Miyake and Norman, 1979) – and in the context of enabling innovations, reveal opportunities hidden in paradigm flaws. Structuring thus provides logic and language to describe an otherwise complex, ill-structured problem space. This logic captures ambiguity in a mutually exclusive and collectively exhaustive way for further probing of possible (problem and solution) gaps and possible hidden paradigm assumptions, and helps drive the understanding of such a space to a desirable level of actionable detail.

Many tools/techniques can be employed to scaffold the behavior of structuring ambiguity and behaviors identified herein as core such as recognizing and labeling patterns, breaking ambiguous ideas into tangible parts, diverging-structuring-converging, employing multiple perspectives, and shifting search directions seem to underpin such tools and techniques. One technique frequently employed to create these perspectives is the creation of "issue trees" (Minto, 1996). Issue trees aim to comprehensively capture all "how" or "why" answers to a given key question in mutually exclusive (avoiding overlaps between issues) and collectively exhaustive (making sure the tree is comprehensive or inclusive of all issues) ways. Examples of applications of this behavior related to enabling innovations include, for instance, articulating and organizing the governing paradigm in a challenge, envisioning and organizing the set of issues surrounding a "grand challenge," creating a comprehensive landscape of commonly employed solutions or the potential impact landscape of an idea. Overall, the goal of structuring is to create a foundational understanding that can help unearth latent assumptions related to challenges and/or opportunities to achieve enabling innovations.

Yet for enabling innovations in specific, structured perspectives of ambiguity seem to have led to the identification of unique paradigm flaws. The concept of unit operations is one example of how structuring ambiguity can help drive impact. This concept helped shape chemical engineering as a discipline as it structured the seemingly ambiguous (and then assumed unique) characteristics of chemical processes into a series of "unit operations" steps that could then be combined to more easily understand such processes and help drive/assemble new processes (Rosenberg, 1998). In addition, structuring ambiguity also played a role in the history of microfinance, especially when Yunus decided to investigate poverty in his attempts to address famine in Bangladesh (Yunus, 1999). Through his research, Yunus understood that governments and social scientists had no clear definition of "poor." Poverty definitions of the era varied and included categorizations such as "jobless people," "illiterate," "landless," "unable to feed their family," "with a given set of housing conditions," "with malnutrition" or "not sending their children to school." Likely due to his training as an economist and inherent focus on measurement, he reflected that efforts to address poverty should be founded on a clear definition of the issue. Therefore, he created his own definition of poor according to three broad categories: 1) the bottom 20% of the population (absolute poor); 2) the bottom 35% of the population, and 3) the bottom 50% of the population. Further, within each category, he created sub classifications on the basis of region, occupation, religion, ethnicity, gender, and age, thus creating a multi-dimensional understanding of poverty that was distinctive and unambiguous. This perspective helped Yunus realize that most development programs were not targeting the absolute poor. Often times these programs widened the gap between the poorest sectors of the population and the people that development programs typically targeted such as farmers and land owners. Structured perspectives of ambiguity can thus provide a framing of a challenge from which questions to a paradigm that reveal possible flaws can stem.

Analysis of the performance tasks for participants who had an inclination to provide structure to the ambiguity in the EV challenge (e.g., Drew, Mike, Don, Victor, Walter) also helped exemplify how unknowns and knowledge gaps are identified and assessed. Insights from select performance task excerpts that suggest possible actions/principles for structuring ambiguity are described in the following paragraphs.

Structured perspectives of ambiguity thus help identify unknowns and knowledge gaps, and assess the significance and uncertainty of such gaps. In his performance task debrief, for example, Mike synthesized the importance of this exercise to develop an understanding a seemingly “obscure” topic:

> *“I mean, I think that's what you – so it’s both – so I'm sure it’s like nature and nurture, so it’s like – meaning it’s both what you practice when you do consulting and it’s also like, I think people who have a natural tendency to kind-of categorize and think about things in the MECE manner are attracted to consulting and do well in it. So, to me, it’s sort-of like – it’s sort-of how I understand the world. Like it’s – when something is kind-of confusing or baffling to me, the first thing I'll do is try to be like, what are we talking about, like what are the categories of this, or – and how does this fit into some bigger thing, and I don’t have a specific example right now, but – but that's just a natural – and basically like how does this fit with the rest of my knowledge base and reality and I found this was very true in medical school, is that we have these lecturers come in and they kind-of didn’t know that a lot of us didn't have as strong a science background as some of the other folks. Like some folks were like, by the time they got to medical – school, they had taken all anatomy and advanced physiology and like, had done research and everything, and some of us just did the bare minimum requirements and that was what I did to – in terms of pre-med requirements, and I found it was like, incredibly difficult to follow what the heck they were talking about, until I had like, some type of mental framework for like where it fit in the world of the universe. And so and the way I thought about it afterwards was this analogy around like, a map, where like they're coming in and they're basically tell me about like a specific street corner, and I don’t even know where the heck I am. Like it’s been a – I've been plunked down in the middle and they're describing some street corner, and I'm like, what country is this, like what city is this, what – you know what I mean? So what I found is it was much better to think – to look ahead, what is that lecture going to be about? It’s going to be about – some obscure topic within immunology. So first thing you got to get to is like, what is immunology. I mean, presumably you know that, but you might want to start that broadly, and then be like, well, where within immunology are we talking about?*

> *We're talking about the reactive or not the baseline but the adaptive, and then within that we're talking about the white cells and within that we're talking about the specific chemo receptors on the white cells. It's like, OK, now I can pay attention to what you're talking about, even though, frankly, it still has no bearing on my med school training at all because it's a ridiculously obscure research topic that only you care about. But at least now I can follow the [laughter] I can follow the topic, and so that's basically what you do."*

Iterations between inductive and deductive approaches to structuring seem to more comprehensively capture knowledge gaps based on a strategic intent or vision. These inductive-deductive iterations ensure that a structure is mutually exclusive and collectively exhaustive (MECE). Also in his debrief, Mike, for example, explained how the ideas he generated could have been "pushed forward" to create a more exhaustive perspective of the problem and solution spaces.

> *"So now that you have all this, you'd – and as you're doing this, you just – you're kind-of taking it on faith that by triangulating things in this way you sort-of end up with a MECE and fairly comprehensive list – of potential categories of things, and then if you don't, if you realize as you're going through it, what about this, then you have to think back and you say, "Wow that's a category of stuff I'm missing… then in terms of this, this is sort-of like the next – so this is somehow synthesizing that [laughter] so it's like multiple levels of synthesis where you're trying to think about what are ways you can synthesize what you just talked through, and here I came up with like, different ways of doing it. I don't know that it's perfect, but it's certainly useful to push stuff forward. And the reason for that is that you have to get to like – you kind-of want to get to categories and then categories within categories so that you can feel like you're being exhaustive in your solution development, and you're not like – you have confidence – like I have pretty good confidence that I don't think we necessarily got all the ideas, but I think if we went through these lists of all the circled things and made sure we had ideas – against each of them, then I would have pretty high confidence that we had kind-of covered the gamut. And we could continue to brainstorm and – but there's sort-of a notion of diminishing returns."*

In some cases, existing frameworks seem to be a useful starting point to quickly learn and develop an understanding of a situation. Drew and Mike, for example, chose to use frameworks as a starting point and then attempted to gain more knowledge by probing such frameworks, while Victor, tried to break down the EV challenge into a set of circumstance-based categories that he defined:

> *"The approach is very simple, that I go back to some of the tools and techniques which are normally common, and that allow you to structure a problem or to approach it in a linear thinking. So the first model I normally use is customer, competitor, and cost, the three Cs. That's another – (inaudible) that's the way normally you get it pretty right." (Drew)*

> *"It can be useful to frame it through the lens of just your own thinking. So because you can get too bogged down in like, the details. So I think the way I would think about this is I would think about – I'd think about specific ideas that you could go act on and the specific ideas I think would be a couple different categories and there's – and initially I'd probably just brainstorm like categories of ideas, so you could like – you could decrease the barriers for those that are inclined. Like there's sort-of this like – I mean, you want to think about overarching framework initially, and so one overarching framework that seems pretty useful here is just the sort-of the conversion funnel, or I forget what it's called, the marketing funnel, but it's basically awareness, consideration, sort-of purchase, sustained use. I'm getting the things all wrong. And then repeat purchase. So this is like you don't sell it once you get it, and this is like you buy it again if it breaks down, and so I think first of all, you – so you could think about these different stages." (Mike)*

> *"There are three circumstances that I see – and I'm going to try to break this up. And so there's what I would call the urban, suburban, and field… okay, there are personal transportation vehicles. There's heavy transit. And then there's mass transit." (Victor)*

5.5.2 Questioning the Paradigm

Questioning a paradigm is also a relevant behavior to defining problems by framing worldview flaws. This behavior is herein defined as asking "why" and "what if" questions that challenge the status quo, especially questions that aim to reveal flaws in a paradigm and opportunities for enabling innovation. Prior literature that focuses on questioning highlights how asking *what if, why*, *how*, *what if not*, and *what are the consequences* (Graesser et al., 1996; Dyer et al., 2008), can call attention to contradictions and/or knowledge gaps (Otero and Graesser, 2001). Often times, the pursuit of a "stretch goal." can facilitate "openness to questioning the validity of old assumptions, old information, and old frameworks" and drives individuals to "find new sources and types of information and also new ways to process [such] information" (Sitkin et al., 2011).

The behavior described here as "questioning the paradigm" departs from this literature by focusing on a specific type of stretch goal (enabling innovation), which has a set of defined characteristics. Structured perspectives of a problem or solution space can serve as a focal point of questioning. Because enabling innovations drive a change in paradigm, questions can focus on challenging fundamental paradigm assumptions in the pursuit of revealing latent flaws that can potentially be translated into innovation opportunities.

Historically, questioning a paradigm has helped realize enabling innovations. For instance, microfinance resulted from questioning banking practices that did not account for the poor, who were perceived as seemingly unbankable. As a result, banking paradigms and access to capital by some sectors of the population in developing countries were questioned, eventually giving birth to modern microfinance practices. Yunus (1999, p. 52), for example, recalls a conversation with a banking manager in which he questions banking in Bangladesh:

> *"So I have come here today because I would like to ask you to lend money to these villagers."*
> *The bank manager's jaw fell open, and he started to laugh. "I can't do that!"*
> *"Why not?" I asked.*
> *"Well," he sputtered, not knowing where to begin with his list of objections. "For one thing, the small amounts you say these villagers need to borrow will not even cover the cost of all the loan documents they would have to fill out. The bank is not going to waste its time on such a pittance."*

> *"These people are illiterate," he replied. "They cannot even fill out our loan forms."*
> *"In Bangladesh, where 75 percent of the people do not read and write, filling out a form is a ridiculous requirement."*
> *"Every single bank in the country has that rule."*
> *"Well, that says something about our banks then, doesn't it?"*

Insights from the performance task help further define this questioning behavior and its emphasis on challenging paradigm assumptions. As an example, in his performance task, Ken questioned the relationship between travel patterns and vehicles in general to formulate his recommendation:

> *"Most cars are designed to be compromises between travel patterns. So the question – the important question that arises is how can you change that?"*

Questioning a paradigm is related (yet different) to the aforementioned core behaviors. This behavior is related to the core behavior of separating negotiable norms from non-negotiable rules, because the answers that result from the questioning process need to be further analyzed to be classified as negotiable norms or non-negotiable rules. In addition, questions from multiple perspectives, e.g., technical, economic, systems, psychological, and sociological can employed in challenging a paradigm. Henry, for example questioned a paradigm by, focusing on issues with vehicles, sales cycles, people's enjoyment of their cars, and opportunities for social interactions facilitated by EVs:

> *"So I guess what I would do is begin by trying to understand what are some of the different assumptions about the landscape, doing some general secondary research. And then try and understand how the experience has been for some early adopters across different segments, things like consumers, people who run fleets of cars and then dig into what would be the right types of partnerships, what could you do by aggregating some of the data from the cars, what are some of the dependencies, try and understand what are some of the differences in maintaining cars for EV versus traditional combustion engine cars, internal convention cars. What are some of the advantages? Why do people enjoy EV cars more than traditional cars? What does a sale cycle look like? Are there opportunities to create new types of relationships*

> *between people or people and their cars? Could you create more social communities by doing car sharing with them because people feel better about EV cars?"*

The process of asking "why" and "what if" questions also seems to require exploration of deeper levels of inquiry, i.e., probing to uncover first principles and/or second and third order effects. These levels of questioning imply understanding when to continue or stop the question asking process by differentiating answers that satisfice from those that merit further exploration. Such a differentiation exercise helps avoid "devil's advocate" approaches (i.e., questioning for the sake of questioning) and can help drive purposeful questioning. As an example, for example, Victor, in his performance task continuously asked questions to uncover second and third order effects in the lack of use of EVs in heavy and mass transit:

> *"And now I'll come back and say, so why wouldn't heavy transportation trucks, etcetera, be an opportunity? And the reason we don't have electric trucks is because of the power required to move them. And so we have the issue that electrical – well, the belief, the bias, that the electrical engines aren't big enough, strong enough, to move that, but that's not true, because we have rail. Okay? And so it does exist. It's just the amount of energy that's required to move that is huge. And so the issue with heavy transportation is the energy required per vehicle. And I assume that's the same issue with mass transit. Okay? And so the current design of the systems, which are, quote, light rail and all the rest of those things, because of the energy that is there, is where the challenge is. Hmm. Is there a way to reduce that set of requirements? Is there a way to transfer that? Today's systems of mass transit don't have the vehicle – don't have a storage capacity for those vehicles. So the issue is that these are all currently direct drive. Why? Why are they direct drive? Because that's where they started, and that's what was – that's how it has evolved. So why, if I can do this, if I can put batteries in electric cars, can I not put them in these bigger vehicles?"*

5.5.3 Spotting Opportunities in Flaws

Rather than simply defining problems, the enabling thinking framework focuses on opportunities (herein defined as discovered or created ideas or aspirations to drive impact), and particularly on spotting opportunities in paradigm flaws. This search for flaws in paradigms helps explicitly articulate the change in worldview that is necessary to drive an enabling innovation, thus defining an area of opportunity. This behavior is assumed complementary to the aforementioned structuring and questioning behaviors in efforts to reveal paradigm flaws and emphasizes translating the flaws identified through these behaviors into possibilities for impact creation.

Entrepreneurship research (e.g., Short et al., 2009) can inform this opportunity search process. For example, opportunities are said to stem from a process of intuition, interpretation, integration, and institutionalization (Dutta and Crossan, 2005). Research also suggests that some opportunities are discovered while others are created (Alvarez and Barney, 2007) and that ideas and aspirations can (but not necessarily need to) develop into opportunities (Dimov, 2007; Hsieh et al., 2007). Further, systematic approaches to opportunity search are assumed to be more effective than general alertness (Fiet, 2007), because opportunity discovery can be considered a problem-solving process where an organized search can lead to answers about unsolved problems (Hsieh et al., 2007).

In the history of enabling innovations, spotting opportunities in flaws has played an important role. The history of anesthesia exemplifies this behavior when in a laughing gas demonstration, a dentist in the audience noticed that one of the demonstration participants got injured, but because of the laughing gas had no pain reactions (Sykes and Bunker, 2007) thus likely triggering the realization that this gas could likely be used for pain management (a paradigm flaw that had until then gone unnoticed). The dentist then arranged for a private demonstration of the gas and translated this paradigm flaw into opportunity for pain management in dentistry (which then evolved to additional application spaces).

Excerpts from the performance task further illustrate this behavior. For example, spotting opportunities in flaws implies finding a flaw (e.g., through structuring and questioning) separating problems from solutions, breaking a problem or solution into components and attributes, and attempting to separate one's mental framing from accepted practice to translate a paradigm flaw into an opportunity. Victor engaged in these actions, challenging by breaking down the EV challenge (and thus engaging in a core behavior) and challenging his own preconceived notions of such a challenge:

> *So why don't we have electric trucks? And the reason we don't have electric trucks is because of the power required to move them. And so we have the issue that electrical – well, the belief, the bias, that the electrical engines aren't big enough, strong enough, to move that, but that's not true, because we have rail. Okay? And so it does exist. It's just the amount of energy that's required to move that is huge. And so the issue with heavy transportation is the energy required per vehicle. And I assume that's the same issue with mass transit. Okay? And so the current design of the systems, which are, quote, light rail and all the rest of those things, because of the energy that is there, is where the challenge is. Hmm. Is there a way to reduce that set of requirements? Is there a way to transfer that? Today's systems of mass transit don't have the vehicle – don't have a storage capacity for those vehicles. So the issue is that these are all currently direct drive. Why? Why are they direct drive? Because that's where they started, and that's what was – that's how it has evolved. So why, if I can do this, if I can put batteries in electric cars, can I not put them in these bigger vehicles? Because the batteries have to be bigger. They have to have a bigger charge. They're not as efficient. So I'm caught in the dilemma of energy conversion versus mass. Okay? And so today, technology seems to be able to manage the smaller mass, call it less than two ton vehicles. But we don't yet have the ability to manage the greater ones unless we keep them in a direct drive system, or an immediate feed system, because of the amount of energy. Is that real? What examples do I have that say that's not necessarily true? It's just the paradigm I'm stuck in? And what I'm trying to do now is try to work my way through, is there a paradigm that I'm stuck in that is causing me to – that's causing me, like everyone else, to walk away from solving this problem – and going to solve this problem that people have been working on*

> *now for decades. Okay? And so why would – you know, because there's an obvious solution set on how to make this happen. It's not easy, but it's obvious. The question is, is there something here that would make this highly valuable? And why would I want to do it? And so the biggest thing that I see is if I was going to look at mass transit, we're still stuck in the same issues of, okay, if I make mass transit electrical, yes, that uses less fossil fuel. But I'm only really going to make a significant change unless – if I can transfer people from this to here. And that's a separate problem that has not been evolving at a successful rate.*

Excerpts from the performance task also suggest that the search for opportunities in flaws can be developed by studying the rationale for status quo links between problems and solutions. For example, Drew spotted an opportunity in separating the refueling mechanisms from refueling processes, emphasizing that a battery swapping service would make recharging as fast or faster than filling a tank with gasoline:

> *So the second one is then the convenience, and convenience says that I have to change this battery, but that's for me as – that's for me equal as it is, for example, going to a fuel station. So if I find a way to replace the batteries, I think that should be possible. There is this guy in Israel, what was his name again? But what I'm saying is, the assumption four is that in terms of convenience, the swapping is equal as fueling a car. A car fueling takes roughly 5 minutes, and if I get to the 90 seconds, I'm fine, too. So now the question is where do I change these batteries? So let's think about that. (Drew)*

Further, opportunities implicit in flawed paradigms can be identified by understanding what is done by norm rather than by absolute necessity (effectively engaging in the core behavior of separating negotiable norms from non-negotiable rules). For example, Ken, questioned the car buying process and its traditional payment schemes (buying and leasing):

> *So the question is – the question that I had is if you want to drive – well, I guess the question that I have is around the tradeoffs that a commuter would be willing to make to get a vehicle specifically designed for them. So when you think about that, the traditional buying model of a car doesn't*

> *make any sense, because a commuter isn't thinking of a – of a car in terms of its overall expense per year, necessarily, right? What really matters to them is how much does it cost me to get to work versus how much money am I going to earn going to work? Or how much is this trip going to cost me at a specific time, right? So the way – so what I would think of – think about when I think about driving electric vehicle adoption is to think about ways to flip the – kind of the incumbent model of purchasing a car or putting a lease with a financial guarantee into something that is more along the lines of a model where you pay for use or pay for utilization. (Ken)*

The core behavior of systematically exploring variations in idea directions proactively can also play a role in spotting opportunities in paradigms flaws. Effectively, one can zoom-in on norms and proactively consider different idea variations for reconfigurations or departure from the status quo. Illustrative examples from the performance task include Don's description of "levers" that can be pulled to address gaps in tradeoffs, and Rand's description of looking at the future of energy in genetics and biological processes (a different perspective from solar cells and other status quo approaches):

> *And see if that's a way of identifying a gap in terms of their performance tradeoffs with the competition and maybe suggesting some potential levers that could be pulled. (Don)*

> *Yeah, I mean, this is like the kind of stuff we talk about, just in general. We don't tend to be people who like, talk about pop culture and stuff like that. We tend to talk about like, what's the future of EVs or biotechnology. Like I was just researching the other day efficiency of photosynthesis versus solar cells, photovoltaic cells, because I kind-of like come from a biotech background, dad's a doctor, kind-of grew up around that, so I see the future of energy production not necessarily in solar cells, but actually in genetically engineering like, algae, for example. So I was just kind-of looking into that for fun [laughter]. (Rand)*

5.6 Seeing Technical, Economic, Systemic, Sociological, and Psychological Forces

Information gathering is critical to design activities (Bursic and Atman, 1997; Atman et al., 1999). Although beginner designers tend to *skip research* in favor of generating solutions immediately, informed designers have a tendency to *do research* on stakeholders, artifacts, methods, and/or details/specifications of their ideas (Crismond and Adams, 2012). Entrepreneurs for example, are often assumed to gather functional, social, and emotional information about possible opportunity areas that are important, unsatisfied, and widely held (Anthony et al., 2008).

Yet because of its potential for broad reach and comprehensive significance, designing for enabling innovation requires collecting information with a broader lens by aiming to proactively gather technical, economic, systems, sociological, and psychological information (see Figure 5.14). Every choice in the realization of an enabling innovation is inherently embedded with these types of forces, which will strongly influence the outcome of innovation efforts, even if not acknowledged. For example, due to interactions with multiple complex systems, enabling innovations will likely encounter systemic forces to a greater degree compared to progressive innovations. Therefore, such forces should be proactively taken into account throughout a design challenge to consciously address the inertia of status quo paradigms and the latent and often previously encountered emerging challenges in driving a new paradigm.

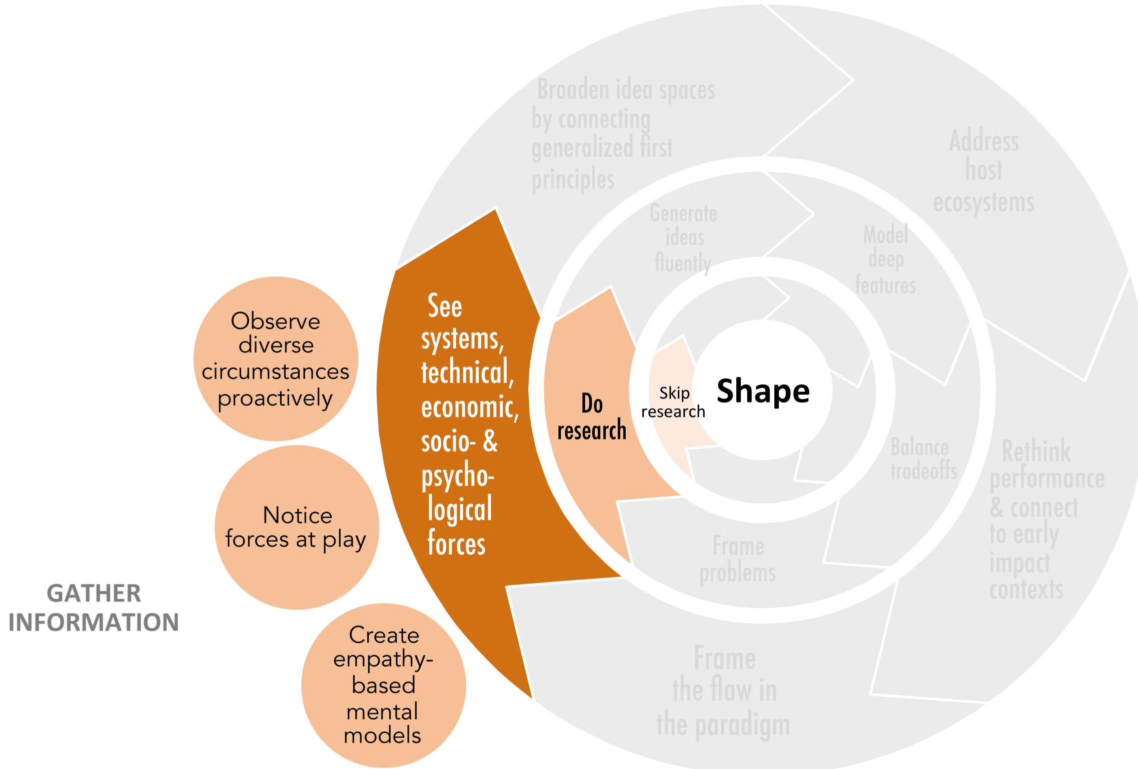


Figure 5.14 See Technical, Economic, Systemic, Sociological, and Psychological Forces

The following sections describe behaviors that can be employed to see technical, economic, systems, sociological, and psychological forces. Specifically, the behaviors of observing, noticing, and creating empathy-based mental models are described in more detail, integrating evidence from all methodological approaches (see a behavior summary in Table 5.4).

Table 5.4 Behaviors to See Technical, Economic, Systemic, Sociological, and Psychological Forces

Behavior	**Definition**	**Related literature**	**Unique link to enabling Innovation**	**Link to seeing technical, economic, systemic, sociological, and psychological forces**	**Example actions/activities of the behavior**
Observe diverse circumstances proactively	Engaging in constant observation across diverse circumstances to inform and observe hypotheses	• Kaish and Gilad (2001) • Dyer et al. (2008) • Schön (1983) • Heuer (1999) • Beveridge (1950)	Critical sparks for many enabling innovations have been triggered by observations in diverse circumstances outside of an intended domain	Observing diverse circumstances can help one gain exposure to a more comprehensive set of issues that could affect innovation efforts	• Mentioning cases or situations that would be ideal to observe • Suggesting ethnographic activities to engage
Notice forces at play	Perceiving proactively all possible significant influences in a given situation based on hypotheses, prior experiences, frameworks, changes, or unanticipated patterns	• Kaish and Gilad (2001) • Schön (1983) • Heuer (1999) • Beveridge (1950)	Enabling innovations often involve previously unexplored issues, and because of the novelty of the types of issues encountered in driving a new paradigm, noticing relevant signals (and separating them from noise) becomes critical	Noticing tacit or unexpected forces related to enabling innovations often requires some degree of perceptual sensitivity to identify any factors that might play a role in the success of an innovation	• Being intentional/systematic in recording observations • Employing frameworks or hypothesis to search for implications/forces • Searching for noticeable differences compared to prior experiences or knowledge
Create empathy-based mental models	Creating mental models that account for the behavior of technical, economic, systems, sociological, or psychological phenomena from self, other, cognitive, or affective immersive experiences	• Grant and Berry (2014) • Levenson (1992) • Strobel et al. (2013) • Norman and Verganti (2014) • Endsley (1995)	Mental models, for instance, of empathy with stakeholders, or of physical systems, facilitate an understanding of root causes that drive behaviors/system states underlying enabling innovations that have no prior models available for reference or study	Mental models that are empathy-based can unearth forces that will likely be ignored without interactions and exploration of such models	• Creating personas or profiles of stakeholders or end users • Putting yourself in the place of others intellectually or emotionally • Describing empathy-resembling mental models of how artifacts or physical phenomena interact with each other (i.e., with a frame of reference within the phenomena)

5.6.1 Observing Diverse Circumstances Proactively

One way to gather information is to observe diverse circumstances, artifacts/objects, and/or stakeholders. This behavior implies being proactive about the types of circumstances to be observed. Prior literature has focused on the differences in information patterns between entrepreneurs and executives and the exposure of entrepreneurs to non-traditional environments in the pursuit of opportunities (e.g., Kaish and Gilad, 2001; Dyer et al., 2008). Yet, for enabling innovations in general, beyond haphazard exposure to non-traditional environments, proactive pursuit of diversity in situations to be observed can trigger novel or different insights and unearth the broader set of forces (positive or negative) that will likely affect an idea with enabling potential.

The insights to conceive microfinance, for instance, in Muhammad Yunus' efforts, came from systematic exposure to diverse situations in Bangladesh, including observations of farming and their practices in the village of Jobra, Bangladesh. Through a project called the Chittagong University Rural Development Project (CURPD), Yunus encouraged his students to go into the village and devise creative ways to improve day-to-day life and "almost completely abandoned classical book learning in favor of hands-on, person-to-person experience" (Yunus, 1999, p.37). Routine exposure to the many circumstances and challenges encountered by the farmers such as crop yields, farming practices, labor distribution, and profit sharing among stakeholders, led Yunus, with time, to realize the potential benefits of small micro loans. This sequential exploration of a diverse set of issues (e.g., crop yields, labor distribution, profit sharing) highlights the importance of "finding the first-principles" through observation activities – i.e., gathering information through observations to get to the root of an issue. Further, in their efforts, CURDP stakeholders understood many of the sociological and psychological barriers and motivations of villagers, beyond technical farming issues and economics – effectively employing multiple lenses in their observations.

The scientific method literature outlines that observing can occur in passive or active ways (Beveridge, 1950). Passive observation implies scanning unfamiliar and/or diverse circumstances, which can reveal unexpected insights that might have previously gone unnoticed in a situation. Passive observations imply basic awareness of desirable circumstances to be observed with a rationale for such selection. Such passive observations can occur in either close or (seemingly) distant situations relative to the challenge at hand (Beveridge, 1950; Johannson, 2004), which emphasizes the need for diversity in the scenarios observed. In contrast, active observation implies a hypothesis-driven, proactive interaction with a situation and often implies having basic awareness of things (competing hypotheses) to look for and actively scanning a situation to reject or fail to reject hypotheses (Beveridge, 1950; Heuer, 1999).

Because of the simulated nature of the performance tasks, seeing participants observe a situation in practice was not possible; nonetheless, many did acknowledge the role that observations would play in their traditional/usual design and problem solving approaches. Max, for example, stated:

> *"I see a lot of value in qualitative research particularly in observational research. If you have that demo we talked about, you know, not a working vehicle but a physical vehicle that a consumer can interact with you can learn a lot with how they interact, about how they interact with various features and capabilities. I don't – I would never say that you would wanna short quant research. I've used it on many products from training platforms to dentist chairs, right? The things you observe, the ethnographic research really does end up influencing the feature and functions that you can make for a product."*

Instances of observing in the performance task often emphasized circumstances participants would have liked to be able to observe. For example, Max emphasized the importance of seeing how people interact with an idea/solution, and is aware of the things he usually looks for in these immersions:

> *The first type is more like this, just observational research, right? We'll go into the field and we will try to speak with a mix of folks who have these different types of vehicles that you've laid out here or have traditional vehicles with combustion engines to get a sense of both what's the end-customer is enjoying about the electric vehicle they have or the challenges that people see and for not adopting a particular – not moving from a combustion engine to an electric-powered vehicle… You're actually – you're sitting down and observing people in their environment and just trying to pick up on the various aspects of what they do and how they do it…"*

5.6.2 Noticing Forces at Play

Beyond proactive exposure to diverse situations to be observed and employing multiple perspectives, gaining insight from information gathering activities requires learning (implicitly or explicitly) to *notice*, i.e., to separate relevant signals from noise. Many schools of thought in design and innovation thus argue for "observational approaches" (e.g., Dyer et al., 2008; Kelley and Litmann, 2005) but few provide guidance on *how* or *what* to notice, i.e., how to separate signal from noise in the observations. Yet noticing, especially learning to notice signals based on archetypal patterns, is important to enabling innovation efforts because (more often than not) concepts with enabling potential have no historical predecessor to separate relevant signals from noise.

When gathering information, one can notice two types of signals: *spontaneous* ones, which are unexpected, and *induced* ones, which are deliberately sought, typically based on frameworks or hypotheses and proactive interactions with a situation (Beveridge, 1950). In both cases, the behavior of noticing involves processing, selecting, and recording an aspect of a circumstance that might be different than expected (Beveridge, 1950; Heuer, 1999). It is by noticing these signals or moments of insight that the spark for many enabling innovations has been ignited.

Frameworks from relatively different domains can provide insight into the types of issues and the process of noticing. Spradley (1980), for example, provides categories of items to notice in ethnographic observations including spaces, actors, activities, objects, acts, events, time, goals, and feelings. In the engineering domain, Peck (1969) devised an "observational method" to continuously monitor observed deviances from planned conditions in the construction of earth structures, integrating such observations into design and construction iterations. When generalized to any type of challenge, this method effectively calls for 1) being proactive and explicit in conducting preliminary explorations, 2) assessing most probable conditions and most significant deviations from such conditions, 3) creation of working hypotheses, 4) selection of variables to be monitored, 5) establishing courses of action in advance, 6) monitoring of such variables and assessing implications on original working hypotheses, 7) and iterating on the process. In another example, Anthony et al. (2008) highlight the need to focus on jobs-to-be-done to identify functional, social, and emotional tensions and barriers between the problems that different stakeholders are trying to solve. At the intersection of such frameworks are actions that can help one *notice*, and awareness of a thorough set of possible relevant variables can help generate more thorough working hypotheses that guide observations.

This noticing behavior was observed in historical cases of enabling innovation. In his account of the discovery of X-rays, for instance, Kevles (1997, p. 19) described the record keeping orientation and methodical ways of Nobel laureate W. Röntgen, who recorded all of his observations prior and after his discovery of a previously unnoticed glow while studying cathode rays:

> *"By chance, a cardboard screen like the one Lenard had used (it was coated with barium platinocyanicde, a fluorescent material used frequently at the time to develop photographic plates) lay on a chair a few feet away. Once his eyes had grown accustomed to the dark, Roentgen noticed a soft glow coming from the screen… He stopped for a moment. The glow, in the shape of the letter 'A,' came from a screen several feet away on which astudent had*

apparently written after dipping a finger in the liquid barium platinocyanide. It was the kind of glow he had expected to see if he had put the screen a few centimeters from the tube. But there was nothing he knew of, including Lenard's rays, that could use fluorescence at such a distance. Puzzled by the phenomenon and unable to explain it, he dropped his original plan and began to investigate the strange luminescence."

Röntgen then proceeded to methodically study the rays for several months until his public announcement (as discussed in Chapter 4 of this dissertation). Given the attention that the X-ray discovery caused, others claimed to have seen the rays as well but had chosen to ignore them instead of methodically study them (Kevles, 1997).

The performance task also highlighted instances of noticing forces at play. These performance task instances highlight that beyond being aware of what to look for, noticing also implies recognizing elements of a circumstance/situation that are deviant from prior experience, knowledge, or framework-guided patterns. These deviances seem to need to be named/articulated and captured. Nicole, for example, described the status quo paradigm of driving a vehicle and then started to notice barriers of different types that a transition to an EV paradigm would involve. Similarly, Kate noticed an (in her own terms) "emotional superiority" that currently motivates people to purchase electric vehicles, but also acknowledged that such benefits would decrease with market penetration.

"Looking at (inaudible), you have the current delivery model and the type of vehicle. I don't know if actually type of vehicle is right. You know what? Kind of the customer experience because people, the drivers, they have habits and it's really hard to break habits. So right now you go home, you drive to and from, you park the car, you get out of the car, you turn off the car, you get out of the car and that's it. And it's pretty much the same experience with the Prius in the electric to fuel you there's a whole new step there, you have to plug it in. And then with the Volt, you have to plug it in but if you forget one day, it's not the end of the world. It's kind of like if you forget to plug your iPhone in one night, you're going to be okay, it's still going to have battery the next day. It's not a crisis. Whereas I'd imagine potentially an all electric, it's a little bit higher anxiety if you've forgotten to plug it in. So

there's kind of this the customer experience, the degree of habit change required and when you look at it that way, actually the current, which I'm just calling the gas vehicles, and the fuel power hybrids are actually pretty much kind of the same point." (Nicole)

"So anyway, so this thing about emotional superiority is definitely a real benefit that people have from a car like this. I have an uncle on Facebook who like that's all he talks about is his Volt. He's old but the only thing he ever posts is like his mileage. So anyway, he's still really – it's been like a year. He's still really excited about it. So it feels like I said kind of superior, kind of different, kind of better. So that's some sort of – so some sort of solution about it would be to like help people recognize that you could feel really cool and awesome or increase the cool and awesome feeling. Of course if we actually increase the penetration that much then that's going to reduce potentially" (Kate)

5.6.3 Creating Empathy-Based Mental Models

While gathering information, there is an opportunity to use any insights gained to develop a richer understanding of a phenomenon under investigation. In the case of enabling innovations, this richer understanding can stem from mental models that can facilitate a deeper exploration of information gathered in both human and physical systems through thought experiments. These mental models and thought experiments can generate additional insights, especially in situations, such as the pursuit of enabling innovation, in which actual information to inform efforts might be limited due to the novelty of an emerging paradigm. While prior research emphasizes empathy in efforts to innovation, especially in human-centered design schools of thought, the combination with mental models and thought experiments and the application of this behavior to gain insights even in situations not related to human empathy is unique.

With regard to human behavior, these mental models are often referred to as empathy. Empathy is an ambiguous construct with multiple meanings (Strobel et al., 2013), but in the context of this dissertation, empathy is defined as the ability to accurately detect the information being transmitted by another person – regardless of whether this information is technical, economic, systemic, sociological, and psychological. This definition is inspired by the work of Levenson and Ruef (1992), who provide a similar definition of empathy, yet with a focus on the emotional information being transmitted. Empathy facilitates inferences regarding the underlying motivations (often via a second or third order cause/effect exploration) of human behavior. For example, Ken described a mental model of people's relationship with their cars and the underlying sense of independence that cars provide as one of the beginning stages of his performance task (before attempting to generate any solution):

> *"There's some sort of weird emotional thing that people have with cars. I'm one of them. A car means certain things. So emotionally, it fills a goal of independence. There's something about fun, speed, and (inaudible), I'd say. And this means – independence means that you should be able to travel in almost any condition, right? So there is actually a transportation – part of it is driven by a transportation need, but part of it is also emotional. It says that I can get to where – I am comfortable knowing that I can always get to where I need to go. All right?"*

Empathizing often results in a mental model (i.e., an explanation of someone's thought process about how something works in the real world) (Gentner, 2002; Jonassen, 2003) of other people's behavior. This mental model of human behavior can help to "make a problem personal" (Sinfield et al., 2014). The proactive use of such mental models can help uncover hidden meaning, second and third order effects, rules, norms, or assumptions, as well as conflicts, tensions, barriers, and opportunities embedded in the way people think, act, and feel. For example, research has found that adopting others' viewpoints (Parker and Axtell, 2011), especially when fueled by prosocial motivation (i.e., attempts to help others), enhances the creativity and intrinsic motivations of relevant stakeholders (Grant and Berry, 2011). For example, in the EV performance task, Max described a hypothetical "persona" (or end user profile) that he would create to better think through the challenges of EV adoption:

> *"We would then start to ascribe attributes to that type of person that fall under each of these categories and let's just do one for the sake of an example. I'm gonna just see which one. So I think I would just go with the green -- what I call the green – consumer and you would describe attributes that might not align exactly with vehicle choice but it gives you an idea of how they think in making their decision so I would expect these people, for example, to shop locally versus at a national or a regional establishment, for example, right, because they want to support their local community. I would expect that these folks, you would find a lot of volunteers within this group so they're giving back to their community in some fashion, whether that's giving money to the United Way or actually going and giving some of their time for a particular in their community. I would expect to find a lot of folks in that category as well. I would expect to see that they're energy-conscious beyond just their car choice. You might see some sophistication within this group and, by that, I mean, you know, if they're truly energy and cost conscious you could see things like they're using home-energy automation systems for example so there might be a parallel there to the choices they're making. Well, you get a sense of what we're trying to do. We're trying to describe a person and the attributes around that person or a group of people so that we can understand them in more detail."*

Engaging in empathy effectively, however, requires a degree of self-awareness and understanding of possible personal biases (Heuer, 1999). For example, in his performance task, Victor seemed fully self aware of the process he employs when trying to empathize and create mental models and the importance of being proactive about empathizing with many types of people beyond one's network:

> *"The first one is the recognition that you're an N of one. So I am an N of one in a world of a million. Okay? So that becomes the first premise that I always work with. And oh, by the way, my N of one may actually be an N of zero if I'm not a consumer. So the first recognition is that what I see of the world of the problem may be absolutely insignificant. So I've got to then say, okay, so what I think doesn't count. And so then I have to then find somebody who I know, because we all know people, who I can then say, no, that's the person that we're thinking about, talking about. Here's how, based upon my experience with them, I believe they would be. Because you've got a mother. You've got a sister. You've got a brother. You got a – you know, you got soccer buddies. You got – I mean, we all have those experiences. It's just a matter of pulling them back in, and saying, oh, that could be Fred. That would be, you know, Sally. Okay? And now you're*

> *saying, okay, so now let's – what would Sally do? How would – and so they may not have the same thousands of names that I have, but we've all got hundreds of them. And the last point is the recognition that every once in a while, you're going to get yourself in a place where you don't have anybody, at which point in time you say, I got to go find that."*

Beyond helping to understand human behavior, a mental model of physical systems that is similar to an empathic perspective can also be developed to better visualize the components and interactions in physical systems. Thus the behavior of empathizing and creating mental models described herein is broadly applicable. For example, in his memoir of the development of the laser, and its critical predecessor, the maser, Charles Townes (1999, p. 51) explained how he "empathized" with molecular systems, specifically ammonia molecules:

> *"…my career brought growing familiarity and fascination with molecules. How molecules absorb and emit energy, their motions, and the behavior of their electrons and nuclei – all those things, while never actually seen by anyone, became real for me and easily visualized. When I try to figure out how a molecule behaves under particular circumstances, it seems almost like a friend whose habits I know. Ammonia, without a doubt, has been my favorite. Its simple arrangement of a single nitrogen and three hydrogen atoms has been pivotal in many important moments of my career. I have met this very familiar molecule in the inside of masers, as the mainspring of atomic clocks, in clouds among starts at great distances from Earth and in atmospheres surrounding some starts."*

5.7 Broadening Idea Spaces by Connecting Generalized First-Principles

Levels of practice for the design stage of generating alternatives vary according to the fluency with which ideas are generated. Beginner designers tend to generate a scarce number of ideas (Crismond and Adams, 2012), while informed designers seek to be fluent in the generation of ideas. This idea fluency can come from brainstorming, design heuristics, lateral thinking or generic parts techniques (Daly et al., 2012b; DeBono, 1970;

McCaffrey, 2012). In complex challenges, however, the size and scope of problem and solution spaces must broaden compared to routine challenges, guided by boundaries that are flexible yet pragmatic, to avoid searching across spaces in which useful ideas are unlikely to be found.

In the context of the enabling innovation model, being expansive and pragmatic in the generation of alternatives helps ensure that ideation processes match the characteristics and strategic intent of particular stage of the model. In the stage of breakthroughs, for example, ideation strategies should address critical barriers. In the enabling window, ideation strategies should connect generalized first-principles of a solution to a broader set of contexts of application that can monetize/fuel the development of such solution while advancing select performance dimensions. In the progressive cascade, new platforms and progressive innovations should be envisioned.

At each stage of the enabling innovation model, core behaviors such as distilling ideas from contextual influences, proactively shifting perspectives, diverging-structuring-converging, and prioritizing play a role in conducting an exhaustive yet pragmatic search for ideas. Distilling ideas from contextual influences can facilitate connections between ideas that are seemingly unrelated but share underlying principles that are applicable to multiple problem/solution spaces. Thinking about the underlying principles of ideas (e.g., describing what a technology *really* does without ties to a context) can help unearth new possibilities (Sinfield, 2005). As such, distilling ideas from contextual influences can help overcome behavioral tendencies such as *functional fixedness* (a tendency to fixate on traditional uses/applications of artifacts) (Duncker, 1945), and what we herein define as *application context fixedness* (a tendency to inherently link ideas to a specific context). Systematically exploring variations can help facilitate a more comprehensive idea search, particularly when these variations ensure that ideas are sought after in diverse ways (e.g., opposites, intersections, adjacencies, analogies, additions, subtractions). Iteratively diverging, structuring, and converging, ensures that "idea spaces" (see Ogle, 2007) are mutually exclusive and collective exhaustive. Finally, prioritization ensures that goals and bounds provide guidelines to be expansive yet pragmatic (see Sinfield and Anthony, 2006; Anthony et al., 2008; Sinfield et al., 2012; Sinfield et al., 2014 for an entrepreneurial perspective).

Adding to these core behaviors are specific behaviors that can ensure that connections between underlying principles that expand idea spaces are occurring, shown in Figure 5.15 and synthesized in Table 5.5. These behaviors include *interacting with new schools of thought* to multiply ideas, *linking core ideas to diverse problem and solution spaces*, and *exploring morphological combinations/variants*. Networking across contexts implies that interactions with diverse social networks (Dyer et al., 2008) can help multiply and test ideas, particularly when proactively sought after and when ideas are understood without ties to a specific disciplinary context. Linking diverse problem and solution spaces is defined as an umbrella term for behaviors such as associative thinking (Gavetti and Rivkin, 2005; Gavetti et al., 2005; Dyer et al., 2008), analogical reasoning (Ball et al., 2009), which typically refer to the formation of links between ideas or select aspects of ideas across contexts. Exploring morphological combinations/variants helps ensure that many variants in the configuration of possible ideas that result from an exhaustive conception of problem and solution spaces are considered, including those that are potentially counterintuitive. As such, this behavior goes beyond traditional conceptions of morphological analyses (Zwicky, 1969; Ritchey, 1998, 2011), ensuring that each row/column in a morphological chart holds a mutually exclusive and collectively exhaustive structure and that each cell can be decomposed into its underlying components if needed (see Sinfield et al., 2012 for an example from the entrepreneurial domain).

The following sections describe these behaviors – interacting with new schools of thought, linking problem-solution spaces, and exploring morphological variations – in more detail and using evidence from all three methodological approaches. The importance of core behaviors is highlighted when relevant.

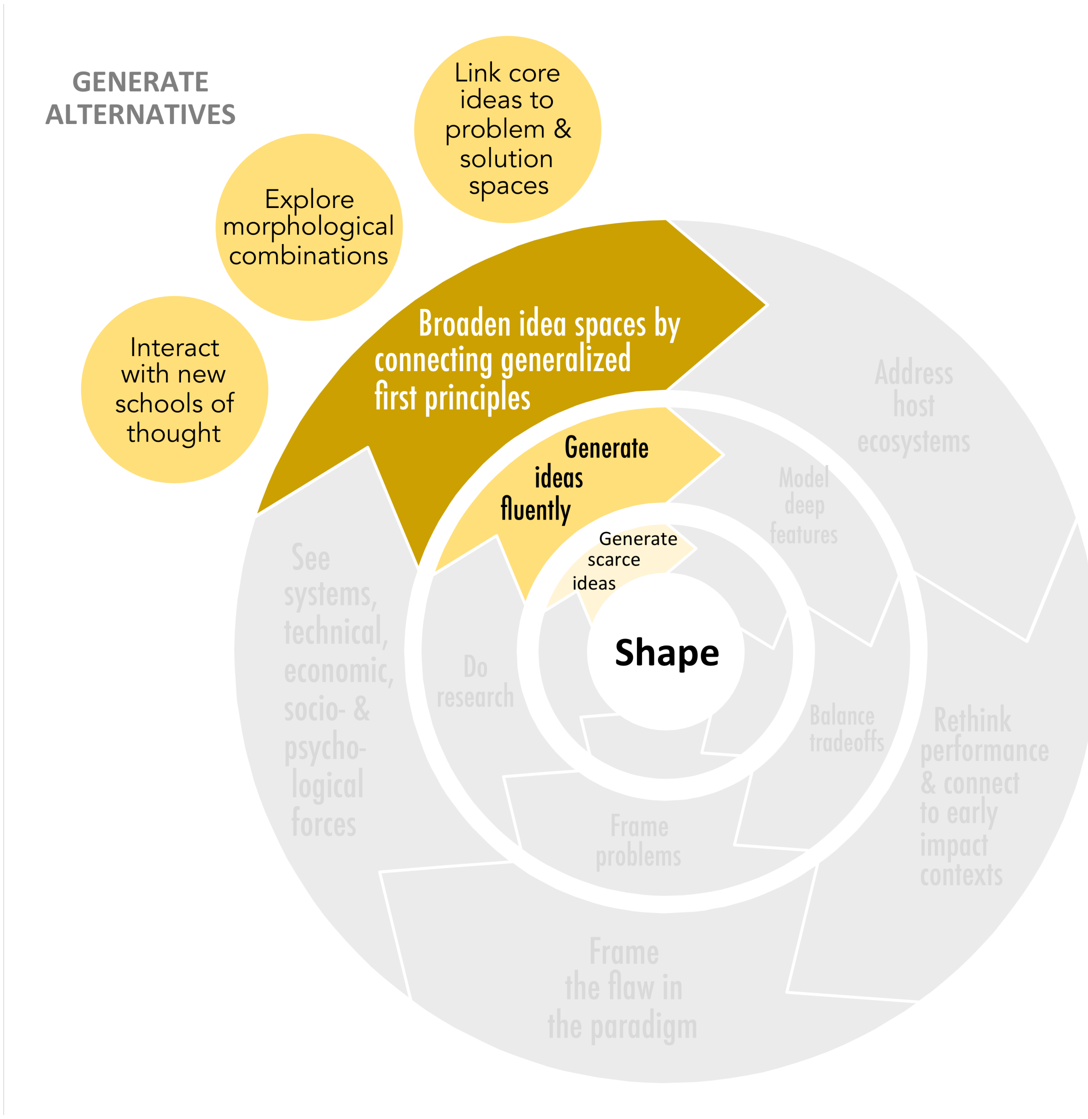


Figure 5.15 Broaden Idea Spaces by Connecting Generalized First-Principles

Table 5.5 Behaviors to Broaden Idea Spaces by Connecting Generalized First-Principles

Behavior	**Definition**	**Related literature**	**Unique link to enabling innovation**	**Link to broadening idea spaces**	**Illustrative actions/activities**
Interact with new schools of thought	Obtaining and testing ideas through many types of interactions across counterintuitive contexts or at the intersection of fields	• Rodan and Galunic (2004) • Johannson (2004) • Dyer et al. (2008) • Sinfield et al. (2014)	Critical insights for enabling innovations may likely stem from contexts not originally considered as relevant to an enabler thus calling for proactive interactions across an expansive set of contexts and through distinct channels (e.g., social/verbal, written)	Ideas to address challenges and opportunities regarding enabling innovations are often found through interactions in counterintuitive fields/contexts. Pushing and pulling ideas across contexts can help broaden idea spaces and garner feedback	• Attending events/ conferences outside of ones discipline/field • Talking to people from counterintuitive domains • Proactive social interactions with people outside one's discipline/ field • Proactive exposure to information outside one's field/discipline
Link core ideas to diverse problem and solution spaces	Finding cause-effect patterns in problem and solution spaces by noticing trends that are seemingly unconnected	• Gavetti et al. (2005) • Dyer et al. (2008) • Moreno et al. (2013) • Sinfield et al. (2014)	Ideas with enabling innovation potential are likely transferable across multiple diverse problem and solution spaces as generalized first principles	An idea space related to an enabling innovation can expand based on similarities in underlying causal features/traits with ideas from other problem and solution spaces	• Connecting ideas across contexts/ spaces • Thinking of analogies for problems or solutions at hand • Connecting underlying principles between ideas in separate fields
Explore morphological combinations	Exploring all possible idea variants that result from combinations in the identified features/ aspects of problem and solution spaces	• Zwicky (1969) • Ritchey (1998, 2011) • Sinfield et al. (2014)	Enabling innovations are inherently combinatorial and complementary to other ideas and a broader examination of morphological possibilities (including broader systems issues) can amplify a concept's cascade potential	Exploring a rich, mutually exclusive and collectively exhaustive set of combinations of ideas may trigger new problem and solution insights that expand an idea space	• Creation a comprehensive perspective of possible combinations of ideas • Trying out different idea combinations and their implications

5.7.1 Interacting with New Schools of Thought

Idea spaces can broaden by *interacting with new schools of thought* to multiply and test ideas, particularly when ideas that are potentially enabling given the potential of enabling innovations to create an impact cascade across multiple application spaces. As such, critical insights for a concept with enabling innovation potential can be found through interactions with counterintuitive contexts. Such interactions can occur though multiple channels (e.g., social, written), for instance, by engaging with diverse social networks, or by actively scanning literature across fields.

Historically, stakeholders involved in enabling innovations, consciously or unconsciously, engaged in diverse interactions across schools of thought (and contexts). In the development of GPS for instance, William Guier described how he had to borrow concepts from astronomy, specifically based on the equinox, the intersection between the earth's orbit plane and the equatorial plane to determine a satellite's orbit: "Bob Newton taught me the jargon of astronomy so I could begin to read what was going on in satellites" (Worth and Warren, 2009, p. 6). These social interactions at the intersection of fields, also happened in the development of anesthesia. Charles T. Jackson, a Harvard Medical School graduate, chemist, geologist, and mineralogist, played an important role in facilitating dentist Thomas Morton's successful demonstration of surgical anesthesia. Jackson's knowledge of chemistry and medicine helped Morton determine the right type of ether to employ in the first surgical anesthetic, advising him to use "purified rather than the impure commercial ether" (Sykes and Bunker, 2007, p. 12). In the history of microfinance, Muhammad Yunus proactively scanned literature on poverty beyond his field (i.e., economics), and across sociology, psychology, and anthropology to build a broader understanding of poverty that could lead to new societal development ideas.

This type of interaction, in entrepreneurial contexts, is pursued by engaging with members of diverse social networks (Johansson, 2004; Dyer et al., 2008); yet in addition to social network diversity, the pursuit of heterogeneous/diverse knowledge seems to also be relevant (Rodan and Galunic, 2004). Lane and Maxfield (1997) describe these social relationships as generative, because they "can induce changes in the way participants see their world and act in it" (Arthur, 2007). Effectively, diverse social networks and diverse knowledge networks facilitate pushing and pulling ideas across both traditional and counterintuitive contexts, and maximize the variety of perspectives that provide feedback. These interactions can also provide "outside-in" perspectives (i.e., ideas from outside contexts that can be brought to a given circumstance) (see Sinfield et al., 2014), or provide additional seemingly unrelated ideas. Overall, pushing and pulling ideas across contexts can help broaden idea spaces and garner feedback that helps further shape a given idea.

Interacting with new schools of thought therefore calls for seeking different perspectives by proactively breaking from one's usual social network. Victor for instance described the types of stakeholders he would engage if in the pursuit of ideas for the EV challenge:

> *"Well, clearly I would get each – I'd get experts in the technology. Okay? So who in the automotive industry would know a lot more – who in the electrical industry, who in the power industry would – clearly some consumers. And when I got into the consumers, I'd be looking at those that are doing hybrids versus those that are doing plug-ins versus those who are doing the electrical, and really understand where they are, because that's a very – you know, this analysis, very assumption-based element. And so if I was going to talk about what I'd be doing for the next few weeks to solve this problem, that's where I'd be going. And clearly, then, going back to political experts, government experts, about, okay, so let's talk about incentives and what works and what doesn't, and what the unexpected consequences are, the unanticipated consequences, of these different incentives, and how do you really think about putting them together? (Victor)"*

Through these proactive social interactions, the goal is to facilitate what Sinfield et al. (2014) call "outside-in" perspectives. Such perspectives can help push ideas across many contexts as a testing mechanism and pull ideas from exposure to non-traditional environments. Drew, for instance, in his EV challenge described how he would try to get many perspectives and made an analogy to practices in the medical field to highlight why such an exercise would be valuable:

> *"I think I would take a car – electric car expert that was very open and doesn't want to dominate and be the expert. I would take someone from the car industry. I think I would take just a representative from everybody from the ecosystem, which now I've identified it, the battery manufacturer, car manufacturer, and customer, and maybe even a fuel station rep. Petrol. Oh, and then I would probably have to take a utility, etcetera. So I would have taken people within the different elements of the potential ecosystem. And that would be interesting, because they have all the know-how. I mean, the electricity guy could tell me right away, okay, if it's possible or not. For example, cost-wise. They have all the know-how, but I have to bring the know-how together. It's similar to the model clinic principle. I don't know if you know the model clinic. So if you go today to a doctor, you go to an expert, he looks at your knee and says your knee is well or it's bad. But maybe you – you never look at the entire system. And therefore, general practitioners are – very often, they find the problems faster than the experts. But what the model clinic does is they – especially for difficult cases, they invite you, and you're interviewed by let's say 20 experts, one by one. And then the 20 experts sit together and look at your case. So someone would say, okay, I looked at the knee. There's nothing. Then the other would say, okay, I looked at the blood tests. I found this. The third one would say, but at the back, I found something which is strange. And then suddenly the guy with the knee, oh, now it makes sense. The guy from the blood would say, oh, now I see what you mean. And in putting these things together, they would come up with a solution. But insulated experts I don't think – well, isolated expert doesn't make sense. But if you bring several experts together and you orchestrate it, then you come to the solution."*

Interactions with new schools of thought need not be necessarily verbal. Susan, for example, emphasized that she often scans journals from different literature sources to search for ideas (particularly flawed paradigms in her case):

> *"So I'm willing to dive into biology and understand that I don't understand it to the depth of a biologist, and in some ways I think that's healthy because then I'm not trapped in the dogma of the field, right. And so I just think differently… I do, you know, scan lots and lots of, say, journal articles in the field I'm currently interested in, and look for commonalities in the flaws and*

don't worry so much if I don't understand everything in depth. I mean once I find the flaws then I can rely on seeing my medical collaborators or my veterinary collaborators, or my biology collaborators to really understand the subject so that they can help me apply my technology to the problem, but I want to understand it just enough so that I can understand the flaw and come up with what I think is a creative solution to the flaw and then grab my collaborators and say, 'This is what I wanna do,' and get them on-board to serve as the domain experts."

This proactive interaction/networking behavior can help trigger chains of ideas, i.e., second or third order effects that participants reflect upon after such interactions, and seemed to be inherent to some participants. As an example, in the EV task, one participant – Rand – stated from the beginning that he would not be able to do much without talking to people because that was his natural design/problem solving approach. Therefore, he used his computer to engage with peers online and started verbalizing his online interactions regarding the EV challenge (within the boundaries of what the administrator considered acceptable). Some examples of his interactions, and how they helped him trigger "chains of ideas," are provided below:

"I'm going to see, I think my friend just messaged me on Facebook, let me see if he wants to jam on this real quick and see if he's got any ideas. More realistic of how I do it anyway. So I'm just messaging, 'doing a study on innovation, need to increase adoption of electric cars in the US. Have any ideas?' I find when you have ideas and you just kind-of toss them back and forth with people, you tend to just kind-of ping ball – or pinball your way into better solutions, at least for me… [let's] [s]ee what my buddy's got: 'Charging infrastructure is a big problem,' OK, so I got that far man, come on [laughter]… Now I'm – what I'm thinking now, boil problems down to price, vehicle options, options, charging infrastructure. Figure incentives could work for all those, [the] question becomes what is the most efficient way to solve those problems. Done. So I guess, for just overarching when I do solve problems, like many people as possible that I think are educated, get in a room and just jam on ideas, with computers looking up stuff as well. He says 'technical limitations of tech.' Explain… 'well batteries generally suck, generally slow to recharge and cold weather drop-off is significant, also very heavy and low energy density compared to gas.' Not real sure that can be solved, just a matter of time. Incentives for charging stations is probably an easy place to start… [Rand continues reading his online interaction:]

> *'Batteries generally suck, cold weather drop-off.' I don't remember that being a problem. Actually, I remember there was rumors of that for Tesla, so I'm looking up Tesla – because the way I see it, Tesla's kind-of the benchmark for successful electric vehicles. They've had the most success with that, commercially and also I think they've done the most in terms of technical innovation with power and range and things like that. So when I think electric vehicles, I think the solution – if you're going for anything, you should go for more Teslas and not more of the other ones, what are they, the – all electric but they have the gas backup. I don't know, I feel like Tesla's proven that you can go straight for the electric vehicle approach assuming you have the infrastructure in place. And it's one of those things too, you can – even though it's like a nationwide problem and the electric infrastructure is probably a bigger deal, especially like in the Midwest and stuff like that where you're more spread out, you can tackle the problem in the coastal areas first and then worry about adoption in the Midwest later, that's the way I see it, also. I mean, yeah, more densely populated, more money to buy things, too, typically. Wealth is distributed towards the coasts in the US, so I think that plays a factor and I mean, you've got to start somewhere, so low hanging fruit would be where there already are charging stations and people buying these vehicles, so how do we get more of them buying those before we try to spread ourselves thin and go after the people who are less susceptible to buying them. Battery life in the cold. A couple articles on this, forums, things like that. So incentives, my buddy had written back incentives for charging stations is probably an easy place to start, and so I asking him if that – he thinks that would be a better use of capital than incentives for purchasing or for car companies." (Rand)*

5.7.2 Linking Core Ideas to Diverse Problem and Solution spaces

Beyond interactions, the generation of alternatives can also be more comprehensive by *linking core ideas to diverse problem and solution* spaces that are seemingly counterintuitive or nonobvious. This expansion of an idea space based on connecting similar underlying/causal features can trigger new or different insights that can help drive an enabling innovation forward, regardless of its impact stage. For the enabling window in particular, core/generalized ideas can likely be linked to multiple problem-solution spaces in the pursuit of eventually achieving an impact cascade.

These links between idea spaces typically stem from noticing links between ideas source (i.e., apparently similar idea from another context) and target (i.e., the context of the challenge or opportunity at hand) contexts (Gentner and Stevens, 1983; Gavetti and Rivkin, 2005; Gavetti et al., 2005). Such links are often initially recognized by identifying relationships in trends, changes, and events and by noticing that such connections form an identifiable pattern (Baron, 2006; Dyer et al., 2008). These associations (also often called analogies) help build connections that facilitate the exploration of different domains and help avoid idea fixation (Ball and Christensen, 2009; Moreno et al., 2013). Such associations can be proactively sought after by, for example, separating problems from solutions, removing ties from specific features to applications within such spaces (McCaffrey, 2012; McCaffrey and Krishnamurty, 2014), and articulating decontextualized perspectives of these spaces (Sinfield, 2005). As a result, links between "obscure" (i.e., previously unidentified) features of such source and target contexts can be made regardless of whether such connections might seem counterintuitive at first glance.

At the heart of these connections is the need to recognize and articulate cause-effect patterns between source (i.e., context from which an idea is borrowed) and target (i.e., context to which the borrowed idea will be applied) contexts. Thus, core behaviors such as distilling the core of an ideas from its context, finding first-principles, breaking ambiguous ideas into tangible parts, and shifting perspectives, play a role in linking underlying features of ideas, particularly when such ideas come from spaces that are not typically connected. For example, in the selection of source contexts to examine, one can shift perspectives directionally, alternating between analogies and metaphors, opposites, intersections, and adjacencies.

Many historical cases described in Chapter 4 of this dissertation illustrate connections between seemingly counterintuitive fields. Two examples are provided here – first from the history of antiseptics and then from the history of the maser and laser.

The history of antiseptic treatment illustrates how linking seemingly unrelated fields can lead to impact-generating ideas. Joseph Lister, a surgeon that played a relatively prominent role in the development of antiseptic treatment, made two key connections between diverse fields that informed the development of one of the first documented antiseptic treatments (Lister, 1867; Clark, 1907; Lidwell, 1987; Lederberg, 2000; Francoeur, 2000; Gawande, 2012).

The first connection linked Pasteur's studies on fermentation to the field of medicine, particularly by hypothesizing the influence of the "germ theory of disease" on surgical recovery and infection. Prior paradigms assumed that infection was due to "coldness" and to oxygen in the air. Lister was among the first to understand the link between Pasteur's germ theory (developed in the context of fermentation, which then evolved to be known as the *germ theory of disease*) and his studies of surgical infection. This link is narrated by Lister himself in one of his hallmark publications:

> *"…how the atmosphere produces decomposition of organic substances, we find a flood of light has been thrown upon this most important subject by the philosophical researches of M. Pasteur, who has demonstrated by thoroughly convincing evidence that it is not to its oxygen or to any of its gaseous constituents that the air owes this property, but to minute particles suspended in it, which are the germs of various low forms of life, long since revealed by the microscope and regarded as merely accidental concomitants of putrescence, but now shown by Pasteur to be its essential cause, rendering the complex organic compounds into substances of simple chemical constitution, just as the yeast-plant converts sugar into alcohol" (Lister, 1867, p. 326; Clark, 1907, p. 166).*

The second link, related to the development of the first antiseptic system based on carbolic acid, stemmed from connecting an event in Carlisle, an English town, where carbolic acid had been used to "deodorize" the sewage system and at the same time destroy any substances contained in the system. Lister "learned that all the cattle accustomed to be pastured on these fields, before the sewage had been thus treated, had been subject to a certain form of entozoan, but, after the use of the acid, they remained unaffected. Professor Lister was at once sensible that carbolic acid was a powerful disinfectant and capable of destroying low forms of parasites which had formerly affected these cattle" (Clark, 1907,p. 167). Thus, in this link, Lister created a purpose-driven association (destroying germs using carbolic acid) between source context (sewage system treatment) and target context (treatment of surgical infections due to germs).

In another historical example, in the history of the laser, Nobel laureate Charles Townes described the importance of seemingly "counterintuitive" connections: "What research planner, wanting a more intense light, would have started by studying molecules with microwaves? What industrialist, looking for new cutting and welding devices, or what doctor, wanting a new surgical tool as the laser has turned out to be, would have urged the study of microwave spectroscopy?" (Townes, 1999, p.75). Yet examination of the history of the laser suggests that Townes' idea was not accidental. After World War II, and prior to the maser and laser inventions, Townes had a goal of expanding astronomy into radio frequencies and met with a Caltech professor who rejected his ideas – as Townes recalls: "he looked at me and said, 'Well, I'm very sorry to tell you, but I don't think radio waves are ever going to tell us anything about astronomy. I just do not think there is anything to do. The waves are too long… the are not directional, they can't really tell us anything.' " (Townes, 1999, p. 42). Townes later reflected on this episode in his memoir of the history of the laser the importance of networking ideas across contexts – even if counterintuitive at first: "…his remarks illustrate what often happens in science. People in well-developed fields tend to be conservative, particularly with regard to ideas from outsiders. As experts they have a feeling they understand the field well and often do not much care for interlopers. In addition, their views of ideas or technologies behind new proposals outside their own fields of expertise are sometimes rather limited" (Townes, 1999, pp. 42-43).

The aforementioned examples highlight that, although connections in ideas from seemingly unrelated fields might seem nonobvious, awareness of the underlying principles of a field's core/central ideas help facilitate connections across fields. These connections thus effectively call for proactively translating key domain specific ideas into generic language when possible. Such a translation can occur through core behaviors such as breaking ambiguous ideas down, finding first-principles to unearth underlying concepts, and distilling the core of ideas from contextual influences to be able to see such connections.

Examples from the EV task further illustrate how links between diverse fields occur. Mike, for example, broke down the EV challenge using an adoption framework from the field of marketing and explored categories within such elements of the framework. For each of the categories, he reflected upon ideas and often used analogies as a tool to trigger insights or more ideas. For example, he imagined an awareness campaign that had elements of present-day anti-smoking campaigns, which he conceptualized as an attempt too drive a social shift (the underlying idea):

> *"Better alternatives, social, negative. So you could have a – you could sort-of have a viral – ad campaign that sort-of is like, making fun of gas users, gas guzzlers or whatever. Like you could basically – you could sort-of have this sense that like – you could create more of a negative social – like where – it's almost like smoking, right? So like the squares were the ones who didn't smoke back in the '50s, but then over time you can transform that, so that's actually an interesting thing to think about is, like, other social shifts where you start with the freaks being the ones who do it, and then over time, it becomes mainstream to where it's almost embarrassing to not do it. So in this case, the analogy is smoking, so it's almost freakish now if you actually do smoke, or you're seen as – kind-of an outsider, whereas back in the day it was you're an outsider if you didn't smoke. And so could you have a sort-of Truth.com type viral ad campaign that makes fun of gas guzzlers or like somehow makes it so that we're not the weird ones, you're the weird ones. The gas guzzlers are the weird ones, you are the weird ones."*

With developed conceptualizations of a target problem/solution that are more easily transferable, one can explore source context candidates that spark ideas of how to address issues in the target context, through analogies, opposites, intersections, and adjacencies. These can stem from (using Mike's terms) immersing in stimuli or from prior knowledge and experiences. For example, Mike continued the aforementioned ideation exercise in which he scanned the web for inspiration, reflected upon his experience and knowledge across domains, and identified analogies for challenges he identified for EVs in ideas from other domains, drawing from source ideas such as the X-prize and the "got milk?" campaign:

> *"…one theme I'm kind-of taking away is that electric cars kind-of suck I various ways, and so it's not so much that people are like – even if the – like it's kind-of like even if the money was equal, there's a lot of people wouldn't want it because it's small, it's ugly, it's unsafe, and I think there's also this notion of that you're like – well that – so that's one problem is to attack the EV cars, unsafe, poor performance – and probably biggest is ugly. Ugly, unsafe, poor performance and was the other one? Aesthetics, safety, expensive, not pleasurable to drive, maintenance costs, max speed, limiting, I'll say. It's limiting in how far it can go, in range. So you're sort-of – you feel kind-of hemmed in, like the fact – like you never actually would want to drive off into the distance, but the fact that you could at any moment is kind-of cool. So I think ideas that get over this, I think first of all, you could somehow have a incentives to car makers. To design better car, car makers or car designers. To design better cars. So what would that looks like? It could be tax breaks, it could be a prize. I kind-of like that idea, like X Prize type of prize, million dollar prize to the car company that can come out with like, the best new electric vehicle, X Prize... So now, let's assume they're awesome. There's the fact that like, negative perception relative to positive. So I think here, we've got a – here I we've got to do an ad campaign, both online and print, and sort-of like Electric Vehicle Association of America – sort-of like got milk."*

Making links between diverse problem and solution spaces implies also identifying aspects of solutions that can be transferred from the source to the target context, and deciding, if a problem/solution is applicable, to translate, and adapt it – i.e., assessing the fitness between source and target. Ken, for example, in his EV performance task, started to thinking about analogies for business models. Through these analogies, he envisioned moving car expenses from "cap-ex" (capital expenditure) to "op-ex" (operating expenditure), and used analogies to imagine how ideas from source contexts could be applied to the EV challenge:

> *"If you think about things that have made transitions in terms of footprints, from converting people who think about large – large single converged purchases into – I mean, like a – like a multi-use op-ex type purchase, right? It's – the analogies aren't super clear, but the most interesting like – it's like own versus rent, right? Which is really – which is really common when you think about kind of the cost per use as opposed to – the cost per use per day as opposed to buying something outright. So like a really big, common one is like – is like Amazon instant video, right? So you can pick either one, depending on what your flexibility is and depending on whether or not you want to own it. So you can kind of make that decision on your own. Another one, you know, is – when you think about infrastructure especially, is Amazon Web Services, where you scale the price of what you need based on your demand when you need it, and you pay for what you need, and you don't – you don't necessarily buy – there's no cap-ex investment. It's just entirely op-ex based. So that's interesting from a financing perspective. From a – from a use perspective, if you think about the things that really spike on those customer needs, at least the ones that aren't super fixed, right? So things that increase utilization of physical infrastructure, or infrastructure in general. VMware, right? I'm just taking the technology case (inaudible). So VMware, it's, well, we can increase your utilization across multiple systems and changes how you you interact with those systems…"*

Ken then used his analogies to think more deeply about how the vehicle industry could move from cap-ex to op-ex. Effectively, he understood and articulated the underlying idea (flexible utilization of assets), and translated it into a business model in which people can use cars that better fits their needs with more flexibility through his imagined car exchange service:

> *"It's (inaudible) was essentially a cap-ex investment, you used to buy from IBM, and you'd do an op-ex investment that you'd buy from us. We're going to rent you what you need when you need it, but otherwise – and you*

> *can come in and you can trade up. You can trade geographies. You can trade locations. If you were worried that a big storm was going to hit a location in Washington, you can trade to a secure data center in Northern Virginia, just like that. And by doing that, they enabled flexible utilization of assets and a higher utilization of their assets than what a kind of enterprise-owned set of assets would have. So that's what I imagine being the only thing that's – well, the only thing that – as being a key driver of the efficiency needed to be able to enable Jose not to go bankrupt owning two vehicles."*

5.7.3 Exploring Morphological Combinations

Attempting to broaden a problem and/or solution space, particularly when enabling innovation is the end goal, often requires being exhaustive in the ideation process and considering all possible idea combinations. This exhaustiveness in problem and solution spaces implies identifying all (or as many as possible) addressable gaps and going beyond "satisficing" (i.e., finding an adequate/acceptable answer at a specified level or criteria) (Petre, 2004).

One way in which the total set of addressable gaps can be assessed is by engaging in a variant of morphological thinking/analysis (Zwicky, 1966, 1969; Ritchey, 1998, 2011; Kumar, 2012) – which emphasizes *exploring all morphological combinations*. In this variant of morphological thinking, a problem and/or solution space is broken down and structured into mutually exclusive and collectively exhaustive categories, striving to identify as many variations as possible within each category. Sinfield et al. (2012), for instance, proposed a method to qualitatively model all morphological combinations of the elements of a business model in mutually exclusive and collectively exhaustive ways. The exploration of such categories and variables within categories can occur at different levels of depth, with many of the modeled variables going beyond functional/technical issues to include economic, sociological, and psychological issues.

Qualitatively modeling to explore all morphological combinations calls for core behaviors such as recognizing and labeling patterns, diverging-structuring-converging, and other behaviors in the framework described herein such as structuring ambiguity and employing multiple lenses. Thus, the goal is to be exhaustive in identifying possible combinations of variables that uncover new possibilities, constraints, or barriers to a given goal.

Even though morphological thinking is a relatively recent concept relative to the time eras in which some enabling innovations were realized, one can observe a similar behavior in historical examples of enabling innovations. For instance, in the development of X-ray machines, Edison and his team systematically tested different configurations in the development of one of the first X-ray devices (Kevles, 1997). Their efforts included a comprehensive exploration of the idea space and testing of different combinations of materials for the different device components. These components included combinations of different types of glass for the X-ray tubes, and different materials to replace platinum wires inside the tube settling on aluminum disks. As an example of how they explore all morphological combinations, Edison's team tested over 8,000 different chemical combinations for the screen's material, before settling for calcium tungstate to replace the barium platinocynanide that was used in earlier versions of X-ray devices. This methodical and seemingly exhaustive exploration of an idea space led to one of the first commercial X-ray devices, which they named the fluoroscope.

Qualitatively modeling all possible morphological variants and combinations implies being able to create goals and bounds for a given challenge, and within such goals and bounds creating a qualitative, mutually exclusive and collective exhaustive, and systemic view of such a challenge – similar to traditional morphological analyses. For each category in this systemic perspective, all possible variants that serve as the basis of combinations need to be mapped, shifting perspectives and lenses to be as exhaustive as possible. Charles, for example, in his EV performance task described how he employs a similar process in his approach to challenges (in general):

> *"…[I] basically sketch the problem, put the basis for the problem in, put the dotted line around the basis, and basically start to define what that is. This is a pretty open-ended problem, a pretty – it's not like a heat transfer problem, that you've got basically one issue you're looking at, is define the system, define what you're interested in, energy in and out. This is one that gets to be a little bit more complicated because it's got a customer and consumer aspect, it's got engineering aspects, and it's got other flow systems that you've gotta worry about, fuel, electrical energy, and so on. So my approach with these things – is generally try to at least – whether on paper or in my head – sketch the problem, lay out the puzzle pieces that you've got that might be pieces of that. It's frequently with an open-ended problem we're not gonna have all the pieces or assets right away, so that's why you try to figure out which puzzle pieces you have equivalent to dumping the 5000-puzzle box out in front of you and start turning a few pieces over and see which ones look interesting, and then that's kind of my process with this, is see what's interesting on the people side, on the organizational side, and then on the other more hard-stand assets: What's fixed, what would it be impractical to build in a short time if I was trying to solve this problem or trying to put together whether it's a new project on campus or a new company or a new capability need to solve a government problem."*

In her performance task, Nicole, also engaged in a similar type of behavior. More specifically, she explored different business models and the different variations within/between business models for EVs capturing different elements of the EV ecosystem, geographic regions, and delivery models:

> *"I think you play around potentially with different business models and run experiments of do you leverage your existing dealer network? Maybe build some retailers, do some mail order. The other thing I would think about is in addition to selling to individual consumers, because these are also cities where car sharing, basically the absence of car ownership is taking hold, can you also target things like Zip Car? Kind of fleet sales, basically. So you'd potentially think about that as well… this is where I think there are some really interesting stuff that could be done. Thinking specifically around the distribution model and is there a way to kind of scrap this dealer concept? Because the dealers, it's such an embedded distribution system that has all of*

its own baggage and own cost structure and people who are used to selling certain fueled vehicles in certain ways that is there a way to change it? And it's tough because there are certainly benefits to the dealer network in that kind of gas stations they're everywhere. And if you need one or not you've kind of always known where one is because they advertise so heavily and their signs are all over. So there are certain benefits to it but I wonder if there's a way to not be captive to it? You could potentially have a business model that looks very similar to the current business model; you use the dealers. But are there ways to change that up whether it's through retailing the way Tesla has, which actually could lay the foundations for paving the way for all electric vehicles. Because I'm sure if GM and Ford and the big guys got into retailing, then it wouldn't just be Tesla against the legislative - legislators, it would be the auto industry against the law makers and it probably would be half the fight that it currently is because of the embedded lobbying of the big auto makers. So I think there's lots of room for experimentation on the business model side. Sorry, let me write something down before I forget it. Dealers, others, retailers, subsidies. There are things that I'm thinking about on business models that kind of goes beyond that is – maybe the back to customers and footholds is there is just a fundamental difference between life in a city versus life in the suburbs versus rural. There's a big difference between east coast, Midwest, South, like regions of the country. It won't be a one size fits all. Probably I can imagine it, just like in LA, there's a reason all this EV stuff kind of really caught hold in California because people are primed for it. The smoke is awful, there are very real important and unsatisfied jobs to be done around just health that are frustrated by existing vehicles. So there's these potential - there's this other element of the business model around where do you start and where do you roll out? And the traditional business model of you make something available nationally, probably doesn't make sense here. I know Volt when it started, they could make ten thousand vehicles so they're like where do we place those ten thousand? Which is even different than how Tesla approached it which is you had to get on the waiting list, so they just kind of shipped from their factory to whoever got on the waiting list. So I think there's - so that kind of business model of almost like mail order to some extent." (Nicole)

For each variant/variable in the qualitative modeling process, one can explore adequate levels of depth/decomposition, identifying gaps, and proactively exploring combinations, particularly those that are counterintuitive, by linking different elements of a problem and solution in a morphological map/chart. Victor, for example, explored different issues to varying levels of depth, such as EVs for urban or suburban areas, charging mechanisms, and vehicle types:

> *"And… how do we incentivize the development of a soccer mom vehicle? Now the soccer mom vehicle, like I said, would have to be a plug-in vehicle with solar recharging type of thing. Because I don't see us having all of these charging stations in malls and – you know, it just like doesn't make sense immediately. I mean, it's just – it's down the road. I mean, I can see how eventually you could get there because if there's money to be made, people will figure it out. Okay? And so, you know, the biggest issue is – the biggest opportunity is a Volt type vehicle that has more capacity and more capability. Because Volt only goes however many miles on a tank of gas, right? So for suburban, I need more space/room, so it's a bigger vehicle. I need more distance, so call it 100 miles. And I need solar capability. Right? Solar recharge. Parking lot. So that's what it – that's what it has to do for my improvement standpoint of the current technology. For the commuter, I just need more distance."*

5.8 Addressing Host Ecosystems Holistically

When analyzing problem and solution spaces, beginner designers tend to focus only on superficial aspects of ideas, while informed designers often represent deeper design features through models, prototypes, and sketches (Crismond and Adams, 2012). Enabling designers, however, simultaneously model and address deep features and systemic issues.

Depending on their impact stage, enabling innovations must often interact with many host ecosystems that are constantly changing over time. Understanding how a solution affects ecosystems, i.e., their nodes and links, can help derive ways to mitigate potential ecosystem barriers to adoption and implementation of the enabling innovation. Addressing host ecosystems therefore needs to happen in holistic ways, accounting for different degrees of complexity and complex system emergent behavior, i.e., the organizing principles beyond the single integration of individual elements (Amaral and

Otino, 2004). These interactions are often non-linear and non-decomposable, implying that systemic behavior is often not reducible to distinct systems (Richardson, 2005).

The systems of systems thinking literature (e.g., Goldenfeld, 1999; Bonabeau, 2002; Barabasi and Bonabeau, 2003; Amaral and Ottino, 2004; DeLaurentis and Callaway, 2004; Richardson, 2005; Mostafavi et al., 2011) can inform the choices to be made when designing a solution that addresses specific elements of a given host ecosystem. Systems of systems is a construct in the systems literature which refers to the notion of an emergent class of systems built from components which are systems in and of themselves – and, for simplicity and theoretical distinction, are herein referred to as *ecosystems*.

A design solution that fails to address its impact on ecosystems and ecosystem components, will likely face barriers to adoption and implementation – thus inhibiting a potential enabler. Instead, because enabling innovation drives significant impact, there must be proactive consideration of ways to mitigate system of systems barriers. These systemic barriers can be due to issues with resources, operations, policies, economics, or stakeholders (DeLaurentis and Callaway, 2004) and efforts must consider ways to separate, combine, relocate, add, or subtract nodes and links in ecosystems that create win-win solutions for all involved stakeholders (Adner and Kapoor, 2010; Adner, 2012).

Although the study of systems often takes a quantitative modeling focus (e.g., non-linear dynamics, statistical physics, network theory, agent-based models), qualitative systems modeling can complement/enhance one's understanding of ecosystem issues. Qualitative representations of ecosystems strongly influence the outcome of system analyses whether these approaches are implicitly or explicitly considered, and being cognizant/aware of behaviors employed to qualitatively model and address ecosystems can inform design choices. For example, the aforementioned core behaviors play an inherent role in addressing host ecosystems. Finding first principles, for example, facilitates searching for the underlying principles/ideas that may govern a paradigm driving system behavior.

Breaking ambiguous ideas into tangible parts helps succinctly decompose a system into its nodes, links, and exchanges, and helps recognize and label patterns that reflect the current state of a system. This act of mapping and decomposition is important, particularly when it reveals hierarchies (Amaral, 2008) and transforms a problem/solution space originally perceived to be complex into a problem/solution space that was simply missing logical depth (Gell-Mann, 1995). As such, this process of breaking ambiguous system ideas/components into tangible parts is also linked to the core behavior of diverging-structuring-converging. Exploring variations systematically can then help envision/ideate possible ecosystem reconfigurations (e.g., Adner, 2012) that can result from the enabling innovation. This ecosystem reconfiguration could benefit from understanding historical norms that govern its functioning and separating such norms from non-negotiable rules.

Adding to these core behaviors are specific system-related behaviors to help address host ecosystems in the pursuit of enabling innovations, shown in Figure 5.16 and summarized in Table 5.6. These behaviors include *mapping ecosystem elements*, *porpoising* between different levels of system analysis that alternate first principles and high-level ecosystems perspectives, *modeling future ecosystem states* to understand the implications of decisions, and *reconfiguring ecosystem nodes, links, and exchanges*, particularly their configuration, to enhance the impact of an enabling innovation. The following sections characterize each of such behaviors in more depth.

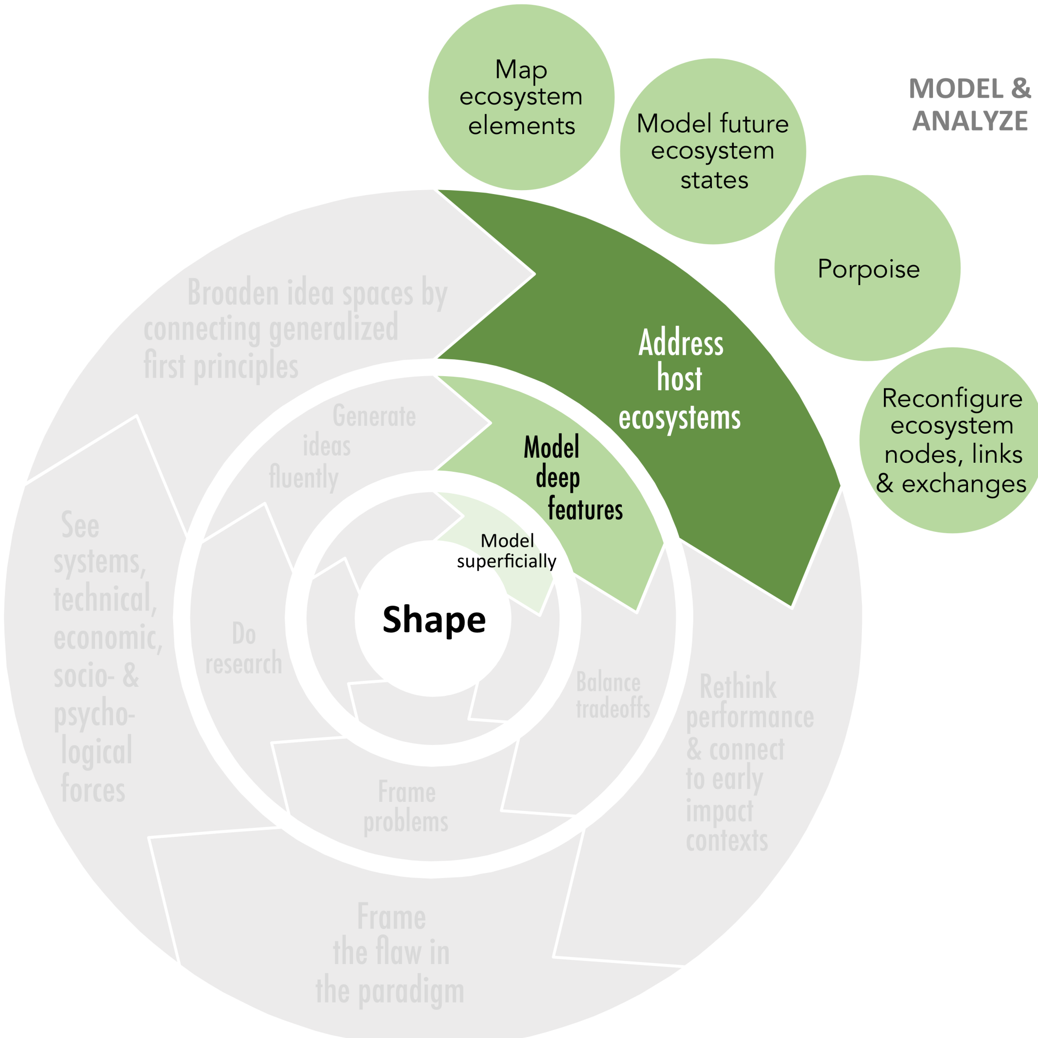


Figure 5.16 Address Host Ecosystems Holistically

Table 5.6 Behaviors to Address Host Ecosystems Holistically

Behavior	Definition	Literature foundations	Unique link to enabling innovation	Link to addressing host ecosystems holistically	Example actions/activities
Map ecosystem elements	Mapping system elements to understand its interactions at different levels of analysis	• Maier (1998) • DeLaurentis and Callaway (2004) • DeLaurentis et al. (2011) • Adner (2006) • Amaral (2008) • Geels and Schot (2007) • Maroulis et al. (2010) • Mostafavi et al. (2011)	Barriers and opportunities for enabling innovation often stem from interactions with select ecosystem components	Explicit mapping and understanding of ecosystem elements (nodes and links) can be an initial step to addressing host ecosystems	• Naming the components of a system • Attempting to understand the relationships between system components and the different levels of system depth
Model future ecosystem states	Understanding future possible ecosystem scenarios and the implications of such scenarios for present-day innovation efforts	• Mostafavi (2013) • Maroulis et al. (2010) • Adner (2012) • Bonabeau (2002)	The introduction of a potential enabling innovation will likely drive ecosystem changes and thus anticipating such changes can help embed elements into a solution that address future barriers and/or needs	Explicit understanding of possible changes in an ecosystem due to a paradigm change can facilitate the design of solutions that address such future ecosystem states	• Envisioning/ imagining future states in an ecosystem • Exploring the implications of future states for the present states • Engaging in “backwards design” types of activities in which possible future ecosystem states guide design activities

Table 5.6 Continued

Behavior	Definition	Literature foundations	Unique link to enabling innovation	Link to addressing host ecosystems holistically	Example actions/activities
Reconfigure ecosystem nodes, links, and exchanges	Designing solution components that have potential to influence the configuration of ecosystem components/ nodes and links	• Maroulis et al. (2010) • Adner (2012)	An enabling innovation that proactively embeds aspects in a solution that employ system nodes and links as levers can enhance its impact	Addressing host ecosystem barriers/issues may require reconfiguration of an ecosystem's components/nodes and links	• Describing how elements of an ecosystem could be reconfigured with the introduction a solution • Describing possible changes to an ecosystem that could facilitate the adoption of an innovation
Porpoise	Knowing when first, second, and third order effects are important	• DeLaurentis and Callaway (2004) • DeLaurentis et al. (2011) • Amaral (2008)	Alternating between first principles and system perspectives can help identify logic gaps in shaping an enabling innovation	Changes at an ecosystem level might have implications at deeper levels of analysis and vice versa, thus addressing ecosystems should proactively shift between big picture and detailed perspectives	• Switching between system perspectives and "deep dives" into analysis • Iterations between broader problem perspectives and details in each problem/solution components to search for logics in gaps

5.8.1 Mapping Ecosystem Elements

Proactively addressing ecosystems that host/incubate enabling innovations could benefit from an explicit understanding of the configuration of such ecosystems. Such an understanding is herein defined as mapping and articulating a perspective of a system's functioning that outlines its *nodes* (i.e., its key components), *links* (i.e., relationships, flows/exchanges, and interactions between components), and *interactions/exchanges* (e.g., resources, information) at different levels of analysis. These perspectives are important to articulate because barriers to hinder – or opportunities to enhance – the impact of an enabling idea often reside beyond the solution in and of itself and can be the result of interactions with an ecosystem(s). Further, ecosystem perspectives help create a common language/lexicon that can be used to describe its elements at distinct levels of analysis (DeLaurentis and Callaway, 2004; DeLaurentis et al., 2011). To create this language and articulated perspective of systems, DeLaurentis and Callaway (2004) describe the need to map resources, operations, policies, economics. Similarly, Mostafavi et al. (2011) describe a three-phase system definition process: definition (context, categories, levels, and barriers), abstraction (players, institutions, activities, networks, and resources), and implementation (objects, methods, classifications, and data).

Core innovation behaviors such as breaking ambiguous ideas into tangible parts, finding first principles, diverging, structuring, and converging are critical to recognizing and labeling the patterns that make up a representation of a complex ecosystem. Breaking ambiguous ideas into tangible parts helps ensure that all system components are labeled and represented. Finding first principles can help unearth the links and exchanges between system nodes/components (i.e., describing system governing principles). Diverging, structuring, and converging iteratively can help ensure that the representation of the system is as mutually exclusive and collectively exhaustive as possible (of course within the boundaries of system decomposability).

Secondary sources on the history of enabling innovations suggest that some participants were aware of ecosystem elements for their success. An example is the development of the aforementioned "fluoroscope," one of the first generations of an X-ray device developed by Thomas Edison. While Edison and his team worked diligently on the components of the device itself, they also seem to have been methodical in their interaction with ecosystems. Accounts of the development of the fluoroscope, highlight consideration of systemic issues, such as utilizing contract manufacturing instead of manufacturing fluoroscopes themselves, and thinking about marketing and adoption issues of the device (Kevles, 1997), which were incorporated into Edison's team's decision making.

The performance tasks also provide insight into the ways by which designers and/or decision makers can map ecosystems. Mapping the elements of an ecosystem seems to require the selection of a representation method to articulate and better understand the ecosystem – including its components, links, stakeholders, and interactions. Henry, for instance, started his EV performance task by listing the system elements of the challenge – the ecosystem nodes, links, and exchanges – highlighting inputs from key stakeholders that would enhance his understanding of the system:

> *"So I guess the first thing I'd want to do is kind of dig into what the current market share looks like across I guess you described the three different types of vehicles. I imagine there has to be some pretty well known research on that and then I'd want to really get in to trying to understand who the players are in the market, if there are companies that lease, what are the oil and gas companies doing. I have to believe they have some sort of interest in this market. What are car manufacturers doing? What are governments putting in place to support adoption? Whether there are any early electric mobility players only out there and then I'd be interested in the whole telematics area. What kind of instrumentation could be designed into new cars? Cause it seems like an opportunity to do some innovation there. I guess beyond that there's be another tier of players. I'd be interested in what some of the technology companies are doing. There's all this brouhaha about self driving cars. I'd want to look at the battery manufacturers. I'd probably spend some time looking at what Telecos are doing, obviously the utilities and the grids and probably even look at some NGOs. After that I'd probably*

> *want to spend some time looking at the different types of market opportunities out there for customers, consumers and fleets for private drivers and for urban delivery might be a third option."*

Drew engaged in a similar approach, perceiving the EV challenge as an ecosystem type of challenge:

> *"So – and the solution in a very few words summarized is that you have to take the elements of the ecosystem apart, and you have to see who – what is the role of every stakeholder, and what are the decision criteria, and that today, we are stuck, because we are comparing the electric car in terms of model. That's a eco model, if I can use that word, the same as it is done with traditional cars, with fuel."*

One of the key issues most participants seem to be aware of in the EV challenge is the link between EV adoption and EV infrastructure, which effectively represents a system type of barrier. Don and Ken synthesized this ecosystem challenge as follows:

> *So things like perhaps they [the government] could support the development or subsidize the development of a charging network since it's a little bit of chicken and egg problem that you can't get private investment until there's enough EVs on the road, but there's not enough EVs on the road, so you don't get investment. So they could probably stimulate that. (Don)*

> *So the first thing we're going to do is we're going to redesign the car itself, so we're going to – so there needs to be – industry needs to create a better car. Government needs to create supporting infrastructure. (Ken)*

Consistent with the system of systems literature (DeLaurentis and Callaway, 2004), mapping an ecosystem also seems to imply understanding the system level that is relevant for analysis – and for the enabling innovation model, the impact stages could provide guidelines. In her EV task, Nicole discussed how initiatives at the city level, rather than the national or state level could be more effective in addressing the EV challenge given the current stage of EVs:

> *"Is not going to move the needle to a significant increase because there's a huge portion of the country that's just like, they don't need to change. They're not in a highly congested area like LA or New York where pollution is a huge problem. They actually probably have to drive, their commutes are longer than folks based in the city so range anxiety is much more acute for them. But you've got to plant the seeds, drive the awareness, and all of that. I think the more compelling points of intervention are really at the state level and the city levels. So you take - highly populated states like California, Connecticut, New York, Mass, what are some of the other commuter states? Whatever. So pretty densely populated states but then especially you're going to get into cities, which I think is where I think it can be really, really interesting and that's like LA, New York, Atlanta, Chicago. I was going to say Dallas or Houston, but those are cities where oil is king. So let's not worry about them for a moment. Are there others? San Fran. So if we just take those five and say these are where we're going to put all of our energy... sorry, no pun intended, I just realized that. So if we're going to put all of our efforts into really driving electric to fuel hybrid adoption, and we're going to do that through additional subsidies, additional tax deductions, we're going to identify places where there's an outlet so existing refueling stations, so to speak, potentially make some investments into building new repowering stations, which I wonder how much that would cost?" (Nicole)*

5.8.2 Modeling Future Ecosystem States

Addressing host ecosystems also implies understanding future possible ecosystem scenarios and the implications of such scenarios for present-day innovation efforts – i.e., modeling future ecosystem states and identifying the implications for present day innovation efforts. This thought exercise of thinking about the future and identifying the implications of the present can help identify the ecosystem changes driven by the introduction of a potentially enabling innovation (and can also inform the development of roadmaps for the envisioning and evaluation/section design stages). Based on envisioned changes, one can thus proactively embed elements into a solution that address future barriers and/or needs into a current ecosystem (a behavior herein described as *reconfigure ecosystem nodes, links and exchanges*, which is the focus of the following section). Prior research suggests that better forecasting occurs at the intersection of probability and statistics and psychology (Mellers et al., 2014). Thus, this notion of modeling future ecosystem states needs to go beyond quantitative efforts common in the systems modeling literature, to including qualitative perspectives or models of future states that account for emerging paradigms due to an innovation.

Many of the aforementioned behaviors in the enabling thinking framework can help model possible future ecosystems states. Core behaviors that are relevant to modeling future ecosystem states thus include recognizing and labeling patterns and trends, particularly those that hint at the evolutionary direction of an ecosystem, employing multiple lenses, and synthesizing insights into future ecosystem perspectives, as well reflecting and iterating throughout the process to overcome behavioral biases. Beyond this, other core behaviors include separating negotiable norms from non-negotiable rules to understand possible flaws that will likely be questioned by stakeholders in future ecosystem states. Envisioning such ecosystem states can also benefit from information gathered and alternatives envisioned at different stages of the design process. For example, networking with diverse stakeholders can provide insight regarding future ecosystem states. Similarly, linking the ecosystem at hand with other ecosystems that might have historically undergone similar changes can be facilitated by connecting decontextualized principles through analogies.

Modeling future ecosystem states can help understand changes that a system needs to support to facilitate the adoption of an enabling concept. In his EV performance task, Ken, for example, seemed to always refer to the future ecosystem state, primarily the state of the highway/roadway infrastructure and identified possible changes to this infrastructure for his smaller concept of an EV car designed for specific use cases:

> *"And the second one is you need to – policy needs to support physical adoption in the sense that if we're moving – if we're proposing a move to smaller commute-designed cars, we need to have – not only do we need to build roads that support smaller, short (inaudible) based vehicles in a safer*

> *way, and as well as kind of all the safety things that go around the road, they need to maintain them in the right way. You also need to potentially think about ways in which you could build additional infrastructure that benefits those vehicles alone. So you can imagine low speed, no stoplight cloverleafs, different kinds of interchanges and intersections, where the more nimble vehicles would be able to pass through at a higher rate. So it's almost like building a parallel – thinking about building a parallel infrastructure to support just the commuting use case."*

Beyond physical system issues, visions of future ecosystem states can also include relationships between stakeholders. Max, in his performance task, for example, identified key partnerships that need to be in place in a future ecosystem for any EV initiative to succeed, outlining steps in the pursuit of this partnership to influence future ecosystem states:

> *I think some of the things that I would think about as a precursor to putting this on the roadmap and a partnership perspective where we've got the business case that we've put together, we've identified partners, we have to vet those partners, we have to make a decision on whether or not we wanna own any portion of that infrastructure, right, or do I purely wanna hand it off to a partner and have nothing to do with it and wash my hands of it? Probably in this case you'd wanna wash your hands of it, right? You don't wanna make your piece of the overall effort overly complex and then I'm trying to think of what other elements (inaudible). It's (inaudible) the other streams of work that you need to consider, marketing be a key one. I think I always try to include that in a roadmap to understand both what I'm trying to accomplish and what I wanna accomplish it by so you're developing your marketing practice in 2013 and trying to develop a demand for the product so we have marketing, we have partnerships, I would say we have vendor/manufacturing partner track as well. I'm assuming we don't have the capability to build this ourselves and don't wanna build it, right? So we need to find someone to manufacture the vehicle for us, kind of like the OEM model for consumer electronics for example. Maybe it's a Ford who actually does the manufacturing but we brand it as whatever we call this product but that's another key consideration when thinking about how I get this market and thinking about the cost, right? So I'm assuming that we're gonna find a manufacturing partner who will actually do a development of the car and then we're rebranding that and that goes back to the market so we have a marketing stream, a partnership stream and a vehicle stream, which is really what is this product. We have a vendor or manufacturing-*

> *partner stream, which is who's gonna manufacture it with agreements that we have in place. (Max)*

More abstract concepts can also form part of visions of future ecosystem states. For example, Ken described how "economic value chains" (i.e., a model that describes the links and steps by which value is generated in an economic system) might be affected by the introduction of his envisioned op-ex model of vehicles:

> *"So in the future, which you might – you might imagine the value chain looking something like this. The value chain – we'll call it (inaudible). There are some sort of supplier somewhere. There is a car manufacturer, there's a – oh, what will I call them? Renter (inaudible) rental/financial intermediary. So the transition from here to here goes – From car manufacturer to financial intermediary/rental company, this cap-ex to op-ex, this is the result of this (inaudible) transfer. This is financial (inaudible) – this is (inaudible), this is (inaudible) incentives. [Under breath]. That's interesting. This is (inaudible) for the car makers – [Under breath]. This is – this could be an insurance company. Could be financing. Could be the financiers. Yeah. [Under breath]. Driver – and the driver could be part-time. (inaudible) full-time (inaudible) needs. So if you were thinking about it from a business model perspective, well, you need governments to do some things. You need car manufacturers to do other things, mainly design a different car. The real business model innovation happens with these guys here. Whoever is running (inaudible) or car exchange, whatever you want to call it, is – they're the ones that are creating the truly disruptive opportunity, because it's changing – it's fundamentally changing the relationship that someone has with a car from being a owned asset to being a used asset, something that you think of as an operational versus one that you think of as yours, singularly."*

5.8.3 Reconfiguring Ecosystem Nodes, Links, and Exchanges

Addressing host ecosystems also implies employing new solutions or embedding elements into a solution that have the potential to influence the configuration of present and/or future nodes and links and enhance the adoption of a potentially enabling innovation. These elements embedded in solutions can work as levers to enhance the impact of a solution and proactively address a host ecosystem. Creating such levers, however, likely requires understanding the status quo of an ecosystem (i.e., mapping its elements) and understanding possibilities for future ecosystem states (i.e., modeling future states). With these perspectives in mind, one can then start to understand possible present or future modifications/changes that can be pursued across ecosystems. Adner (2012), for example, synthesizes a set of possible ecosystem changes such as separating, combining, relocating, adding, or subtracting elements of an ecosystem. Enabling innovations in particular can influence the configuration of multiple ecosystems in a given paradigm by adding new stakeholders, channels, creating or removing relationships between system nodes/components, and/or by making entire sets of components, links and exchanges (e.g., stakeholders, markets, value chain links) obsolete.

Core behaviors also play a role in this systems-related behavior. A systematic exploration of ecosystem variations can help envision a broader set of possible configurations when opposites, intersections, adjacencies, additions, subtractions, relocations and combinations are methodically considered. When generating alternatives for these ecosystem modifications, exploring as many morphological variants as possible (guided by a set of goals and bounds) could also help generate ideas for ecosystem reconfiguration.

The performance task provides examples of ecosystem reconfiguration ideas for the EV challenge. For example, Ken, in his EV performance task and his idea of transitioning vehicles from being a capital expenditure to an operating expenditure, identified that major ecosystem changes would likely rely on a financial intermediary for which a business model should be developed:

> *So in the future, which you might – you might imagine the value chain looking something like this [draws figure]. The value chain – we'll call it (inaudible). There is some sort of supplier somewhere. There is a car manufacturer, there's a – oh, what will I call them? Renter… rental/financial intermediary. So the transition from here to here goes – from car manufacturer to financial intermediary/rental company, this cap-*

> *ex to op-ex, this is the result of this (inaudible) transfer… [Under breath]. That's interesting. This [manufacturer] is the car makers. This is – this [financial intermediary] could be an insurance company. Could be financing. Could be the financiers. Yeah. [Under breath]... So if you were thinking about it from a business model perspective, well, you need governments to do some things. You need car manufacturers to do other things, mainly design a different car. The real business model innovation happens with these guys here. Whoever is running [the] car exchange, whatever you want to call it, is – they're the ones that are creating the truly disruptive opportunity, because it's changing – it's fundamentally changing the relationship that someone has with a car from being a owned asset to being a used asset, something that you think of as an operational versus one that you think of as yours, singularly.*

Max also envisioned how to reconfigure the EV ecosystem. Throughout his performance task, he often mentioned the opportunity that resides in building a business case for existing fuel providers and the needed ecosystem stakeholder links that would need to be created to enhance the adoption of EVs:

> *"So with that in mind as in kind of a blocker of adoption what you're hitting on already is you need infrastructure beyond the vehicle, right? This is not just a question of a product that I have to design effectively for it to be attractive in the market. I also need to be concerned with the infrastructure being in place to facilitate the use of that product, which complicates matters greatly in the case of an electric vehicle so I think while a product's definition is probably fairly straightforward, it's a tradeoff, you know? You're basing it around the idea of an electric vehicle, the rest of the features are just simple tradeoff decisions: What does the market want, what don't they want? I can quickly come up with a list of things that I would include or I wouldn't include in the vehicle and the harder part is what partnerships do I need to put in place to facilitate the infrastructure side of things, right? So I have to in some way, shape or form replicate what we have -- the infrastructure that we have – for combustion engines and the tradeoff there is obviously do I build them or do I partner for them? Given that this is the governments, I would say that we're gonna need to have partners… In my opinion we would need to look at someone with a footprint, nationally, in place so that you don't have to take on the costs of building actual physical structures so you're just adding on a charging capability to an existing structure so I would look to partner with probably retail establishments, potentially, or actually gas and service stations as well as an obvious"*

Drew made a similar argument to Max with regard to devising ways to motivate utility companies (e.g., gas, electricity) to participate in the EV ecosystem. He argued that these changes, when possible, need to be studied from an ecosystem perspective to uncover emergent behaviors that can only be understood holistically:

> *"I think to de-risk it, you need that all – all the stakeholders have to play together in an ecosystem, so that the entire ecosystem looks equal, works together. I don't think that it makes sense to insulate different elements. That's the way I would do it. I would say, fine, let's start with a certain city. Let's start with a state. Let's start with something, and just simulate the reality as it could look like, and just eliminate all the risk factors. So customer (inaudible)? Yes. Car manufacturers will then produce? Yes. Battery manufacturers will the produce? Yes. Are they long term – is there long term interest? Yes. And then really simulate the reality as it would look like with all the stakeholders involved. That's the way I would do it. Of course, you can insulate or isolate some of the elements, but I don't think that's the real – the – you don't crack the case like that. I think you really have to make play everybody together. And you can subsidize – some elements you can subsidize, and you can help. But some, you have to let them play as they would play in reality. And then you will see if the behavior pattern is really – really great or not... And I think that was the problem with the Better Place. I don't think – that they weren't far too ambitious. They should have – if you take the system, for example, in Sweden, where they have Stockholm and people are not allowed to drive in the town anymore, you put taxes on it, etcetera, I think that's quite interesting. And then you have one city, and you check it, and then you will learn with it. And you will only learn like (inaudible), but it has to be the entire system (inaudible). And these tests, for example, are pretty successful. Will they be rolled out worldwide? We'll see. But – because what they learned is that there are some behavior patterns they did not expect... So having said that, I would – my recommendation would be to develop in the first phase, together with the utility, in a certain state or in a certain (inaudible), a business model that is viable for them in the long term. And the business model should include in terms of the customer value proposition a – not the offering of the batteries, but the maintenance of the batteries, the charging of the batteries, the replacement of the batteries, almost in a kind of closed system."*

5.8.4 Porpoising

When studying ecosystems to be addressed in an innovation effort, one can engage in a behavior that in management consulting circles is often called "porpoising." This behavior refers to the notion of varying the level of depth (for example, from a macro scale to a micro scale) at which an analysis is performed to identify logic gaps and create/facilitate more comprehensive analyses. Effectively, this behavior calls for knowing when first, second, or third order levels of analysis are important yet without losing track of additional levels of analysis that need to be considered. As such, this behavior calls for alternating between first principles and systems perspectives. This dual focus on different levels of analysis facilitates the identification of elements and linkages of ecosystem issues (DeLaurentis and Callaway, 2004; Mostafavi et al., 2011). Effectively, a decision at one level of analysis will have implications that often need to be studied at other system levels of analysis.

Core behaviors such as finding first-principles, and iteration and reflection help ensure that the study of host ecosystems alternates between systemic perspectives and first principles perspectives. Throughout the performance tasks, many participants, particularly the design/innovation consulting professionals, iterated continuously between the aforementioned two levels of analysis, often triggered by reflections on their approach and thought process.

In the EV performance task, Ken often alternated between thinking about details of his concept car, the infrastructure required, and possible business models, thinking about the systemic interactions in these components, and the details of each of these components. Two examples of how he "porpoised" are provided below:

> *"Two things stand out to me. One is that you have – you have a – you have an infrastructure problem. So you have an infrastructure problem that's driven both at the (inaudible) and infrastructure level, so even if you could*

give everyone in this country an electric car and the grid could support handling that amount of electricity, there's certainly aren't enough places for you to plug in in places where you normally have cars. Right? So access to electricity – electricity to car infrastructure is a problem. And also, the time. So if you think about the energy density of gasoline, your ability to transfer that density in a small amount of time is actually really incredible, whereas charging a battery takes a lot longer."

"I was thinking, you know, that just came from thinking about efficiency in different – like what different kinds of vehicle designs could enable different efficiencies for. So very specifically, you think of a smaller vehicle, you're like, oh, I could pack them side by side. I could – because they have shorter wheel bases, I could actually turn them tighter, even if it's at lower speeds, so I can prevent them from stopping. Well, how do you prevent things from stopping? Well, you prevent traffic from stopping by putting less stoplights, and that's where that came from. It wasn't something that was like inherent to the problem. It has nothing to do actually with electric vehicles whatsoever."

Nicole summarized this behavior when describing her "usual" approach to addressing challenges in her professional activities:

"So it's entirely the hypothesis driven approach and the concept of very quickly pushing to do a hypothesis that can be tested has totally shaped the way I think about problems. The approach of breaking things down first has always been instinctual just because problems of any kind can seem overwhelming, but when you break them down into smaller parts, they seem much more manageable. So that's instinct. I think what I did before learning the hypothesis driven approach was I would then go and kind of boil the ocean within each tiny bucket and learn as much as I could and get data and all that and kind of build up to an answer instead of breaking things into buckets, then pulling back, developing a hypothesis then going back into buckets, then pulling back up and kind of ricocheting between details and high level. I used to immediately kind of go into detail."

5.9 Rethinking Performance and Connecting to Early Impact Contexts

Compared to the relatively little attention paid by beginner designers to tradeoffs and constraints, informed designers tend to balance benefits and tradeoffs by qualitatively exploring problem and solution spaces (Crismond and Adams, 2012). In complex challenges, however, one of the critical choices in the evaluation and selection of alternatives is to identify the appropriate tradeoffs necessary to maintain the feasibility of solutions. A key differentiator of the framework described herein from other innovation frameworks is the focus on proactively pursuing application contexts that can generate early trial and early impact of the current state of a solution, often in counterintuitive contexts. Although tradeoffs are at the core of design thinking and often discussed throughout the literature, the focus on matching tradeoffs with application contexts is not often discussed in design or innovation circles, making this selection/evaluation pattern unique, and adding another dimension/layer of complexity to an enabling innovation challenge. McGrath (2011, p. 8), for example, without referring to the notions of enabling innovation and/or the enabling window, exemplified this tradeoff-context match: "Consider the commercialization of nanotechnology: Eventually we'll be able to construct objects at the level of individual molecules, which will be a truly revolutionary change. But that future is likely to be a long time coming. So for the time being, how are we using nanotechnology? Think wrinkle-free Dockers pants. Think cell phone displays that don't show fingerprints. Those more modest projects make a lot of sense: They apply brand-new technology to familiar products, which fosters learning." Beyond learning, the enabling thinking framework and its emphasis on tradeoff-context matches call attention to performance advances, facilitating worldview changes, generating impact *and* gathering resources in the pursuit of such connections, as described throughout the following sections.

When the challenge is to achieve enabling innovation, one can pay particular attention to tradeoffs – both accepted and counterintuitive – and match them to contexts that could embrace the benefits and limitations of such tradeoffs to garner feedback, resources, and drive an idea toward a path of least resistance to impact (Sinfield, 2008). Effectively, these proactively sought-after contexts "host" an innovation, accept its current performance/capability (even if perceived to be limited for its end goal), generate impact, help unfold a new paradigm, and garner resources that allow an idea to advance/survive, while strategically improving select performance dimensions. Historically, this pattern has been realized (although rarely in a proactive manner) in multiple enabling innovations. Both X-rays and anesthesia made jumps from the entertainment domain to dentistry, before being adopted in the field of medicine and beyond as described in Chapter 4 of this dissertation. Microfinance began as a project to diminish famine in Bangladesh, evolved to a farming-improvement university-based community project, to private loans managed by its founder, before jumping into the institutional domain. Although these context "jumps" occurred as a result of random sequences of events, there remains an opportunity to proactively pursue a match between performance and contexts (even if counterintuitive) for enabling concepts that generate the aforementioned benefits for these ideas.

This performance-context matching process will vary according to a concept's position on the impact curve (i.e., enabling window, progressive cascade). For the enabling window, this performance-context decision can influence a concept's timing and impact due to the resources, interest, momentum, and performance advances that these "early trials" can generate. Making this selection implies understanding and articulating the current performance state of a concept, and the measures of desired performance in future states. Further, this selection also calls for awareness of possible contexts that might consider the current tradeoffs of a solution as "acceptable" or "good enough" and thus motivate stakeholders in such domains to host/incubate a solution, typically driving further improvements.

There are two key components in this pattern: *rethinking performance dimensions*, and *connecting to early impact contexts*. These components can be decomposed into identifying dimensions of performance and headroom, evaluating accepted and counterintuitive tradeoffs, characterizing impact contexts and matching impact contexts with tradeoffs and headroom, as shown in Figure 5.17.

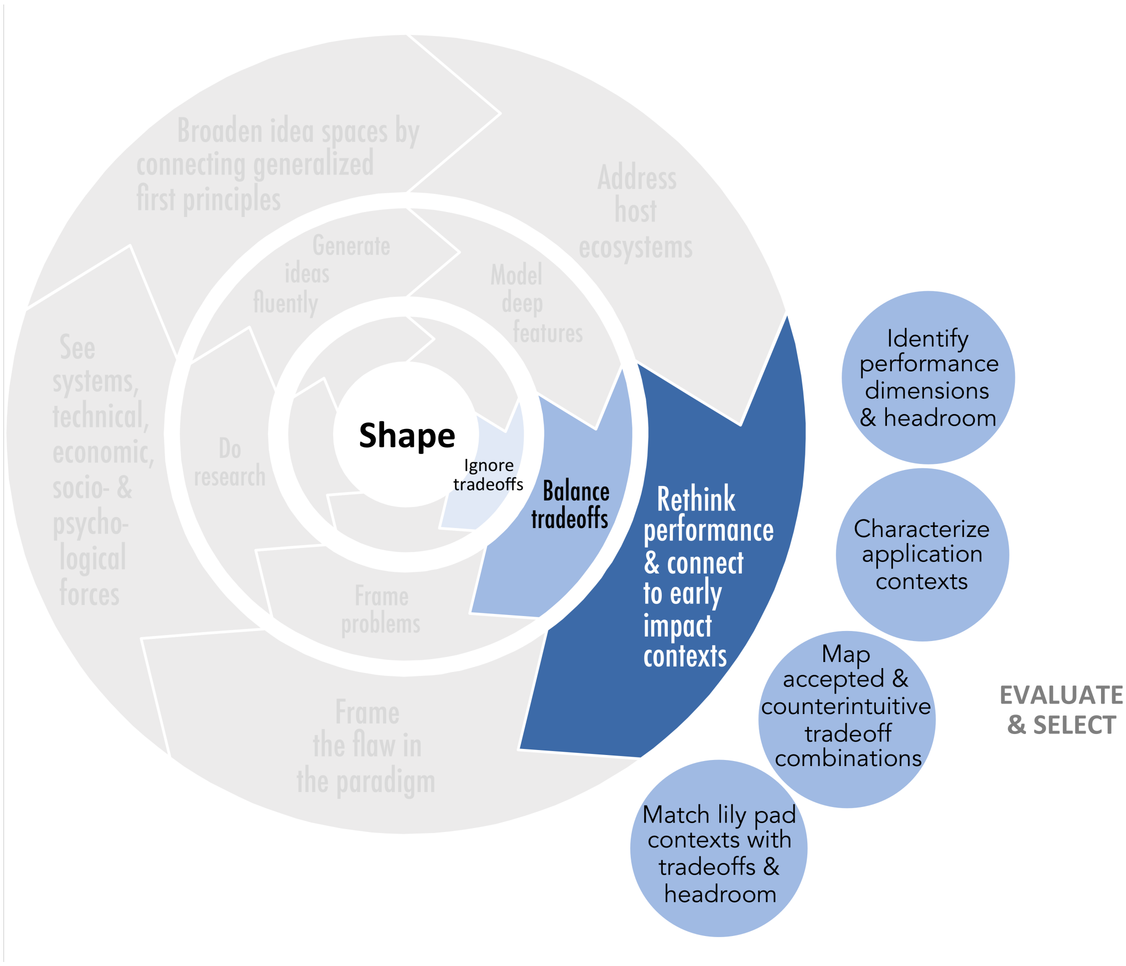


Figure 5.17 Rethink Performance and Connect to Early Impact Contexts

Rethinking dimensions of performance implies being able to *identify performance dimensions and headroom* of solutions to then *map accepted and counterintuitive tradeoff combinations* that facilitate access for potential problem spaces. Solutions can often be characterized using a set of pre-existing performance dimensions (Kim and Mauborgne, 2005). Enabling innovations, in their many variants and across their different impact stages, typically encompass tradeoffs between status quo and new or different dimensions – similar to the tradeoffs frequently made by entrepreneurs (Anthony et al., 2008). These choices in tradeoffs could be counterintuitive at first glance because of paradigm transitions. In many cases status quo solutions repeatedly engage in the same set of tradeoffs, often (but not necessarily) due to historical precedent. An explicit identification of these "working paradigm" dimensions as well as dimensions that result from an emerging paradigm can facilitate the pursuit of tradeoffs that, even if counterintuitive, uniquely position the enabling innovation for connections to early impact contexts. These tradeoffs could, for example, lower performance to acceptable on unimportant dimensions in working and emerging paradigm, seek to address headroom issues for future development (if needed), and incorporate additional dimensions of performance that might be necessary to participate in a given application context and that stem from an emerging paradigm.

Beyond tradeoffs, *characterizing application contexts* and *matching lily pad contexts with tradeoffs and headroom* can help create a roadmap of contexts of application that outlines possible ways to achieve impact with least resistance. Often times, an implicit assumption is that moonshot ideas need to stay in the application context in which they were conceived. However, application contexts that historical norms would regard as counterintuitive and that involve connections to new circumstances of use or need may embrace the benefits and limitations of the current state of a solution creating possibilities for faster adoption and impact. Early trials in these contexts – termed "generational enablers" in the enabling innovation model – could serve as "lily-pads" or "stepping-stones" in the pursuit of a grander (i.e., more advanced/significant) goal.

As a result, a performance-impact roadmap of an enabling concept can be created. This performance–impact roadmap combines the notion of the study of performance dimensions (e.g., Kim and Mauborgne, 2005) with a roadmap of lily pads for solution and impact development, creating a unique lens with which to examine and pursue innovations. The pursuit of lily pads can generate feedback that can be incorporated to fine-tune a solution (and in some cases a problem), advance select performance dimensions, garner critical resources for continued development, generate impact, and highlight possible solution development paths.

Core innovation behaviors play an important role in discerning, recognizing and articulating patterns regarding which performance dimensions to pursue, in which contexts, and with what desired impact. These connections are more readily made if ideas, particularly first principles, are distilled from their contextual influences that help link diverse problem-solution spaces. Counterintuitive performance tradeoffs and contexts of application are derived by proactively shifting perspectives, particularly after gaining insights regarding what is done by negotiable norm/tradition rather than by an absolute necessity (i.e., a non-negotiable rule). In addition, these insights need to be synthesized in a concise roadmap that can guide decision makers in their activities.

Table 5.7 summarizes the aforementioned behaviors to rethink performance connect to early impact contexts. The following sections explore these behaviors in more depth linking them to prior literature, historical cases, and performance task examples.

Table 5.7 Behaviors to Rethink Performance and Connect to Early Impact Contexts

Behavior	**Definition**	**Related literature**	**Unique link to enabling innovation**	**Link to rethinking performance and connecting to early impact contexts**	**Illustrative actions of the behavior**
Identify performance dimensions and headroom	Creating a mutually exclusive and collectively exhaustive perspective of technical, economic, psychological, an sociological dimensions of performance	• Anthony et al. (2008) • Kim and Mauborgne (2005)	Enabling innovations can be characterized using a set of evolving performance dimensions and an indication of headroom for performance improvement	Articulating an exhaustive description of the dimensions of performance in a solution and possible host contexts can help unearth all possible performance dimension combinations	• Explicitly identifying dimensions of performance • Explicitly identifying scope for improvement
Characterize application contexts	Creating a perspective of the reach, significance, and paradigm change that can be pursued and the performance requirements in a given context	• Solis and Sinfield (2014) • Feland et al. (2004)	Enabling innovations often participate in multiple ecosystems and application contexts within ecosystems, which should be understood when introducing a solution	Articulating a comprehensive/ exhaustive description of the impact that can be generated in an array of contexts can help understand which contexts can be most feasible and/or desirable	• Explicitly identifying contexts and relevant dimensions of impact • Explicitly characterizing contexts in which solutions will participate

Table 5.7 Continued

Behavior	**Definition**	**Related literature**	**Unique link to enabling innovation**	**Link to rethinking performance and connecting to early impact contexts**	**Illustrative actions of the behavior**
Map accepted and counterintuitive tradeoff combinations	Evaluating possible variations in dimensions of performance in an idea, even those that might be considered counterintuitive	• Anthony et al. (2008) • Kim and Mauborgne (2005)	Enabling innovations often need to reconfigure their tradeoffs/capabilities in the path toward achieving a "base" set of capabilities which facilitate an impact cascade and paradigm change.	Innovation is often made unnecessarily complex due to the presumption of "required" performance, and thus exhaustively mapping (and testing) solution tradeoff combinations can identify alternate performance-context paths towards a "base" set of capabilities that lead to an impact cascade.	• Comprehensively mapping combinations in performance dimensions • Exploring different lever/ variable configurations
Match lily pad contexts with tradeoffs and headroom	Connecting solution to contexts that embrace a given set of tradeoffs, even if outside of traditional expectations/ boundaries, to accelerate impact	• Sinfield (2005) • Sinfield (2008) • Solis and Sinfield (2014) • Sinfield and Solis (2015)	Stepping stones to a grander goal can be pursued in lily pad contexts that embrace the current state of a given solution, generate early impact, advance select performance dimensions, retain interest, and help unfold a new paradigm	Limitations in one context may be perceived as benefits in another context, and the pursuit of impact in diverse contexts can bring multiple benefits to the pursuit of an idea with enabling potential, ultimately facilitating a transition to a true stage of enabling innovation	• Matching performance tradeoffs with contexts that might find such tradeoffs desirable • Creating performance-context roadmaps for the evolution/ development of an (enabling) innovation

5.9.1 Identifying Dimensions of Performance and Headroom

Rethinking performance and connecting to early-impact contexts inherently requires a comprehensive perspective on a solution's current and desired performance. To achieve this perspective, one can decompose a concept into its constituent performance dimensions and create an inventory of current and desired future levels of performance for each dimension. These performance dimensions can be technical, economic, systems, sociological, and psychological. Overall, this perspective can help unearth all possible performance dimension combinations for solution comparison/evaluation purposes.

The core innovation behaviors described in section 5.3 can thus help decompose an idea into its fundamental performance dimensions. Relevant core behaviors include breaking ambiguous ideas into tangible parts, shifting perspectives proactively, separating norms from rules, finding first-principles, employing multiple lenses, and distilling core ideas from contextual influences. Performance dimensions can be hidden under contextual influence and core ideas may need to be distilled.

Many frameworks exist to break down solutions into performance dimensions. However, an often-cited framework to think about such dimensions of performance is Kim and Mauborgne's (2005) strategy canvas, which is also often called a performance map (Anthony et al., 2008). This framework characterizes each performance dimension as not good enough, good enough, delightful/excellent, and overshot (note that the evaluation of dimensions of performance is herein described as a separate behavior). In the performance task, participants often employed this framework as one of their first steps. Don, for instance, employed this framework to decompose an EV into its dimensions of performance trying to be as expansive/generative as possible; and Ken also started to identify the performance dimensions of the EV challenge as one of his first steps:

> *"So I'm drawing a performance map here. So I have a good enough line, delightful line, overshot line and then I'm going to start by laying out some of the things that I've talked about that presumably people take into account*

> *when they're buying a car. So one would be – so I guess fuel economy is probably the thing that people think about. They think about cost. They think about performance. Here, I'm thinking horsepower, et cetera. They think about utility. Define what that means but maybe that's things like seating, trunk, a few other things. They think about comfort. We'll move cost over here because I want a couple of categories of cost. So I want – so vehicle cost. They might think about lifetime costs. So there's probably some social emotional things related to – image. Do I have anything else? Oh, they might think about resale value. So let me squeeze that in here. Resale value… So looking at these things together, I'm thinking about kind of the different dimensions of this problem, and kind of the leverage you need to pull to find a solution." (Don)*

> *"Two is kind of the – (inaudible) kind of the job to be done of a vehicle, right? It's to get someone from point A to point B. (inaudible). And it's not – it's not just – it's not just about transporting a person and just your stuff, because if that were the case, a lot more people would embrace public transit more effectively. It's about making that transition as easy as possible. So I would dial one level deeper and say convenience is an important dimension. Privacy is an important dimension… There's some sort of weird emotional thing that people have with cars. I'm one of them. A car means certain things. So emotionally, it fills a sense of independence. There's something about fun, speed, and (inaudible), I'd say." (Ken)*

The uniqueness of all design challenges will naturally call for different levels of depth with which performance can/should be characterized. Effectively, depending on the goals of the design exercise/challenge examination of performance dimensions across contexts can vary in the level of detail required. While some non-technical contexts may use high-level dimensions such as "convenience" or "accessibility" to examine solutions, environments such as engineering often require a level of technical depth in the consideration of performance dimensions (without ignoring economic, social, and emotional factors). To reach these levels of depth, each performance dimension can be decomposed into further dimensions until an actionable level that matches the need of a design exercise is reached. Thus understanding the context of a design challenge can help drive the generation of an exhaustive list of dimensions of performance that has the appropriate levels of depth. Victor, for instance, often analyzed performance at a relatively high level, diving into relevant details of such performance when needed (see example below). In contrast, Charles was one of the only participants that decomposed batteries into key technical performance dimensions, perhaps due to his domain expertise in this arena, as shown below.

> *"And so the tradeoffs that I get into is why do I want to do this? What would it take to make me do this? Or to cause me to do this? And the two most obvious is it costs less, it saves me time, and convenience. That's interesting. A – so – well, and then as we had always talked about, confidence, okay? If I'm not – if I'm not confident that it's going to work, that's got to be the first thing in place, is I know I'm going to have my vehicle when I want it. I'm not willing to trade off money, time, or convenience for lack of confidence. So assuming we've got that one addressed, that becomes the key. So we have to have a vehicle that has that." (Victor)*

> *"I'm trying to think what else we've got here. The other thing is, in the resource area, is training, because the life of the batteries –basically, an EV is a battery system or some sort of energy storage system. So if you look at that energy, that storage life – I've actually had some students doing some research and working with some battery companies for EVs - And the issue with the battery life is really how much are you trying to get. So if you kind of – there's four things that impact battery life, is the state of charge swing, the average state of charge, the temperature, and the C rate, or the abuse of the battery – basically how fast are you discharging. So if you've got a 70 -- Kw battery with a C rate of 1 that would be saying I'm discharging the entire battery in an hour. So one of the things we found is if you go look at the state of charge swing, a larger swing is more harmful to the battery or impacts the battery life more. The average state of charge, higher is better, so if you charge your phone all the time, it's gonna have a longer life. Not subjecting it to high temperature, because the dendrites and the degradation of the battery are temperature-dependent, and the C rate is kind of a temperature dependency. You try to take energy out of it really fast; you have a high – a high kind of friction or resistance, kind of, inside the battery, so that causes the temperature to go up. The state of charge swing – all these things have some interdependencies, too. But if you look at the state of charge swing, if you try to go from, say, 95 percent to 55 percent, that's – That's probably better than trying to go from 100 to 50 and the reason is trying to get to that last 5 percent has a very low efficiency of trying to pack energy in. For what you put in, less is charged. So I'd say part of this is training, 'cause we've frequently criticized drivers, saying that they're range-*

> *anxious, kind of saying that they're looking for a charging station all the time. But the data tends to say that the range-anxious driver probably is going to have one that is going to have a state of health of the battery, which is going to last a little bit longer, be it have a little bit more value, so if you look at the three-year trade-in, the O&M, the purchase prices of the vehicle, and then the net-present value, based upon what's there at the end, it could actually be higher. So trying to make sure that you get all these things in from the training, you gotta find the right assets, and it might be that parents – it's like we've got many folks in our community -- for instance, that have a lot of business in Chicago or Indianapolis, and an EV is not really practical if you're gonna do that, because you have the range of almost getting there. You're not gonna get home without a charging station. But if you kind of look at this parent thing, which says, well, gee, our county's about 20 miles square in Indiana, so having a vehicle that barely gets out of the county and gets you back home basically says your kid is not gonna get too far from home without you knowing about it, because you're gonna get a phone call that says --The vehicle is out of charge -- Come get 'em, right? So that's where I kind of look at some of these asset kinds of things. So if you were actually gonna try to improve the acceptance of this, I would be looking at how do you influence parents and students to basically say, how do you make EVs an asset and make it cool to drive an EV to high school, for instance, where we have lots of kids who go to high school. Look at a lot of studies, fleet operations – again, kind of, if your solution set is just basically how do I sum to get more vehicles, then you've gotta look for places that -- that this whole system can be a benefit or an asset." (Charles)*

Beyond a simple list of "expert-derived" dimensions of performance, i.e., a list generated by those who are often assumed to have the relevant disciplinary expertise, being truly expansive calls for generating a mutually exclusive and collectively exhaustive set of performance dimensions. To achieve this expansive/comprehensive perspective, performance task participants seemed to employ lenses, and iteratively shift perspectives to search for historically overlooked dimensions of performance that can challenge a paradigm. Ken, for example, decomposed car acquisition experiences into either cap-ex and op-ex, and decomposed each of these mutually exclusive and collectively exhaustive categories into further dimensions:

> *"So what this means (inaudible) want to talk about this, is this would mean things like – say today when you get a tax break for electric vehicles, and you*

> *get that once a year based on purchase, so it's actually a cap-ex model, whereas if you were to imagine a electric vehicle op-ex model, you would say – you would – maybe you would pay 90 percent of a cost, the op-ex cost of driving your car back and forth, and the government would kick back 10 percent to be managed through some sort of middle financing. So the government would not charge you that, and then – well, whoever owned the car in the op-ex model would take that collection (inaudible). So there's some financial alignment of policy incentives that's necessary."*

In addition to characterizing the current state of a solution by articulating its performance dimensions, generating a proactive understanding of its headroom can yield an understanding of the potential future of a solution and the implications to achieve such a state. Charles and Victor, for example, envisioned future performance (at a systems level) that would be required to drive EV adoption. More specifically, Charles focused on describing the implications of a "smart grid" that could tell vehicles when (and when not) to charge, while Max briefly discussed manufacturing and charging station capabilities.

> *"The smart grid problem is basically, if you want to try to waste less electricity, essentially the electricity system is set up to make sure that there's an electron ready to jump off the plug that I'm going to insert into the outlet and power my device, then that means there's gotta be electrons flowing and ready to move there. So it's kind of a large systems design problem… So if the smart grid could really get smart enough to communicate with our vehicles, to tell it when to charge and when not to charge, so we don't want everything in a critical mode, that we plug in all of our vehicles and brown out the electric grid at night. What we need to do is to have a smarter grid that manages to shift and manage loads. Some of the shifting and managed loads could also be other things, like building heating and cooling." (Charles)*

> *"The other difficult tradeoff decisions or opportunities are to outsource as much of this effort as possible. We don't have manufacturing capability, we don't wanna build them. We don't. The infrastructure is not in place today for having charging facilities. We need to find a partner to do that. We don't wanna be in that business. We recognize the need to service vehicles. We have to be in that business in the short term but we wanna be out of it within three to five years but I think we've designed as a result of an*

> *attractive and viable product that can be – that can get us – into market and help us to grow from there." (Max)*

5.9.2 Characterizing Application Contexts

Matching solutions and their tradeoffs to application contexts requires creating a detailed perspective/understanding of the characteristics of any possible application context. Profiles for these contexts should outline desired performance profiles in solutions, status quo solutions employed, and areas of possible impact. Effectively, each context in which early trial and impact could be pursued has a desired solution profile and provides opportunities to generate impact across economics, environment, health, and culture. This comprehensive description of possible application contexts can help identify feasible and/or desirable contexts to pursue because as solution performance advances, new application spaces will inherently open up.

The characterization of possible application contexts can be achieved by describing the roles that a solution could play in a given context, the performance configuration(s) that could be desirable, the barriers to introducing new solution in a given context, and the impact that the solution can generate if introduced and successful. A likely goal is to be expansive and inclusive of contexts that would not typically be associated with a given solution. Thus, using generic language (i.e., distilling core ideas from contexts) in descriptions of roles, performance, barriers, and impact for possible application contexts can facilitate problem-solution connections beyond historical norms. Sam, for example, an expert in consumer sciences, described the context in which EVs should play a role and the impact that is likely required for EVs to be successful, considering multiple elements described in the enabling innovation framework (economics, environment, and culture in this particular example):

"So increase EV adoption, five years. Okay? I think I start by thinking about the history of the automobile in the United States, and the history of the automobile worldwide, and ask the questions about societal use of the automobile… So I guess one of the things I would do is – and if you think about the technical pieces – but there are cultural pieces, too. And so it's going to take people who are – who come from different backgrounds. And I would look for experts around this – these different pieces of technical, cultural, social structure, implementation. And clearly, apparently, according to this model, we've got a variety of academics and industry executives who are interested in this. So using those people to identify individuals who can then either do research, have research done, or present research they've already done around these cultural and technical kinds of pieces. There's another side of this, too, and that's the economics. Clearly, we've supported the internal combustion engine with lots of price supports. I mean, building the road system, building the infrastructure. I mean, look at saving the auto industry in the recent downturn as another example. You've got to do those things. So there's an economic piece of this, too, that's I think important, and you would need experts there as well, that look at what are the economic incentives… We in America have taken our approach, I think if you look at the social history of the cowboy, lone ranger, individual, get in your car, you're protected approach. So automobiles are very culturally American. Okay? Which in some ways is going to make this an easier task than if it were increasing train participation or the use of mass transit. So from a cultural perspective and an economic – well, cultural perspective, I think it's aligned with America. I don't think – from what I've seen, Americans could care less if it's electric powered or gas powered. It's their car and they get to drive it where they want, when they want. So there are some technical issues. Can you drive an EV where you want and when you want? ... and what are the incentives around the economics of electric vehicle. Clearly, it's cheap. I mean, if you can get the system set up, you're running $1.00 a gallon instead of $3.00 a gallon. So that incentive is clear. But there is a buy-in cost. You've got to have a plug-in system. You've got to be able to set that up. And there's some models out there. Tesla's model is clearly an interesting one, with recharging stations that basically work like gas stations. What kind of economic systems could we think about? So – but that's also a technical constraint. Recharging is clearly one of the technical constraints. The battery systems are another one of the technical constraints. So I think you'd have to have reviews by experts of these different constraints around electric vehicles. So you've got to do an analysis of the barriers, and initial cost of economics is one of those barriers that would have to be addressed. Could you tax internal combustion engines? Could you disincentive internal combustion engines because of the pollution that results, and therefore by de facto, you know, incentivize the battery-powered

> *systems? So that's sort of the big picture. I mean, that's – the technical, cultural, economic, and I'm sure I've missed some pieces there, but those are the big three pieces that would come to mind. So how would you go about doing that? If you're really serious about this, I think you'd have to – well, there's also the political. Let's not forget the political. Oh, it's a huge one. I mean, and it relates to the cultural. The advantage of the political is in a fundamental sense, for the average American, they're still going to get to drive their automobile. They're not going to have to take a train. So that's an advantage. You know, if this were a task of adopting mass transit, it'd be a whole different – whole different set of issues. And in some ways, this easier. But there are still political issues, and you've got the different organizations and pieces of the political process. The oil companies are a good example, the auto companies. And there's lots more. Looks at Tesla trying to sell cars in the old way of having an auto dealership versus buy it online."*

5.9.3 Mapping Accepted and Counterintuitive Tradeoff Combinations

With a list of identified performance dimensions, one can evaluate possible variations in levels of performance across a spectrum of dimensions in a solution space. This evaluation of performance dimension configurations should consider tradeoffs that are commonly accepted and those that, at first glance, might be considered counterintuitive in a given context. This explicit and proactive consideration of seemingly counterintuitive performance configurations can unearth opportunities for innovation. Anthony et al. (2008), for example, argue that innovation opportunities often reside in historically overlooked dimensions or combinations of dimensions (Anthony et al., 2008a) and innovation is often made unnecessarily complex due to the presumption of "required" performance.

Engaging in this behavior implies defining different levels of performance and the meaning of such levels in the context of focus. For instance, categorizations could include defining performance as not good enough, good enough, excellent, and overshot (Anthony et al., 2008) or low or high (Kim and Maubogrne, 2005). Nonetheless, the meaning of such categories of performance for a given solution will vary across contexts.

In his performance task, Max described a categorization used to evaluate tradeoffs in solutions in his EV performance task and explained how he would use such a categorization to identify a minimum viable solution/product:

> *"…essentially it's a chart and there are three lines on the chart. The top line is what we call a set of delighter features. These are features that are in a sense nice to have but not required to drive adoption. The center line are really what we would call performance or satisfier features. They're not necessarily must-haves but the more of them that you can provide the more attractive the vehicle, in this case, would be and then the bottom line is must-have, right? If you don't have this particular capability then nobody is going to purchase the product that you're putting together and really what you're looking at on the vertical axis is customer satisfaction so the more features obviously provide, potentially the higher the satisfaction of that customer and really, on the bottom, it's more about pure presence of a characteristic on that, the horizontal axis, whether or not it's there, right? So you're looking at whether or not it's there and how much that influences customer satisfaction and customer satisfaction, in this case, is a stand-in for how attractive it would be for the market and how much, you know, what level of adoption you can expect and this is a very subject exercise but I always find it valuable to doing a group setting so you basically break out your requirements for the very tangible features of a vehicle and you list them individually and have people map 'em with the three lines, right? So you come to a common understanding of, at the most basic level, what must I have? What must my product have so that I can get out the door and the world that I work in we usually describe that as a minimum viable product and a minimum viable product that I can get out the door and actually expect someone to pay money for it. That center line, the performance or satisfier-type features, really there that's where you're doing prioritization and just tradeoff analysis, you know, just looking at each characteristic or feature on that line and understanding how much more it would contribute to adoption. Delighters are the things I would put really towards the end of the line, you know? Probably not – I keep saying more software-esque terms but I think they apply to a physical product as well. Release one of the product or the first vehicle that I roll up, although it's probably not gonna include (inaudible) delighters, those are things that come with the model a year from now or a year after but what you're in essence trying to build towards is a product roadmap that ascribes or describes exactly what features I'm going to have available in the vehicle at what date and just given the way the automotive market works that would probably map out to an annual kind of release schedule or a release plan."*

With a list of performance dimensions and an articulated categorization/conception of application contexts, one can exhaustively map performance combinations that can help one align an enabling innovation's emerging capability set and paradigm, with contexts that may embrace such combinations and serve as lily pads to an enabler. To map these combinations, one can: a) identify all possible tradeoff combinations in a solution, b) search for dimensions of performance overlooked in a working paradigm that are relevant to a new paradigm, c) define what excellent and acceptable mean in the new and working paradigm, d) increase performance in dimensions that stem from an emerging paradigm, and e) search for evidence of misalignment between capabilities/performance and a given context that may be stifling progress. Consideration of current dimensions of performance (i.e., status quo dimensions) as well as future (desired) dimensions of performance can help create a roadmap of performance to be developed. Charles, for example, in his EV performance task, more specifically in the aforementioned discussion of the electric grid, identified status quo and alternative performance configurations of the electric grid and the impact of vehicles on such a grid:

> *So it's kind of a large systems design problem. The issue you've got is you've gotta have a pretty smart system to make sure that if that electron doesn't jump off on my device, how can we store it? So if you start looking at a larger systems approach, you're going to have to look for other energy storage techniques to try to improve the power system. Estimates are the power system wastes somewhere between 30 percent and 60 percent of the energy that we start to put on the electric grid never gets used because it's there kind of on contingency purposes. So if the smart grid could really get smart enough to communicate with our vehicles, to tell it when to charge and when not to charge, so we don't want everything in a critical mode, that we plug in all of our vehicles and brown out the electric grid at night. What we need to do is to have a smarter grid that manages to shift and manage loads. Some of the shifting and managed loads could also be other things, like building heating and cooling is typically done with chilled water or heated water – so those systems have giant buffer capacities. Unfortunately, many of 'em in the old way of thinking are basically set up to be constant 58-degree water or constant 100-degree water or whatever. But if you could make that smarter and be able to accommodate more storage of energy in the water, either in cold water in the summer or hot water in the winter, you have a giant buffer*

capacity there that you could actually store a lot of that electricity and make sure the power grid gets more efficient as well. Now, it doesn't work without a smart grid that can pretty accurately sense a load and manage the loads. It's a very similar thing to work – the research work we did – that I did in the military, where we were seeing power systems work in the Army. Many of the Army applications are going to be small forward-operating bases or command posts that are going to be totally autonomous. Think of those as micro-grids. And so that micro-grid application is going to have the same problems. You've gotta fix power generation -- Source. You've got fixed loads that are going to vary, depending on environment and conditions. Unfortunately, the military usually sizes a command post for one generator set or perhaps two, a primary and a backup, and they size them for the worst case loads. So the electric load in the Arctic with all the electric heaters on, or the electric load in the tropics with all the cooling on and all the mission equipment going independently, so if you could start thinking about a micro-grid that says, well, gee, instead of a 40kw generator, what if we had multiple 5kw generators that are networked, can sense a load, and can fire up more generators with some perhaps battery storage, and there's plenty of data. I mean, there was a paper I know that we published with some of my Army friends a couple years ago that looked into and said that there's 30 percent to 40 percent of access capacity in most of those generator sets. Impact with that is you don't use the capacity on a generator set. You don't have the load built up. The generator doesn't operate -- at its full efficiency. I mean, that's clear. When it's not at its full efficiency, it's also not at the right temperature, so if it's not the right temperature, it burns fuel. It has incomplete combustion. It causes the combustion chambers to carbon up and essentially build the coke up inside the combustion chambers and seize the engine. So that was a major problem we had. Some of the early approaches we had to solving that problem in the military were just let's build a giant resistor bank. Let's put it on top – you know, a thermal heater. Let's put it on top of the generator and let's just shed the extra energy as heat. Well, so we're taking fuel, we're making heat, and we're heating the environment. So that's not necessarily a very efficient way of doing things. We've got a number of ways that we can look at EVs, micro-grids, the battery storage, and what we're learning from trying to get EVs on the road. So for instance, the batteries that we put in electric vehicles, if added to that generator set for the military, there's some recent studies that show that you can turn the generators -- off for six hours at a time. You can do a 30 percent to 40 percent increase in fuel efficiency beyond the other fuel efficiency measures you can actually have on a command post. Now, that can be kind of cool, because if you're actually in a deployment situation and if noise management becomes an issue, then you've got an operational advantage. You can make the command post relatively quiet for at least

> *some blocks of time. The other issue is if you think about trying to live in one of these forward-operating bases with generators blaring in the background, it's not going to be a place for great thinking, great communications, great meetings, or great sleep. So if you add a couple of times a day that you can kind of make this a more quiet situation, you can allow for some sleep cycles that are more normal. You can allow for meeting cycles to happen that basically are not difficult or otherwise harmful to try to get all the information out and do it in an efficient way. So there are some other efficiency things that we can get out of this. Essentially, if you go to EVs - you can – like, you won't necessarily change the amount of energy that we use to do our normal life. You can change where the energy forms are coming from. You can go to more renewable resources, and you can basically rethink how we're importing – what imports we have for energy. Most of the electric – sources of electric energy are domestic. The renewable ones, like wind and solar, have to be domestic. They're close -- where our load banks. Coal is in great quantities domestically. Nuclear is in great quantities domestically. So all of our electricity sources basically don't require very much import. There's an abundance of natural gas that's kind of being used for peak generation. So unlike petroleum, which was much more – it was about 70 percent imported, is now -- I think recent reports are it's around 50 percent and dropping because it's – probably because we devalued the dollar, and we've made it a lot cheaper to extract here than to import, so – (Charles)*

Core behaviors also play a role in this behavior. Critical to this behavior is exploring all possible configurations of performance dimensions, even those that might seem counterintuitive at first glance – within the pragmatic boundaries of a given challenge – thus calling for proactive shifts in perspectives. Multiple lenses are also helpful in identifying seemingly hidden (but often relevant) performance dimensions, particularly those of sociological or psychological nature – i.e., those due to the influence of social groups or of mental states. Often times certain dimensions of performance are the result of historical norm, rather than absolute necessity, and thus separating negotiable norms from non-negotiable rules becomes relevant to understand the possible variables that can (or cannot) be adjusted.

Overall, this behavior calls for proactively exploring tradeoff possibilities for the current and future performance of a concept. Ken, in his performance task debrief, summarized this behavior as moving "levers," which seem to be critical in evaluating tradeoffs:

> *"I started with constraints and dimensions around the problem, to understand what the – what possible levers you can pull on in order to enact change in the given timeframe, or actually enact change in this case at all."*

5.9.4 Matching Lily Pad Contexts With Tradeoffs and Headroom

With articulated perspectives on solution performance dimensions and contexts in which such solutions can play a role, one can connect solution tradeoffs (i.e., combinations of performance dimensions) to contexts that accept such tradeoffs and accelerate impact (i.e., lily pad contexts). Often times, an implicit assumption is that new ideas need to stay within the context (e.g., an industry vertical or application area) in which they were conceived, which ignores possibilities for faster adoption in contexts outside of traditional boundaries. These counterintuitive contexts, however, may embrace the benefits and limitations of the current state of a concept/solution because limitations in one context may be perceived as benefits in another. Lily pad contexts help stakeholders garner feedback, resources, and a path of least resistance for an idea while building performance in critical long-term dimensions and/or driving related learning. Connecting solutions to lily pad contexts likely requires the ability to distill and describe the essence of ideas without ties to a specific context (a core behavior), to separate negotiable norms from non-negotiable rules, and to be able to make proactive connections to possible host contexts that are ripe for a paradigm change.

Drawbacks to this performance-context match exist. The use of solutions in "outside" contexts might require making performance dimension tradeoffs that might not have been envisioned at the onset or may not be considered optimal for a particularly desirable performance development trajectory. It also requires addressing host ecosystems, which may be in low knowledge domain for the idea developed, that incubate the enabling idea and provide resources for its development (a separate related pattern of the framework described herein) in ways that were not previously anticipated.

Yet the potential benefits of this solution-context matching behavior potentially outweigh these drawbacks, particularly for concepts in the enabling window. In the enabling window, each solution-context match represents a “lily pad” or “stepping stone,” i.e., an opportunity for proactive early trial in the pursuit of a grander goal – here the potential to become an enabling innovation. Beyond solution optimization, a roadmap of lily pads helps garner critical resources to pursue the development of desired attributes, which in turn reduces the time to “results,” demonstrates progress, and opens up additional application spaces.

In the history of enabling innovations, many of these connections have happened implicitly or are often portrayed as a result of seemingly serendipitous insights – despite the fact that such connections can be proactively identified. Anesthesia, for instance, made “jumps”/”connections” from entertainment (laughing gas), to dentistry, to surgical procedures. X-rays also followed a similar pathway, from science, to dentistry, to forensics, and to medicine, before being adopted in fields such as security, counterfeiting, and astronomy. In the case of X-rays, for example, long exposure times needed to generate an image of the human body made it easier for the technology to be adopted in the field of dentistry first, where images could be generated quicker, until advances such as ray collimation and the Coolidge tube were developed. In the case of lasers, where the technology sparked interest in many fields alike, these connections were made proactively and, to an extent, influenced the speed with which laser technology was diffused with applications in science, medicine, and communications within the first five years after its invention. In all the aforementioned historical examples, an opportunity existed to make such “jumps” between contexts proactively through the behaviors described in this pattern.

Frameworks that help link desired results/outcomes with specific circumstances of use can be adapted to engage in this behavior and help characterize the roles that a solution can play in a given context. For example, when attempting to find problems (or "jobs") for an evolving solution, Anthony et al. (2008) suggest examining performance dimensions exhaustively, permuting such performance dimensions, and assessing context/circumstances in which solutions might be helpful. Similarly, when attempting to find solutions for a set of problems (or "jobs") that are emerging due to a paradigm transition, job-circumstance matrices in which desired "jobs-to-be-done," or the problems that stakeholders want to solve, are contrasted with multiple circumstances to understand opportunity areas. In addition, while characterizing such contexts, separating negotiable norms from non-negotiable rules and finding first principles can help understand novel roles or advantages that a new solution might have. Effectively, these frameworks help link desired results/ outcomes and specific circumstances.

In the performance task, participants often acknowledged the importance of selecting contexts that might embrace the current tradeoffs of electric vehicles. Henry, for example, mentioned the importance of exploring markets with the greatest interest:

> *"I'd want to be looking at different markets to understand the size of the markets and the market opportunities particularly around where you see greater interest in adoption. I think there are some places in the country that are going to be more interested in being early adopters of the EVs and others so one of the challenges will be understanding which are the right markets you should be investing time in."*

Beyond simply selecting contexts, these performance-impact matches must address the question: "for whom is my concept/solution 'good enough' or 'adequate'?" Max, for example, in the EV task, engaged in a similar behavior by matching the performance dimensions of EVs (range for example) and the possible contexts in which the vehicle can be adopted, which have their own set of characteristics, such as available EV infrastructure:

"I marry up those two things to understand what are – what is – the – what are the capabilities of this vehicle that I need to have in place to even go to market and can I come up with a minimum definition that allows me to get out the door sooner? I don't wanna do is design a car that's over-engineered, in the near-term, and potentially price myself out of the market or find that some of the capabilities that I've included in the vehicle are actually not that interesting to consumers, right? It's better to learn as your product evolves than to try to over-engineer it, in the beginning… Then we to start understanding what's the timeline for getting that infrastructure in place so, as I'm thinking this through, the real challenge to me is not the vehicle. It's the infrastructure. If I developed a roadmap for that, the vehicle itself, it's probably kind of a pretty straightforward thing where I'd say, "Over the next 3 years I'm just drawing up kind of roadmap here for 2014, '15 and '16," and what I would describe in that roadmap is – and try to bring together all the elements that I need to understand in order to take this thing to market so, from a vehicle perspective, let's just say I made a decision on what my minimal – minimum – viable product is, you know? I need a battery that's capable of a range of 200 miles. I need a set of features or capabilities within the vehicle that at least puts it on par with lower-end models in the market, given that we're going after a cost-conscious market segment, so I don't wanna list 'em all out but, for example, you know, you have to have some kind of some kind base interface for radio, nav, potentially. That might be a little bit high-end, you know? You need everything from the seats to the frame, et cetera. I mean the features themselves are probably straightforward, I would imagine in any vehicle but I would map it out so that I have a vehicle that has range to make it viable, assuming a partnership with Hess so the main question is the battery and that's an engineering question so you'd have to work with engineers to understand the technology and what's available and what the cost is of that. That's all. That's kind of the bottom cost in this case. It's how much is this thing gonna cost is gonna be largely driven by – in large part driven by – the cost of the battery and the available technology. The sets of features I would put around that I think are obvious and can be derived from looking at what other – at other – offerings in the market that target the segment. From there, in 2015, I'd be looking at a couple of things and I'm still on what I would I would call vehicle track of the roadmap. I know you can't see this but [crosstalk] – Yeah, so I would say that it's what I'm looking at in 2015 again I'd be focusing heavily on the battery. I want extended range. Let's say we're assuming a 50-to-100-mile-range increase and what that would allow me to do is start to offer different models in the market so I would probably given that we would have – you know my enthused assumption is

> *that we have two types batteries now with two different ranges, I would have two different vehicle offerings"*

Although participants were unaware of the enabling innovation model, the importance of recognizing the position of a solution in the impact vs. time curve seemed to implicitly play a role in decisions regarding the match between performance and application contexts. For example, Nicole acknowledged that due to characteristics of the environment/context in which EV solutions must play a role, such as the habit change required and the current state of infrastructure, the pursuit of all electric vehicles might not be ideal and thus prioritized the pursuit of vehicles that initially run on electricity and then use an alternative energy source (over all electric vehicles):

> *"Interested in pushing two or three, type two or type three and they want success measured by significantly increasing the EV population… [re-reading EV task brief]. It feels like we're allowed type one because that's just not really of interested to the committee and also I'm not sure it really serves as a good stepping stone to other types of EV's because it just feels like it's no better stepping stone to the type two EV than a regular car is because it doesn't introduce any new anxiety, it doesn't solve anything new, it doesn't change any habit, it's just a gas car but with traditional fuel powered. So that's why I would deprioritize looking at how to redrive adoption of number one because it just doesn't feel like it's important to them currently and it - Doesn't feel like it's a good foothold to achieving their bigger goals. And I would deprioritize really focusing effort and investment on number three, on the all electric vehicles primarily because it requires such a fundamental change in consumer behavior and in existing infrastructures with no ability to leverage anything that's existing on the behavior side or the infrastructure side that it's hard to envision achieving the goal of increasing EV adoption in five years. Now potentially in ten or fifteen years you can be moving a lot of people to that third type but it's just going to require a lot of investment and a lot of change. So it just seems like a five year goal directing all of our - Resources and efforts against type three. It's just not going to yield the results we want. Now certainly if there are things that we can do that lay the groundwork for significant adoption of the type three products ten years from now, we should make those investments but I don't think we should put all of our eggs in the all electric basket. So that's what I kind of deprioritize looking there. So then that kind of leaves looking at the vehicles that run on electricity so the electric to fuel like the Volt as*

kind of where I would put the effort to then really gets prioritized getting deeper on the jobs to be done."

Critical to making (and prioritizing) these connections is the recognition of the desired outcomes of the "lily pads" or "stepping stones" such as garnering resources for continued development, advancing performance dimensions, and increasing interest in a solution. Victor, for example, in his performance task, emphasized that a key element in his solution was to create incentives for companies to install charging stations. His stated goal would be to understand ways by which companies can make money from charging stations, which in turn would generate interest in EVs and fuel their continued development, first in plug-in hybrids (due to an argument similar to Nicole's) and then in all-electric vehicles:

"The first effort is we must find a way to create incentives for electric companies to put in charging stations. So that's the first one. So we must have incentive program sufficient for electric companies, electric parking, etcetera, to, you know, install charging stations. This does two things. It makes – it creates the basis by which we could eventually get to an all electric system, as technology gets us there, but in the interim, it enables – because there is the… Okay. Plug-in hybrid. So the plug-in hybrid is the next evolution step. We have to endorse that. Okay? That this is the next step, in a route to all electric. We're just not going to be able to go all electric. It's just too great a leap. So we need to install that. That enables the – that really makes the hybrid – the plug-in hybrid an easy next step that gives the people the option. And you then get into making this possible. So you install the charging and metering systems, okay? And that's not a small choice. Okay? These incentives to enable this to happen I think are going to be pretty significant. Okay? And then as I've talked before, the ___, what's in it for me? And so the key that makes a flywheel work, or really create the momentum, is finding who those key players are, identifying what's in it for them in a way that they agree and invest, and as soon as you get that, this thing just goes. Okay? And so if you don't have something that the key players see something in it for them, it won't get going. And so again, I use my own consumer goods example of if I can't – if I don't have an offering that the retailer can see that their margin or their volume is going to go up, they're not going to push it. But as soon as I show them that if you sell a few more of these, you're going to make a lot more money, they're going to get behind it, and oh, by the way, they're going to actually start – they're going

> *to reduce my investment by them investing. If the supplier who's providing me the materials to do this can see how they can make more money by me selling this, they're going to figure out how to do it. And so it's all about looking at who those key players are and figuring out how do you make that happen. And again, you could see I came from a consumer-based system that says, okay, the consumer's the hub of it, and so who are all the connectors to that consumer that would motivate and enable the system to go forward? I didn't get to all of them. I was just playing with the top couple, given the time that we had."*

5.10 Persuading to Facilitate Acceptance or Use

Stakeholder resistance and skepticism are natural reactions to change, which calls for persuasive communications that facilitate acceptance and diffusion of ideas (Rogers, 1962; Denning, 2004; Heath and Heath, 2007; Thaler and Sunstein, 2008; Duhigg, 2012; Beckman and Barry, 2009, 2012). Because enabling innovations are driven by impact, which in turn is defined by the significance, reach, and paradigm change of a concept/idea, solutions must often be accompanied by a plan to effectively, efficiently, and persuasively communicate their benefits. Effectively, any change effort must "establish a sense of urgency, form a powerful guiding coalition, create and communicate a vision, empower others to act, plan for and create short term wins, consolidate improvements and institutionalize new approaches" (Kotter, 1995)

Designing for enabling innovation thus implies communicating in ways that persuasively transfer key insights to all involved stakeholders and facilitate acceptance or use, as shown in Figure 5.18. Thus relevant behaviors include *telling stories to paint a vision*, *conveying counterintuitive insights* to overcome preconceptions of what is typically considered "acceptable" to foster diffusion, *creating win-win partnerships* that are mutually beneficial for stakeholders, and *driving habit conversion* to change established behaviors, as synthesized in Table 5.8. Core behaviors such as synthesizing insights, iterating, employing multiple lenses, and finding first principles are thus again important in the exploration of these behaviors. The following sections explore the aforementioned behaviors in more depth.

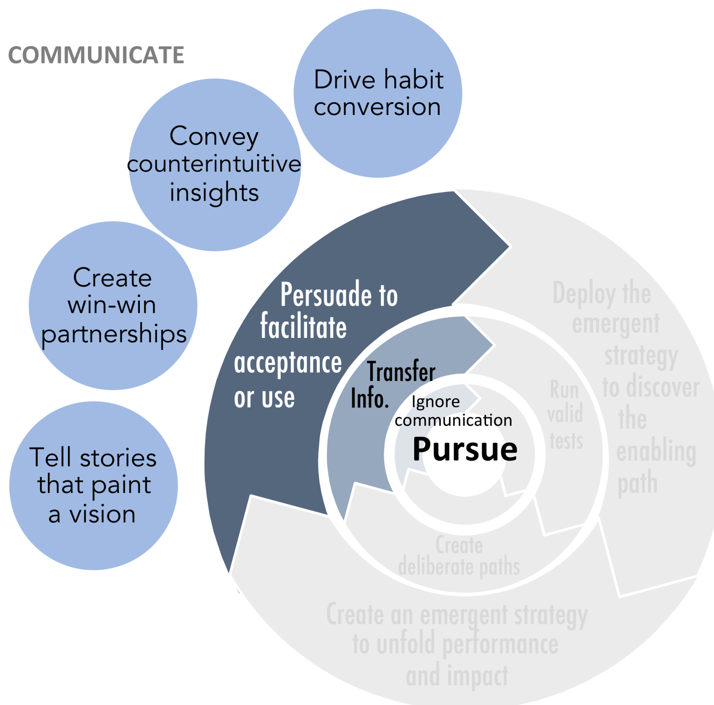


Figure 5.18 Persuade to Facilitate Acceptance or Use

It is likely important to acknowledge that participants engaged relatively less in this pattern (communication) and the remaining patterns in the framework (implementation path definition, implementation, and envisioning) compared to the previously described patterns, perhaps due to the unstructured and undirected set up of the task. (Future work, discussed in Chapter 6, can address these issues.) Nonetheless, select instances of these behaviors were observed – some in the actual performance task and some in the interview debrief. These instances complement insights from the historical analysis, and the scholarship of integration. In addition, the "Informed Design" (Crismond and Adams, 2012) framework does not describe patterns related to communication and path definition for beginner or informed design and thus such patterns are herein hypothesized to be consistent with the rest of the framework.

Table 5.8 Behaviors to Persuade to Facilitate Acceptance or Use

Behavior	**Definition**	**Related literature**	**Unique link to enabling innovation**	**Link to persuading to facilitate acceptance**	**Illustrative actions of the behavior**
Tell stories that paint a vision	Communicating persuasively to build buy-in for ideas	• Lloyd (2000) • McKee (1997) • Denning (2004) • Kotter (1995)	Enabling innovations drive a change in paradigm and storytelling techniques can persuade paradigm adoption	Stories resonate with audiences and persuade them to adopt a given idea/ solution	• Describing stories to communicate • Describing idea pitches
Convey counterintuitive insights	Conveying ideas that deviate from those typically encountered in a given context in tailored/ perceptive ways	• Chi and Hausman (2003) • Kegan and Lahey (2009) • Zull (2002) • Kotter (1995)	Enabling innovations challenge a working paradigm which may trigger resistance from advocates of such a working paradigm	Ideas that challenge the status quo might encounter resistance that needs to be managed	• Creating experiences that convey aspects of an idea • Describing ways to communicate non-traditional insights
Drive habit conversion	Influencing/nudging decisions through the presentation of choices	• Graybiel (2008) • Duhigg (2012) • Smith and Graybiel (2014)	The paradigm change that accompanies enabling innovation often involves transitions in habits and/or cultural norms	The way in which solutions/choices are framed can influence people to adopt them	• Describing stakeholder habits to change • Implementing habit conversion strategies
Create win-win partnerships	Building relationships with ecosystem stakeholders that can influence the success of an idea	• Solis et al. (2013) • Kotter (1995)	Enabling innovations often involve ecosystem level changes, which are unlikely to be achieved by a single stakeholder	Given their multiple application contexts enabling innovations can benefit from partnerships with key players in diverse ecosystems	• Listing stakeholders from which buy-in is required • Creating win-win strategies to partner with such stakeholders

5.10.1 Telling Stories that Paint a Vision

Stories represent a valuable way to communicate persuasively in the pursuit of building buy-in for ideas. Storytelling is behavior that provides a mechanism to make tacit knowledge explicit, promotes reflective practice, and provides an entry point for a community to participate in the delivery of an innovation (Lloyd, 2000). Further, stories can "spark action, communicate identities, transmit values, foster collaboration, tame rumors, share knowledge, and lead people into the future" (Denning, 2004).

In the framework described herein, storytelling is envisioned as a mechanism to paint a vision of an enabling innovation. Stories engage the emotional side of stakeholders (Denning, 2004) and can help manage the potential resistance that may come from an idea that has roots in a novel or different paradigm, particularly if an idea implies change to affected stakeholders. All ideas tend to undergo an "emotional selection" process and research suggests that people tend to be more willing to pass along stories that generate stronger emotions, and that the marketplace for ideas "competes not only over truth but also over emotion" (Heath et al., 2001, p. 1040). Thus, framing a story in a way that elicits a reaction (such as painting a vision that inspires) can drive an emotional response from an audience, while a more "scientific" transfer of information may elicit probabilistic judgments in a more coherent and rational fashion (Sinaceur et al., 2005). Although emotions may not prevent people from reacting rationally/analytically and vice versa, storytelling can serve as a mechanism to paint a vision for an enabling idea, and a conscious complementary effort to engage the emotional and analytical mindsets of audiences considering enabling innovation concepts. Thus, painting a vision for enabling innovations can be particularly useful in periods of investment and decision-making.

This framing of stories is possible even for the most technical or business-oriented (Denning, 2004) challenges, by proactively adapting select elements of "stories" (McKee, 1997) to a given challenge, regardless of context. Eliciting actions from storytelling calls for variations in types of stories, narrative tools and methods, and responses from the audience. Effectively, an a priori knowledge of the desired outcome of a storytelling activity can help guide story structuring activities. In the case of enabling innovation, ideas that deeply challenge the status quo might encounter resistance – which calls for conveying visions that inspire action.

For an idea to persuade to facilitate acceptance or use, it must be transmitted to other stakeholders and compete in the "market place for ideas" or "idea habitats" (Berger and Heath, 2005). Storytelling can thus foster communities of practice in which forms of narration help stakeholders share past experiences, build collective memories, elaborate new ideas, and build brand identities (Bettiol and Micelli, 2014). For example, researchers (e.g., Beckman and Barry, 2009, 2012) define (and teach) design thinking as "figuring out the story" and "telling a new story" and others (e.g., Zurlo and Cautela, 2014) classify design activities as narratives that companies can use to explain and stimulate different types of innovation processes.

The enabling innovation cases analyzed in Chapter 3 of this dissertation often engaged in storytelling moments. As examples, accounts of key dissemination moments/events of the laser (Hecht, 2010) and the X-ray developments (Kevles, 1997), for instance through press conferences and/or briefs, helped paint a vision for the discoveries and evoked emotional reactions from many types of audiences.

Creating stories that paint a vision call for identifying possible audiences and key influences, and structuring a story according to a given context/ circumstance. For example, in the performance tasks, Drew explained how he would pitch his ideas to the CEO and use stories that illustrate the effect of his ideas on end users:

> *"The way you have to pitch it is probably that you really provide first the big image, without getting lost in technology talks, but that you say, okay, the fuel consumption, blah blah blah. I mean, it's not sustainable. I think*

> *everybody would agree with Al Gore and all the global warming, and we are – I mean, you will find the story which is pretty compelling, and you will say, okay, the way towards electricity, that that's the way to go, and everybody will probably agree with you, with the big picture. Okay? That's the first one. The second one is then really that you show it from a customer perspective, because every CEO in the normal – they will not go into technology. That's not what they're interested in. They only thing they're really interested is common sense, how would I as a normal customer behave? And so I would tell a kind of – use this scenario, story, the way it could look like as a point of approval."*

Storytelling also calls for creating contrasts and turning points to highlight key insights, balance logic, emotions, and knowledge, and integrate stories with a resolution. For example, Max highlighted that communicating his ideas or pitch to executives would involve walking people through the journey of a roadmap to increase the adoption electric vehicles, more in a story format rather than in a yearly plan:

> *"Pretty straightforward so really I mean without going too much further on the roadmap itself what it becomes is a single, large artifact that can be shared with anyone that has any – any stakeholder in the program that wants to understand infectively that this is what we need to do, as an organization, to get this product out the door. This – my – view is kind of the front page of the pitch stack of the (inaudible) or the government or very – your stakeholders are, in this case, and this is what you walk them through to make them – help them – understand how we get from A to B, right, how we achieve the market share that we've collectively targeted and who the players that need to be involved to get it done. Behind all this is sufficient, you know, is a great – a very – detailed business plan, right, that covers all the aspects of the roadmap at a kind of a more granular level, right, so the business case for the partners, the business case for the service model. How do we option, how do we outsource that? What partners do we need to have in place? So there's a large amount of work that has to go on behind kind of the scenes of the roadmap to get this thing out the door but to me that's what drives ultimately the decisioning and the tools that you use to get there, in my opinion, are very research-driven. You need to – my bias is always to look at, as I said I think at the beginning you – start from the customer and work back… I mean I would call – I would call 2014 the acquire phase, 2015 the enhance and 2016 the growth phase, right? It's just in my experience it's*

> *very simple way to summarize a roadmap that people think (inaudible) for particular executives that like to think of things not necessarily as years but as a phase in a journey."*

5.10.2 Conveying Counterintuitive Insights

Ideas that deviate from those typically encountered in a given context need to be communicated/conveyed in sensitive ways. In the case of concepts with enabling innovation potential, conveying counterintuitive insights takes particular importance because these concepts often challenge working paradigms thus triggering resistance to change that needs to be managed.

Conveying counterintuitive insights could benefit from insights from the change management literature and the learning sciences. Managing resistance to change requires transformation of three components often engrained in stakeholders: help re-organizing knowledge/reality, managing emotions/anxiety, and mitigating conflicting aspirations/ideas (Kegan and Lahey, 2009). In addition, there is a need to provide a clear direction, proactively engage the emotional side of stakeholders, and tweak/alter the environment/context in ways that the counterintuitive insight/idea/change is supported (Heath and Heath, 2010). Similar arguments are made in the learning sciences, in which some types of "misconceptions" (i.e., ideas that are flawed, which resembles the flawed paradigm language used in this dissertation) have been identified as more resistant to change, particularly those that require a change in the ontology (i.e., the categorical structure of reality) of a stakeholder. In particular, "conceptual change that requires shift across ontological categories [is] seen to be challenging and radical for a variety of reasons, such as a lack of awareness that such as shift is necessary, unfamiliarity with the target ontology, or the cognitive demand of re-inheriting all the attributes of a concept based on its new categorical membership" (Chi, 2005, p. 188). Chi and Hausman (2003), for instance, argue that the process of discovery often requires that a stakeholder reconceptualizes a problem in a way that crosses ontological/fundamental categories. Effectively, lack of alternative categories (to describe/name novel concepts) and lack of awareness contribute to the difficulty of conceptual change and inhibit the process of discovery, likely motivating the rejection of counterintuitive insights.

A few select performance task excerpts illustrate this behavior. In his performance task, Mike seemed to understand the need to both address knowledge organization and emotions and as one of his ideas mentioned a campaign that aims to convince a broader audience that gasoline use is a socially unacceptable behavior:

> *"So you could have a – you could sort-of have a viral – ad campaign that sort-of is like, making fun of gas users, gas guzzlers or whatever. Like you could basically – you could sort-of have this sense that like – you could create more of a negative social – like where – it's almost like smoking, right? So like the squares were the ones who didn't smoke back in the '50s, but then over time you can transform that, so that's actually an interesting thing to think about is, like, other social shifts where you start with the freaks being the ones who do it, and then over time, it becomes mainstream to where it's almost embarrassing to not do it. So in this case, the analogy is smoking, so it's almost freakish now if you actually do smoke, or you're seen as – kind-of an outsider, whereas back in the day it was you're an outsider if you didn't smoke. And so could you have a sort-of Truth.com type viral ad campaign that makes fun of gas guzzlers or like somehow makes it so that we're not the weird ones, you're the weird ones. The gas guzzlers are the weird ones, you are the weird ones."*

Thus conveying counterintuitive insights in the pursuit of innovation could be, at a very fundamental level, considered a teaching exercise, in which shifts in categorical/conceptual organization of knowledge while managing emotions are barriers to overcome. These barriers are considered as critical when conveying counterintuitive insights since people have prior categories and beliefs grounded in prior experience, and innovation often involves challenging such prior knowledge and emotional structures through an idea that is new and impactful.

Many mechanisms exist to convey counterintuitive insights, and one could use frameworks from the learning sciences such as Kolb's experiential learning framework (Kolb, 1984) to describe characterize such mechanisms. For example, one could attempt to convey a counterintuitive insight to stakeholders in one or more modes of experiential learning: concrete experiences, abstract ideas, active testing, or reflective observations.

Performance task excerpts illustrate the different ways by which participants would try to convey their proposed ideas regarding the adoption of EVs. Max, for instance, emphasized the importance of engaging in all quadrants of Kolb's experiential learning matrix, from abstract ideas in presentation decks to concrete experiences through models and prototypes:

> *"So I think another important thing to get the funding that we need here is assuming we've now defined a roadmap, we've defined a product, we have a vision for what we want in 2014, '15, and '16, you know? That's all fine and good and you can put together a really nice package with nice visuals to hand to the people when they come in for the meeting but I think much more powerful than that is a proof-of-concept or you can think of it as a demo it – you know I don't think it needs in this case to be necessarily operational vehicle but it's a rendering of the vehicle itself that you can interact with and get a sense for the look and feel of the vehicle itself so I think there'd be a significant -- that's obviously a significant – effort and we do that in many of the programs that we undertake and that would be a whole stream of work in and of itself but I would wanna come into that meeting with something that they can look at and they can touch and feel. I think that goes a long way towards getting buy-in for when you're asking for funding. And it also is an early mechanism for identifying challenges for the products and solving them before you're actually in the engineering process or in the manufacturing process in this case so you may find that the kinda diagrams you put together for the vehicle when you actually have a not a functional model but a model nonetheless, you can identify challenges with that design and in manufacturing as with software or any other type of product development, the earlier in the process you can identify challenges the less costly they are to you and the better the product will be when you get to market… I'd want user-experience designers so that I could flesh out storyboards effectively and in a way that's engaging and that can get people excited about the product idea. I think that is very important and*

> *sometimes not a focus so you know it's often that people come in with a PowerPoint and try to pitch you a product idea and it may fall flat just because it's a PowerPoint presentation whereas if you apply a little polish with someone with design experience and deep understanding of interaction you can come in with much more compelling arguments and artifacts to get the funding in this case that you're looking for"*

Drew also emphasized the importance of using different means to convey insights and try to get people to buy into the idea:

> *"So I would show them the ideas. Yeah, you get in the car, then go to the – to your office. At the office, there is this station, duh duh duh duh duh, by the company B. And they would do it, etcetera. I would show them more or less the final point. And then I think the key element to convince them is to do a trial. Let's talk to some people. Let's do this. Because they would not be willing to sign a check let's say for $500 million right away…"*

Frameworks to think about conveying counterintuitive insights abound in the change management and learning sciences literature. Kegan and Lahey (2009) for instance, propose a framework to embrace change, called "immunity to change," in which they call for explicitly unearthing hidden competing commitments and underlying "big assumptions." Further, re-wiring knowledge and emotions, from a neuroscience perspective, implies rewiring the brain and being aware of the factually or conceptually flawed knowledge that learners possess, the incomplete networks/patterns that learners hold, and if their conceptual understanding has networked misconceptions (Zull, 2002). In summary, one must understand and articulate a mental model of the audience that is on the receiving end of the counterintuitive insight.

5.10.3 Driving Habit Conversion

Habit conversion herein refers to the presentation of stimuli, routines, or rewards in an attempt to drive changes in routine behaviors. Habit conversion is important to enabling innovations, because paradigm changes that accompany enabling innovations often inherently require behavior changes in stakeholders. Understanding how habits or routine behaviors form and how they can be altered can thus facilitate such a paradigm change.

In historical enabling innovations many behaviors had to be changed with most of these changes happening over time. In the case of anesthesia, doctors were habitually used to operate quickly to minimize a patient's suffering and had to re-adjust their behaviors for surgical procedures that were more elaborate and less time pressured. Similarly, surgeons had relatively non-hygienic pre-operative habits prior to the discovery of antisepsis and had to modify their behavior to incorporate sterilization/antiseptic routines prior to surgeries. In the case of microfinance, particularly for Grameen Bank, banking practices were viewed as habitual at the organizational level, with routine procedures, requirements, and forms to be filled out, which had to be converted into a new habits that were tailored towards the specific circumstances of the poor.

According to Graybiel and Smith (2014, p. 40), habits "fall along a continuum of human behavior." At one end of the continuum are behaviors that "can be done automatically" thus freeing up brain resources/space for different pursuits. In contrast, other behaviors can "command a lot of our time and energy." Habits fall under the more automatic end of the spectrum, and seem to emerge naturally as one explores physical, social, and emotional environments. People constantly "try out behaviors in an array of contexts, find which ones seem beneficial and not too costly, and then commit to such behaviors, forming our routines" that solidify into habits (Graybiel and Smith, 2014, p. 40). The more routine a behavior, the less aware one becomes of it. Habits become engrained in part due to "reinforcement contingencies," i.e., the consequences and rewards of actions which push behavior one way (towards the habit in the case of a contingency) or another (away from the habit in the absence of a contingency or reward). New behaviors are always explored, figuring out what works and what doesn't. A habit then forms when people repeat a behavior, which stamps out routines. Then the habit is imprinted, i.e., seemingly packaged for efficiency since the brain seems to be always looking for ways to save energy/effort, and cues regarding when to engage in the habit are formed. This process can be summarized as evaluation of behavior, selection (to engage in or not engage in the behavior), chunking (i.e., the process of habit formation), and habit (Graybiel, 2008).

Habits can be neutral, desirable, or undesirable (Graybiel, 2008) and can occur at individual, organizational, and societal levels (Duhigg, 2012), the same levels at which enabling innovations can occur. If one wants to drive enabling innovations proactively then one needs to understand the habits that need to change and design solutions that motivate stakeholders to shift their habits.

Three components are critical to creating a habit and to driving habit conversion: cues, routines, and rewards (Duhigg, 2012). These three components cultivate a loop of routine behavior. Driving habit conversion calls for changes in such a loop. For example, Duhigg (2012) argues that if one uses the same cue, and provides the same rewards, a shift in a routine can occur thus driving habit conversion/change. The difficulty, however, lies in understanding underlying/causal cues, routine and reward. A framework to change habits thus could consist of identifying the routine, experimenting with rewards, isolating the cue, and having a plan to drive change (articulation, observation, noticing of patterns). In addition, while one can be unconscious of habitual behavior, efforts to drive habit conversion can drive conscious awareness of habits, prior to the experimentation with cues, routines, and rewards that imprint a new habit as a new unconscious behavior. This can help more efficiently design "choice architecture" systems that can help overcome inherent biases in routine behaviors and steer towards new behaviors (Thaler and Sunstein, 2008).

In the performance tasks a few participants mentioned the need to change habits and behaviors to foster the adoption of electric vehicles. Henry and Victor, for example, directly acknowledged the importance of understanding habits in the automotive industry and the need to study them in more depth:

> *"And then probably I'd look at their charging habits, try and understand which customer charging habits the industry would need to accommodate." (Henry)*

> *"Yep. Okay. So what we're trying to do is under – what we're trying to do is transition people's habits from moving gas vehicles to all electric. Current situation is that we have lots of gas vehicles. We have a well-defined infrastructure. And fuel is readily available, and fuel is relatively cheap. So all in all, it is convenient, and it's also what I know, what we know. Okay. So that's the current status. I'll build on that some more as I think about it." (Victor)*

Nicole, in her performance task, made an analysis similar to the framework described by Duhigg in which she tried to isolate the routine behaviors that would need to change and the consequences for failing to change such behaviors, which highlight the difficulty of making people transition from gasoline to electricity-driven automotive behaviors:

> *"Looking at (inaudible), you have the current delivery model and the type of vehicle. I don't know if actually type of vehicle is right. You know what? Kind of the customer experience because people, the drivers, they have habits and it's really hard to break habits. So right now you go home, you drive to and from, you park the car, you get out of the car, you turn off the car, you get out of the car and that's it. And it's pretty much the same experience with the Prius in the electric to fuel you there's a whole new step there, you have to plug it in. And then with the Volt, you have to plug it in but if you forget one day, it's not the end of the world. It's kind of like if you forget to plug your iPhone in one night, you're going to be okay, it's still going to have battery the next day. It's not a crisis. Whereas I'd imagine potentially an all electric, it's a little bit higher anxiety if you've forgotten to plug it in. So there's kind of this the customer experience, the degree of habit change required and when you look at it that way, actually the current, which I'm*

> *just calling the gas vehicles, and the fuel power hybrids are actually pretty much kind of the same point… Looking at (inaudible), you have the current delivery model and the type of vehicle. I don't know if actually type of vehicle is right. You know what? Kind of the customer experience because people, the drivers, they have habits and it's really hard to break habits. So right now you go home, you drive to and from, you park the car, you get out of the car, you turn off the car, you get out of the car and that's it. And it's pretty much the same experience with the Prius in the electric to fuel you there's a whole new step there, you have to plug it in. And then with the Volt, you have to plug it in but if you forget one day, it's not the end of the world. It's kind of like if you forget to plug your iPhone in one night, you're going to be okay, it's still going to have battery the next day. It's not a crisis. Whereas I'd imagine potentially an all electric, it's a little bit higher anxiety if you've forgotten to plug it in. So there's kind of this the customer experience, the degree of habit change required and when you look at it that way, actually the current, which I'm just calling the gas vehicles, and the fuel power hybrids are actually pretty much kind of the same point."*

5.10.4 Creating Win-Win Partnerships

Enabling innovations often must play a role in multiple ecosystems and interact with many stakeholders within such ecosystems. It is thus unlikely that a single stakeholder or stakeholder category can drive an idea with enabling innovation potential on its own. Historically, enabling innovations such as the laser, GPS, X-rays, and anesthesia involved the collaboration of many types of stakeholders (e.g., corporate, academic, governmental) across ecosystems. GPS, as an example, started as a curiosity-driven academic project in applied physics, and evolved to a project/program that involved collaborations of academic, government/military, and the private sector. Further, these collaborations enabled GPS to evolve to versions that incorporated the best features from prior designs/generations, which the Navy, Army, and Air Force were independently pursuing in parallel (Bray, 2014). It is herein argued that these partnerships between different stakeholders are critical to drive an enabling innovation through its various characteristic stages: breakthrough, enabling window, and progressive cascade – especially when "win-win" relationships are facilitated.

Creating win-win partnerships for enabling innovations thus calls for building relationships with relevant ecosystem stakeholders that are mutually beneficial and can influence the success of an idea. These relationships need to be built from an understanding of the key drivers underlying the relationship. Solis et al. (2013), for instance, suggest a framework to achieve this understanding based on the analysis of the underlying desired outcomes (called jobs-to-be-done and jobs in business contexts) and the configurations of stakeholder networks through social network analysis. Understanding desired outcomes and their influence on the desired outcomes of other stakeholders can be achieved through the development of what the authors termed "multi-stakeholder job matrices" in which the influence of the interactions between functional, social, and emotional desired outcomes of stakeholders is assessed (Solis et al., 2013). Social network analysis, on the other hand, generates an understanding of the structure and underlying relationship patterns between the stakeholder within/across organizations, assessing metrics such as network centrality, density, and hierarchical structure (Wasserman and Faust, 1994).

In the EV performance tasks, participants often highlighted the importance of partnerships to drive adoption of such a type of vehicle. Participants often emphasized the need to identify the partnerships to be developed in an ecosystem. Mike, for instance, highlighted the different types of stakeholders that would need to buy-in to make EV succeed in the transportation ecosystem:

> *"The other thing we want to think about is I think you'd want to think about funding this, and so here, I think you'd want to form a consortium of interested parties. Sortium of all boats rise, and basically this would include car manufacturers, though you'd want to make sure – you'd want to do the math and make sure it's actually in their interest, because some of the times it isn't. You'd include – charging companies, charging cause, you include solar companies, because that would maybe tie into that. You'd include who else? What did we say back here? Government officials, academics, industry executives. So that's the problem is there isn't – battery manufacturers. So car manufacturers and components, components specific to – components.*

Battery manufacturers. So you'd want to get basically all of their money funnelled and then governments, and the private donors. Maybe Bill Gates would give a bunch of money or something. So you want to get all their money funnelled into a central fund, and then you could basically – partition that out to the different initiatives."

Performance task participants also highlighted the need to understand the "win-win" aspects of possible partnerships. These partnerships can be motivated by many types of desired outcomes, for example, combining efforts/capabilities, reducing barriers, improving awareness, increasing funding, and/or addressing weak links in an ecosystem. Effectively, these partnerships can exist for functional, social, and emotional reasons (Solis et al., 2013). Max, for instance, highlighted the importance of obtaining buy-in from car manufacturers and gas stations in the pursuit of EV adoption:

"I think some of the things that I would think about as a precursor to putting this on the roadmap and a partnership perspective where we've got the business case that we've put together, we've identified partners, we have to vet those partners, we have to make a decision on whether or not we wanna own any portion of that infrastructure, right, or do I purely wanna hand it off to a partner and have nothing to do with it and wash my hands of it? Probably in this case you'd wanna wash your hands of it, right? You don't wanna make your piece of the overall effort overly complex and then I'm trying to think of what other elements (inaudible). It's (inaudible) the other streams of work that you need to consider, marketing be a key one. I think I always try to include that in a roadmap to understand both what I'm trying to accomplish and what I wanna accomplish it by so you're developing your marketing practice in 2013 and trying to develop a demand for the product so we have marketing, we have partnerships, I would say we have vendor/manufacturing partner track as well. I'm assuming we don't have the capability to build this ourselves and don't wanna build it, right? So we need to find someone to manufacture the vehicle for us, kind of like the OEM model for consumer electronics for example. Maybe it's a Ford who actually does the manufacturing but we brand it as whatever we call this product but that's another key consideration when thinking about how I get this market and thinking about the cost, right? So I'm assuming that we're gonna find a manufacturing partner who will actually do a development of the car and then we're rebranding that and that goes back to the market so we have a marketing stream, a partnership stream and a vehicle stream, which is really what is this product. We have a vendor or manufacturing-

> *partner stream, which is who's gonna manufacture it with agreements that we have in place. Another big one in the vehicle case would be a service model so who's gonna service these vehicles? … Yeah, so let's assume that the number is 30 percent of customer who purchase gas actually go into the retail establishment and make another purchase and let's say the average purchase amounts beyond the gas is $10.00, right? So those are some of the elements you need to start to build a business case and then you want to look at the foot traffic introduced into an electric charging station or a vehicle-charging terminal at the location and so assuming the business case for Hess for example would be whatever charge I come up we would agree to for the actual charging service itself, right, which would be a function of the electricity used and some kind of markup and then the value of the additional purchases made in-store by customers using an electric charging station and from that information you could project that annual revenue as a result of having that charging station and assuming that in this case Hess agreed to partner with us because they do have a pretty good footprint."*

Participants also emphasized the value in understanding the gives and the gets of these relationships. For example, Nicole highlighted the benefits of involving private businesses in the EV challenge, specifically industry executives due to their marketing and sales power:

> *"But I think overcoming a lot of those barriers, it's going to take partnership between the government and through private businesses to address that. But I think it's addressable. It needs to be addressed to drive adoption. And then you get into the industry executives. They have the marketing power and the sales power to get that messaging out. So kind of driving awareness they can do that along with the government but probably more effectively through their existing marketing channels."*

5.11 Creating an Emergent Strategy to Unfold Performance and Impact

The change in paradigm that accompanies enabling innovations is wrought with uncertainty, implying that there will be many assumptions and little knowledge about such a concept. Thus, a high "assumption-to-knowledge ratio" will, more often than not, cause enabling concepts to encounter failures along the way. Yet this failure can (and should) be proactively managed to happen in small, low-risk ways that facilitate learning and discovery of the path to success.

Two types of strategies exist to navigate the uncertainty that accompanies a paradigm change – deliberate and emergent. In the design of implementation efforts, deliberate strategies plans articulate intentions as precisely as possible and set formal controls to ensure their pursuit and realization (Mintzberg and Waters, 1985). Thus a deliberate implementation strategy might not be effective because the identification and risk-mitigation of all unknown aspects of a concept that significantly departs from the status quo is often not feasible.

To account for this uncertainty, designing implementation plans for the pursuit of enabling concepts should place the philosophies of "emergent strategy" (Mintzberg and Waters, 1978, 1985), "planning to learn" (McGrath and MacMillan, 1995; Anthony et al., 2008), and "lean startup" approaches (Blank, 2003; Ries, 2011) at the center of implementation efforts. In these philosophies, which generationally evolved from strategy scholar Henry Mintzberg's research (e.g., Mintzberg and Water, 1982; Mintzberg and Waters, 1985), the approach to achieve an overarching goal is allowed to develop as exploration unfolds. At the root of this discovery process are experimentation efforts that highlight which of the many paths to success (which must be proactively identified) could prove feasible and desirable, continuously providing insights to re-direct efforts when needed.

In the context of enabling innovations, and more specifically, the enabling window, emergent strategies should be created to help navigate a unique set of challenges such as performance limitations, uncertainty in application spaces, ecosystem level barriers, and barriers and roadblocks that will emerge. Effectively, this emergent strategy should outline a plan to unfold desired performance and impact across multiple contexts. Thus, the creation of "discovery plans" based on these emergent strategies can guide stakeholders in converting assumptions into knowledge. Relevant behaviors to this "path definition" stage include *envisioning multiple impact pathways*, because likely no single plan can ensure the success of an enabling concept. Further, proactively *identifying learning metrics and assumptions* can help track the process of converting assumptions into knowledge. With an inventory of pathways, assumptions, and metrics, *creating learning experiments* to convert assumptions into knowledge allows stakeholders to discover the path to success. These behaviors, shown in Figure 5.19 and summarized in Table 5.9, are explored in the following sections.

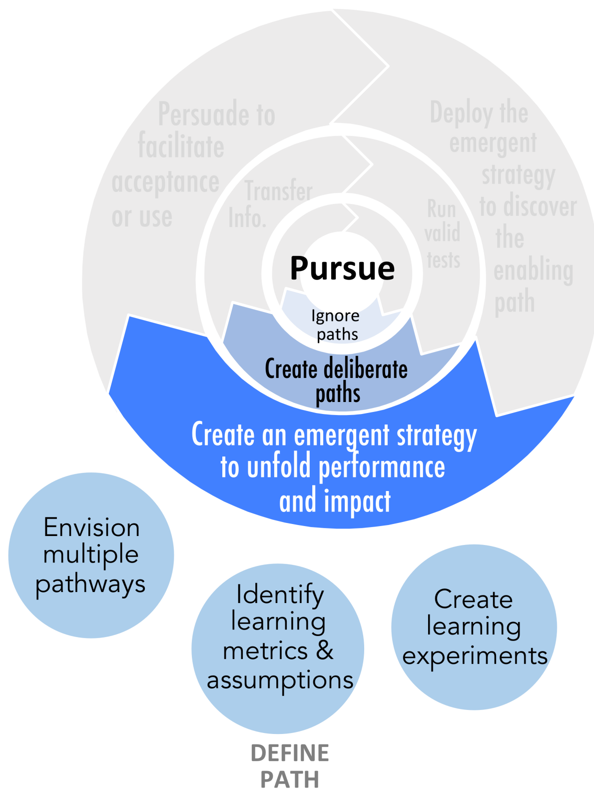


Figure 5.19 Create an Emergent Strategy that Unfolds Performance and Impact

Table 5.9 Behaviors to Create an Emergent Strategy that Unfolds Performance and Impact

Behavior	**Definition**	**Literature foundations**	**Unique link to enabling innovation**	**Link to creating an emergent strategy**	**Example actions/activities**
Envision multiple impact pathways	Mapping many possible pathways to idea success given the uncertainty that is inherent in ideas with enabling potential	• Mintzberg and Waters (1985) • Ries (2011)	Because of the new paradigm and the novelty in a breakthrough idea, multiple possible paths to generate impact exist compared to the possible paths in progressive innovation in which a paradigm is already established	Enabling ideas can be pursued through many potential paths that need to be carefully considered and analyzed to select those might be more viable	• Identifying many possible paths to success • Listing potential pathways of an idea
Identify assumptions and learning metrics	Linking a set of assumptions inherent in an idea to a set of metrics that can be used to track the conversion of assumptions into knowledge	• McGrath and MacMillan (1995) • Anthony et al. (2008) • Anthony (2014) • Blank (2003)	A new paradigm is accompanied by many assumptions that need to be explicitly documented and translated into a set of metrics that can help one track progress in driving a paradigm change	The uncertainty inherent in enabling innovations can be converted into knowledge by employing a set metrics to track evolving assumptions	• Listing assumption inherent to an idea • Identifying metrics that can be used to track the success of an idea
Create learning experiments	Creating a set of experiments that can be used to learn more about an idea and convert its assumptions into knowledge	• McGrath and MacMillan (1995) • Anthony et al. (2008) • Blank (2005)	The uncertainty that stems from a new paradigm and fundamental breakthroughs should be managed through learning experiments designed to help one navigate a paradigm change	Enabling innovations have an inherent uncertainty as a result of a high-assumption to knowledge ratio and learning experiments can help transform assumptions into knowledge	• Listing possible metrics that can be used to track the success of an idea

5.11.1 Envisioning Multiple Impact Pathways

To be consistent with the philosophy of emergent strategy, the design of a discovery plan that unfolds performance and impact should account for the possibilities of failure by envisioning multiple pathways to impact, which for the enabling innovation model specifically, can consist of lily pad sequences. This behavior refers to proactively and explicitly mapping possible sequences of lily pads that can help one achieve a grander, more significant enabling innovation goal. The creation of such a vision can help decision-makers understand all possible implementation options, carefully consider such options, and invest in those paths that might be more viable or have possibilities for least resistance and the greatest potential for speedy attainment of enabling impact. An analogy to this behavior (excluding any political connotations associated with the phrase) is planning to "let a thousand flowers bloom," because, in the pursuit, of enabling innovations many paths will prove unfruitful and thus having a broad array of options for pursuit enhances the possibilities of finding a promising path forward. In other words, given the high levels of uncertainty, implementation efforts tend to be binary, meaning that, without a priori knowledge, such plans will either succeed or fail. The binary nature of ideas in the enabling window highlights the importance of envisioning multiple pathways and planning to learn (rather than to execute), because, as described by McGrath (1999, 2011), in paths wrought with uncertainty one's odds of success seem to improve with more tries.

Impact pathways that focus on lily pads can take multiple forms (e.g., different types of solutions/applications, application contexts, segments, needs/problems). Kate for example, conceptualized them as solution buckets, and Max conceptualized them as segments to pursue:

> *"I think the key thing is probably – I think there's no one solution and I think this is really like an additive kind of thing where you have to come at it from these – there needs to be the cost thing – like you kind of need to hit*

all of these solution buckets. Not any one is not actually going to be enough. That's an epiphany. That's an insight. I'm going to write that down. Key takeaways. You have to hit multiple solution buckets to affect the decision; just one generally won't be enough." (Kate)

"There can't be one particular segment so we have to understand we'd have to target multiple segments and I'm using segments and personas kind of interchangeably at the moment because we've come up as a part of the research that we've done and a part of the process of putting together personas, we've described a market share for them so we understand approximately how many of these folks are out there." (Max)

Envisioning multiple pathways is analogous to taking a portfolio view of implementation possibilities, with impact opportunities lying across a spectrum of different types of paths. Creating these perspectives calls for understanding a concept's position in the enabling innovation impact curve as well as understanding concepts at a generalized level. One could then create a map of possible paths, and assess the resistance likely to be encountered in such paths (e.g., technical, economic, sociological, psychological) in the pursuit of impact, thus effectively engaging in a prioritization exercise. Mike, for instance, stated that, in selecting an implementation plan for his set of ideas, he would rate them in terms of affordability and impact, searching for more affordable ways to achieve larger impact:

"And so I think what you would want to do is you'd want to see – if you're really shooting to get off the ground in the first six months, you'd want to basically take you're three best ideas, create like, glossy brochures about them or glossy one-pagers, and go around and try to solicit enough funds in order to launch those three initiatives, and chances are that wouldn't be too hard, but at least that would then allow you to get those kind-of underway. In such a way that you could then think about how do we fundraise for the other three initiatives, or at least one. But you'd basically want to pick the three that are sort-of – if you think about the expensiveness and the impact, or let's say this is impact, and this is expense, you'd want to take it in this corner and – or sorry, you'd want to take it, affordability let's call it. So the affordability is high and the impact is also likely to be high. You'd want to

see first of all if there are any in this quarter. And so for each of these ideas, you'd need to list them out and get more detail around each of them, and then basically rate each of them on affordability and impact, or maybe it might be feasibility and impact, of which affordability would be one of the variables under feasibility. And then yeah, I think basically within each of these, you would have a period of, say launching, what does launching mean. Six months – you would probably need to – for each of them to set up, initiate. You'd then need another let's say three months to pilot. You'd need – and let's say another three months for a larger scale pilot, and then you'd need – and then you'd scale it. So this could be in place 2015, middle – sorry, middle of 2014, so really it doesn't give you a lot of time to have impact in the market."

5.11.2 Identifying Assumptions and Learning Metrics

An emergent strategy that unfolds performance and impact should define what success looks like before starting, as well as mechanisms to convert assumptions into knowledge. Failure to explicitly record assumptions can result in assumptions becoming facts across individuals and/or organizations, which could steer ideas in the wrong direction, and/or cause a failure to learn from experimentation efforts (McGrath, 2011).

Assumptions inherent to an idea can be linked to a set of metrics, used to track the process of converting assumptions into knowledge, and reinforce a chosen path or re-direct efforts when needed. Victor, for example, stated in his EV performance task that, for his envisioned ideas/plan, he would iterate frequently between assumptions, plans, and consequences, and try to develop and track his assumptions to understand why EVs are not gaining ground:

"Well, I – the next step would be, okay, so here's what my plan would look like. Okay? So this is how I would execute it. Here's how I would do it, in more detail than I kind of laid out here. And then I would do another iteration through what are the assumptions, what are the plans, what's the consequences of that? And the – as I said earlier, the other thing that I would be doing is going back and verifying my assumptions around, okay, is this really what consumers want? Is this why they're not doing it? Because

> *the key question is if my assumption is correct that the technology is sufficient, why aren't people evolving more quickly?"*

As such, a process to create a set of assumptions and metrics could be described as follows. One can effectively break down any idea into its fundamental components, link such components to a given context, and list any assumptions associated with such components (and/or the idea as a whole) that will allow the idea to succeed or fail. Assumptions about links between components (due to systemic interactions) should also be considered, especially in the pursuit of enabling innovations which aim to drive ecosystem and paradigm change. Effectively, for each idea and a given potential pathway to impact, listing assumptions implies proactively and explicitly separating assumptions from knowledge (including but not limited to norms from rules). For each assumption, one can determine the consequence and likelihood of the assumption being incorrect – prioritizing assumptions that could potentially cause the progress of an idea to stall (see Anthony et al., 2008a for an example in business contexts). In like manner, for each assumption one can create/identify metrics that, if tracked, could help convert assumptions into knowledge.

Translating assumptions into metrics seems to call for isolating variables that help understand the relationship between assumptions and metrics, attempting to be as generative/exhaustive as possible throughout the process. These assumptions can vary according to the context/conditions of a given problem and can include technological, economic, systemic, sociological, and psychological issues. For example, in the performance task, particularly in the interview debrief stage, Rand explained the types of assumptions he would test in trying to drive EV adoption, and how such tests/metrics would change if the geographic location of his tests varied:

> *Administrator: What types of assumptions would you test?*
> *Participant: Is charger – are charging stations an issue, does adding more charging stations increase adoption in a certain area, so –*
> *Administrator: So you would add charging stations in that area?*

Participant: Charging stations, increasing the essentially effective range of charging stations in San Francisco, does that increase electric vehicle sales. Maybe try in San Francisco or in California, increase – work with the state government to increase the incentive by another $2,500, does that increase sales, things like that, based on just like the problems there. Like so we have these problems with the chargers, model types, things like that. Maybe work with one or two car companies closely to develop a – and like oversee and subsidize the development of a truck, electric truck, and then put that in market and see, as opposed to going OK, we don't really know if this is going to work or not, but all car companies have to make electric trucks because we think that's the problem. Instead, go OK, Ford, let's work with you and spend the next three months converting your F-150 to an electric model, and then let's see if we can get it on the market, and like do concentrated marketing in a small area and who we think would be most susceptible to buy, and if we can sell it to those people, then let's see if we can control this and like, sell it to more people and then potentially say, OK, everyone has to make X number of electric trucks, SUVs, whatever… That's definitely – if – yeah, that's definitely the thing that made me most I guess, knowledgeable and aware of the importance of testing assumptions and doing it in a small, limited risk way, because I mean, we wasted a [lot] of money doing things we probably – that probably weren't effective and we didn't necessarily – we wasted money even in small test markets doing different marketing efforts that – and we didn't track which ones. We – at the end of the day, you spend X thousand dollars on marketing, and you get X number more in sales, but you don't – you did five different marketing techniques. Which one actually works? So that's why, also, I recommended putting essentially money behind Tesla because it's proven to work. So if it's working and growth rates are acceptable in where you're doing, you want to like, add fuel to that in the same way as if you find out charging stations are working, add fuel to that, and then also continually reevaluate, because just because it worked in San Francisco doesn't mean it's going to work in Indiana, because there's different conditions.

Administrator: So what would you evaluate?

Participant: In Indiana, so you'd probably be able to quantify sort-of what is the ideal density of charging stations, and I feel like that would be very different in some place like the Bay Area than it would be in Indiana, things like that. You have placement of charging stations and how you market them to people, you might be able to do a smartphone app for charging stations in San Francisco Bay Area, because you have a bunch of tech people, but in Indiana, maybe you want a roadside sign. So you'd be constantly evaluating these small little tweaks to try to get to the optimal solution, but at the same time, you don't want to get caught up too much in trying to be optimal and not actually making any progress forward, so that's

> *kind-of a fine line there, and once again, it depends on how many – how much resource you can burn. (Rand)*

5.11.3 Creating Learning Experiments

Possible impact pathways, assumptions, and learning metrics can be synthesized in learning experiments that can methodically transform assumptions into knowledge and address the inherent uncertainty associated with the pursuit of an enabling concept. The goal is to create systematic mechanisms to drive towards what Sitkin (1992) calls "intelligent failure," i.e., failure that: 1) results from thoughtfully/carefully planned actions; 2) have uncertain outcomes; 3) are of modest scale; 4) are executed and responded to with alacrity; and 5) take place in domains familiar enough to permit effective learning (Cannon and Edmonson, 2005). This intelligent or "smart" failure can then highlight when efforts should continue in a given direction or be re-directed (Anthony et al., 2008). For the enabling window, these experiments should create failure that reveals when an application space is (or is not) suited/adequate for the current state of a solution or when a different space should be pursued, which performance capabilities/dimensions should be developed (and where), and what impact the enabling concept can generate.

Tests and learning experiments can be of different types: targeted or comprehensive (Anthony et al., 2008; Anthony, 2014). Isolated learning experiments aim to test one assumption at a time. Comprehensive experiments aim to understand behavior at a systemic level. Both types of experiments are valuable each of these types is appropriate for a given underlying assumption and success metric. However, it is herein argued that the systemic and paradigm changing nature of enabling innovations make both types of experiments a requirement to capture metric-specific behavior, but also to unearth any systemic "emergent behavior" that cannot be observed at a granular level.

In his performance task, when discussing implementation options, Drew engaged in a similar process and outlined hypotheses and possible ways to test his hypotheses, focusing on comprehensive learning experiments (although he acknowledged that component assumptions can be as critical as ecosystem assumptions and often times faster test). From his particular point of view, the EV challenge is an ecosystem type of challenge and thus the learning experiments should reveal information about how an ecosystem works:

> *"Okay. So there are certain assumptions and hypotheses that – the first hypothesis (inaudible) the – let's say performance, performance of electric car, whatever type it is, doesn't matter, equals the traditional car… The second hypothesis will be that the battery price comes down dramatically, and that this is driven by scale. But you need huge scale to drive down the battery, and that there is new technology… So I will not have enough data in 90 minutes to come up with a rock solid recommendation, so what I will do is that I would recommend more a test or a pilot that would allow me to say falsify or verify the hypothesis, which I believe will be critical in order to determine then how long or where I would go… So there's two elements here. The one is the theoretical answer, what is really the thing to do, and the other one is really a practical recommendation in terms of how I would test that in order to get to – the huge cost associated (inaudible) to minimize the risk. I'm basically speaking aloud. So I think the test would be pretty simple. I would probably take in the US a state, and I would – or a city, and I would say, for example, I subsidize cars, and I would charge more for fuel, and I would see how things would evolve. I think to de-risk it, you need that all – all the stakeholders have to play together in an ecosystem, so that the entire ecosystem looks equal, works together. I don't think that it makes sense to insulate different elements. That's the way I would do it. I would say, fine, let's start with a certain city. Let's start with a state. Let's start with something, and just simulate the reality as it could look like, and just eliminate all the risk factors. So customer (inaudible)? Yes. Car manufacturers will then produce? Yes. Battery manufacturers will the produce? Yes. Are they long term – is there long term interest? Yes. And then really simulate the reality as it would look like with all the stakeholders involved. That's the way I would do it. Of course, you can insulate or isolate some of the elements, but I don't think that's the real – the – you don't crack the case like that. I think you really have to make play everybody together. And you can subsidize – some elements you can subsidize, and you can help. But some, you have to let them play as they would play in reality. And then you will see if the behavior pattern is really – really great or not. (Drew)… (When asked why integrated and not isolated…) I think because – I think*

> *the key element in – that's the way I see it here, is that we have to get the ecosystem right. We have to build a new ecosystem. And I'm testing the ecosystem. I'm not testing one element or one stakeholder… They should have – if you take the system, for example, in Sweden, where they have Stockholm and people are not allowed to drive in the town anymore, you put taxes on it, etcetera, I think that's quite interesting. And then you have one city, and you check it, and then you will learn with it. And you will only learn like (inaudible), but it has to be the entire system. And these tests, for example, are pretty successful. Will they be rolled out worldwide? We'll see. But – because what they learned is that there are some behavior patterns they did not expect* "

Even in tests that seemingly need to be comprehensive (e.g., testing for a paradigm change/shift), testing a new part/portion of a concept can provide insights whether a concept will work or will be accepted (or in the case of a negative testing outcome, the entire concept could be compromised). For example, in the history of GPS, "the air force ran tests of the concept. Their 'satellites' were actually balloons that beamed precise time signals to receivers on the ground below. Despite the primitive instrumentation, the researchers were able to calculate the locations to an accuracy of fifty feet. As with the navy's TIMATION tests, the air force experiments left no doubt that the basic idea was sound" (Bray, 2014, p. 98).

Therefore, the process of creating a learning experiment depends on the set of assumptions and learning metrics to be tested and could be described as follows. For each assumption and metric, one could create a hypothesis and understand the key variables associated with such a hypothesis, when possible, isolating dependent from independent variables (Sitkin, 1992; Gilbert and Eyring, 2010; Thomke and Manzi, 2014). These hypotheses can be used as a basis to design experiments, simple tests that can confirm or reject a hypothesis. Each learning experiment should thus outline an assumption (or assumptions), a learning/success metric, a hypothesis, resources needed for each experiment, and parameters to determine whether the outcome of a given test is positive, inconclusive, or negative, a given testing priority based on the consequences of the outcome of the test/experiment, and consequences for each outcome. Learning goals (i.e., assumptions) are prioritized by confidence (or uncertainty), consequence (of a potential failure), and ease of testing (making high-impact, high-uncertainty tests a priority). The goal is to design experiments that are as rapid/fast with a minimal amount of resources, consistent with the philosophy of "investing a little to learn a lot" (Anthony et al., 2008).

5.12 Deploying the Emergent Strategy to Discover the Enabling Path

Even though actual implementation efforts could not be observed in the performance task, the scholarship of integration and qualitative meta/thematic-analysis of historical cases highlight behaviors that are valuable to consider in implementation efforts. Because of this lack of performance task evidence, these behaviors will herein only be briefly defined (as opposed to being described in specific sections as in prior patterns in the framework).

In actual implementation (and not implementation design) efforts, beginner designers tend to run few to no experiments in designs and prototypes when attempting to manage uncertainty, often testing multiple variables in a single experiment, running confounded experiments, and engaging in unfocused troubleshooting (Crismond and Adams, 2012). Informed designers, in contrast, run tests to learn about variables quickly and aim to understand how things work and why (Crismond and Adams, 2012), using both quantitative and qualitative methods to generate insights (Norman, 1996).

Navigating the enabling window through emergent strategies, however, requires a special type of emergent strategy implementation that considers participation in multiple ecosystems, addressing each ecosystem holistically, and persistence through emerging barriers/challenges that were not anticipated and stem from a paradigm change. In the pursuit of enabling innovations, implementation efforts should strive to employ the aforementioned emergent strategy to discover the path through the enabling window. In enabling thinking, implementation efforts are herein characterized from the perspective of behaviors including: *experimenting for smart failure*, *leveraging unexpected* *opportunities*, *reinforcing commitment*, and *adapting based on learning*. These behaviors, shown in Figure 5.20 and summarized in Table 5.10 are defined in the following paragraphs.

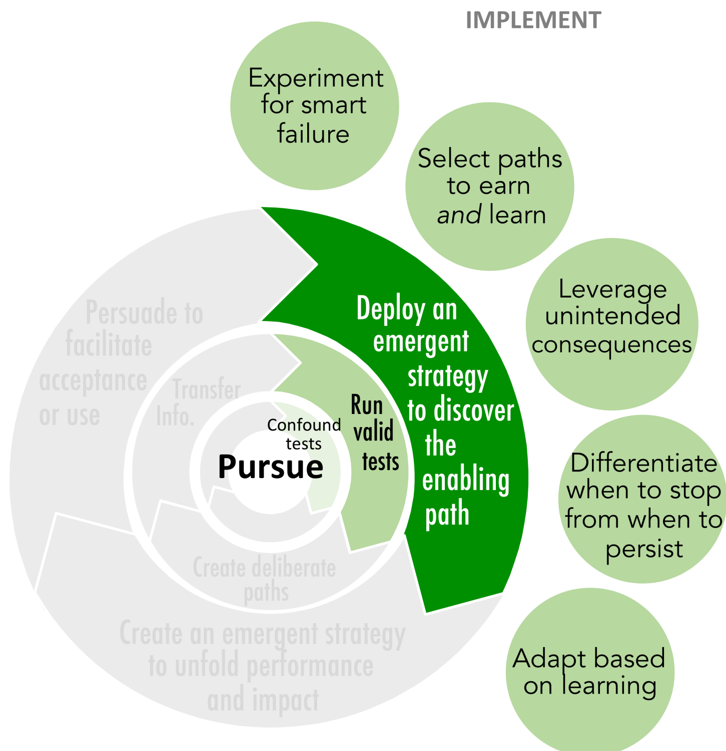


Figure 5.20 Deploy an Emergent Strategy to Discover the Enabling Path

Table 5.10 Behaviors to Deploy an Emergent Strategy and Discover the Enabling Path

Behavior	**Definition**	**Related literature**	**Unique link to Enabling Innovation**	**Link to deploying an emergent strategy**	**Illustrative actions of the behavior**
Select impact paths based on impact potential	Choosing between paths to pursue based on learning potential *and* potential to achieve/earn impact	Sinfield (2008)	The pursuit of enabling innovation, if employing a "lily pads" approach, should be based on application efforts to earn *and* learn (as opposed to just "investing to test and learn" in a moonshot approach)	Path definition efforts and emergent strategies likely offer multiple alternatives and actual implementation efforts will require choosing among paths to pursue	• Selecting among implementation alternatives • Choosing paths are likely to lead to both impact *and* learning
Experiment for smart failure	Pursuing first-hand iterative learning via active experimentation	Blank (2005) McGrath & MacMillan (1995) Anthony et al. (2008)	Historical enabling innovations have inherently encountered failures along the way that were eventually overcome and proactive design of enabling innovation should aim to proactively accommodate such failures in small low-risk ways that minimize consequences	High levels of uncertainty need to be managed instead of predicted and smart failure can help quickly unearth implementation efforts that should be continued or re-directed	• Running experiments to uncover the path to success • Managing the uncertainty of an idea through planned experimentation
Leverage unintended consequences	Capitalizing on unexpected occurrences that highlight new paths, goals, or ideas	Sarasvathy (2001) Wiltbank et al. (2006)	Many historical innovation cases took advantage of unexpected deviations along their development paths which represents an opportunity to proactively document and capture opportunities that develop along the enabling window	Enabling concepts, due to being often full of uncertainty and poorly understood while in the enabling window, will inherently generate unanticipated findings in experimentation efforts that could be leveraged.	• Identifying unexpected opportunities or barriers in the pursuit of an idea • Analyzing the consequences of such unanticipated opportunities or barriers

Table 5.10 Continued

Behavior	**Definition**	**Related literature**	**Unique link to Enabling Innovation**	**Link to deploying an emergent strategy**	**Illustrative actions of the behavior**
Differentiate when to stop from when to persist through failure	Assessing whether efforts for a given concept should continue or halt	Shepherd et al. (2011) Edmondson (2011)	Many historical enabling innovation cases encountered multiple failures along the way, and eventually found success due to the commitment to an overarching goal	Not all enabling innovation initiatives will succeed and implementation efforts should have clear guidelines on when to stop and when to proceed	• Assessing on-going innovation efforts • Evaluating upside versus downside potential of continued pursuits • Differentiating between temporary roadblocks and "deal killers"
Adapt based on learning	Re-directing efforts from insights gained through emergent strategies	Anthony et al. (2008)	At a fundamental level, enabling innovations constitute a learning exercise in which assumptions about a promising concept are gradually transformed into knowledge, and such knowledge represents an opportunity to adapt implementation efforts in the enabling window	After each experiment for smart failure, efforts should be adapted to the new knowledge and insights gained in an attempt to discover paths to success	• Deciding to continue on an existing path • Deciding to re-direct an existing path • Deciding to terminate an existing path • Deciding to explore other alternative paths • Circle back to the roadmap and see if there is enabling opportunity remains

Selecting paths to earn and learn is herein defined as prioritizing and choosing implementation alternatives that can generate impact (some form of earning potential) *and* learning potential. This path selection approach is in contrast to moonshot-based approaches, which typically "invest" efforts in the pursuit of learning and testing. As described in Chapter 4, however, the enabling lily pads approach offers an alternative. Although there may be some instances/efforts that will require paths/pursuits with only a learning component, the lily pad approach outlined prioritizes implementation paths that have the potential to both "earn" impact through application (e.g., gather resources, interest, paradigm transition) and learn what will and will not work to re-orient efforts.

Experimenting for smart failure is herein defined as pursuing first-hand iterative learning via active experimentation. In experimenting for smart failure, efforts are re-prioritized and re-directed after each learning insight to manage (rather than predict) uncertainty. Learning insights come from testing, troubleshooting, and experimentation that is designed to understand key failure mechanisms and learning gaps for a given idea/design through low-risk, low-intensity tests that minimize the impact of failure (Anthony et al., 2008a). These experiments are often run in series, even though sometimes more comprehensive tests are required, to establish cause-effect logic chains that link learning about potential sources of failure to key design variables. Max, for instance, acknowledged the pursuit of intelligent failure in his performance task debrief:

> *"One of the concepts that we refer to frequently is the concept of intelligent, intelligent failure. I don't know if you're familiar with that but a company like this can't be afraid to fail and a way to manage that failure in an effective way is to take things in smaller chunks, right? If you're fail, fail on a small piece so this relates to what I was saying. Let's go with a minimum viable product. Let's not try to package too much and have enormous failure potentially. Let's try to package up something that's reasonable and viable that we can learn from and improve on, right? I think that's a very important way to drive product development in the product evolution… I would call intelligent failure, I'd say it's more like managed failure. It's going in with the understanding that you can't get things perfectly right and to try for perfect is actually a mistake. You learn a lot more from as I think I*

> *said earlier failing in small increments and taking that learning to the next step of the product development process. I think it matches up nicely with agile development, particularly as it goes back to what I said around keeping customers engaged throughout the product development lifecycle. To me it's using agile to intelligently fail and then make coarse corrections along the way so that when you have a product that's ready for market, you've discovered the challenges already that you would've faced or many of them and you corrected for them, right?"*

Experiments for smart failure need to *leverage unintended consequences*, i.e., using contingent/unexpected events/results to the benefit of an idea, especially in ideas with enabling potential. Due to uncertainty in the link between performance capabilities and application spaces, and the emergent behavior of complex ecosystems, the implementation of enabling concepts, particularly those in the enabling window can quickly result in unanticipated opportunities (or challenges). Although implementation approaches that emphasize prediction seek to avoid contingencies, implementation philosophies that embrace learning from failure should seek to capitalize on these occurrences and therefore intentionally leave room for these surprises (Sarasvathy, 2001a; Wiltbank et al., 2006).

As outlined in the discussion of the creation of an emergent strategy, many efforts will be binary (they yield success of failure), thus making the behavior of *differentiating when to stop from when to persist through failure* important. Shepherd et al. (2011) provide a concise summary of obstacles to learning from failure that are relevant to consider in the case of enabling innovations: "Obstacles at the individual level include a history of success (Ellis & Davidi, 2005), low learning- goal orientation (Dweck & Leggett, 1988), and cognitive biases (Kahnemann, Slovic & Tversky, 1982), and obstacles at the organizational level include a non-supportive work environment (Edmondson, 1996), reward systems that punish failure (Sitkin, 1992), and an organizational culture that stigmatizes failure (Cannon & Edmondson, 2001). These obstacles are so pervasive that most organizations still have difficulty learning from their failures (Cannon & Edmondson, 2001)" (Shepherd et al., 2011 p. 1230). Yet in the case of enabling innovations, broader obstacles may exist, including ecosystem and paradigm change obstacles that may indeed cause an innovation to fail. Differentiating between stalling efforts and persisting through these obstacles is stakeholder dependent (i.e., will vary for each individual, group, or societal segment involved), but regardless, clear guidelines to compare upside potential to possible downsides that may result from continued pursuit should be developed.

In the history of the laser, for instance, Townes (1999) recalls multiple instances in which his overarching goal of working at smaller wavelengths failing and being challenged at the organizational level; however, Townes' understanding of his maser resonant cavity concept and its theoretical feasibility helped him decide between stopping and persisting in his efforts. A select number of examples are provided below:

> *"He listened to me outline my hopes for expanding astronomy into radio frequencies, looked at me and said: 'Well I'm very sorry to tell you, but I don't think radio waves are ever going to tell us anything about astronomy. I just do not think there is anything to do. The waves are too long… they are not directional, they can't really tell us anything." (Townes, 1999, p. 42)*

> *"We hardly rode a wave of encouragement. When we showed the [maser] experiment to lab visitors, they would say 'Oh, yes, interesting idea' and leave.*
> *One day after we had been at it for about two years, Rabi and Kusch, the former and current chairman of the department–both of them Nobel Laureates for work with atomic and molecular beams, and both with a lot of weight behind their opinions–came into my office and sat down. They were worried. Their research depended on support from the same source as did mind. 'Look,' they said, 'you should stop the work you are doing. It isn't going to work. You know it isn't going to work. We know it's not going to work. You're wasting money. Just stop!" (Townes, 1999, p. 64)*

In the performance task, Max, for example, in his interview debrief reflected on the above list of reasons why failure is often not embraced, but important to innovation efforts:

> *"That's a culture [issue]. I think it's an organizational culture issue and I would say, you know, well, I guess I could separate from the (anonymized firm) kind of internal reflective and then the company perspective, I would say at (anonymized firm), just by nature of what we do and our focus on customers there's a culture around understanding that we can fail and we can learn from that. I think that the challenge I've faced more often than not is actually with the company we're working for and helping develop a product. I don't find that there is as much of a tolerance for failure along the way and that's for obvious reasons, right? They're paying us a lot of money to get these things out the door but I think it's also a function or it's also people come to us with a vision and they feel very strongly about it, right? It takes a lot to convince someone that their vision is not absolutely correct or doesn't need to be modified in some way so, in effect, they're less comfortable with failure but they're more in need of that intelligent type of failure, right? So I think That we've been effective at helping them recognize that their visions need to be augmented, changed, whatever, by a failing, right, and by managing that failure process effectively, in my experience, the most effective way to do that is to bring customers in, as I said, earlier in the process. We can help them get the product to a better place, right, because we have failed along the way and they didn't recognize that but I think in consulting firms it's part of the culture. In most cases at the other – at the firms that we worked for it's a process to help them understand the value of failure to the product, the end result, the ability to achieve on the market."*

Adapting based on learning is herein defined as re-directing efforts based on the insights gained through emergent strategies to discover the path to success. The results of experimentation efforts can highlight whether efforts should continue in a given direction, be re-directed, halted, or if another direction could be more promising (Anthony et al., 2008). Periodic checkpoints, and evaluation of the upside potential compared to the cost of continuing and compared to other initiatives in a portfolio can help make this determination (McGrath, 2011). Many paths to a novel/different solution exist, which should be allowed to unfold with exploratory activities.

5.13 The Envisioning Stage: Crafting a Strategy to Enable

Reflecting on this comprehensive end-to-end framework, it is evident that being proactive about the different types of issues in the enabling window can likely positively influence the success of innovation efforts. Thus, prior to any design efforts, an envisioning phase can help ensure that one defines a strategy which provides guidance in the many choices to be made while being flexible enough to account for emerging insights.

Although not typically acknowledged in design process models, envisioning an approach to a challenge is at the front end of any design process. Often times, strategies are made implicitly as stakeholders proceed with their status quo approach. However, there remains an opportunity to engage in a proactive process of creating guiding ideas that delineate an initial path forward. These guiding ideas thus are herein envisioned as a strategy, i.e., patterns in a stream of decisions to achieve a given goal (Mintzberg and Waters, 1985).

This unique pre problem definition design stage can create a vision to help drive enabling innovations by design, creating explicit guidelines for the pursuit of innovation while simultaneously embedding flexibility to embrace emergent behavior. Such a vision goes beyond the creation of a design brief. Crafting strategy implies conscious planning of intended decisions and actions to achieve innovation, while leaving room for unanticipated issues to be integrated into a plan that includes intent for impact. This process of crafting strategy is perhaps best synthesized by Mintzberg (1987, p. 73) who stated that: “to manage strategy is to craft thought and action, control and learning, stability and change.”

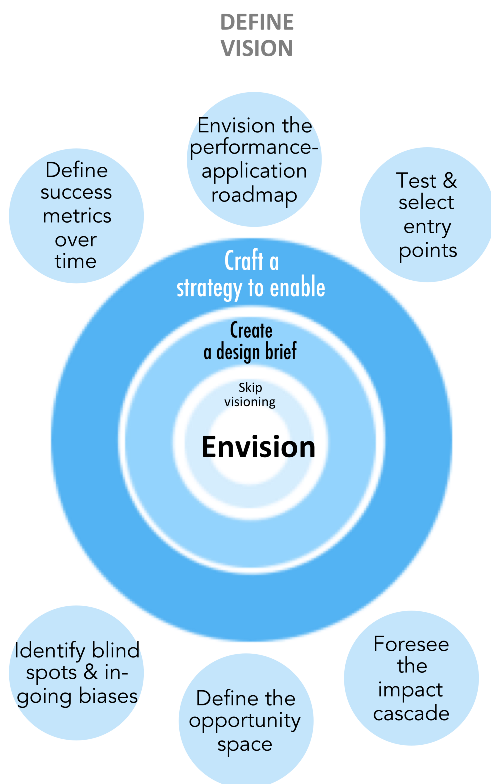


Figure 5.21 Craft a Strategy to Enable

To make the enabling thinking framework truly end-to-end, a set of behaviors are herein hypothesized as key to crafting a strategy for the enabling window: *defining an opportunity space*, *identifying blind spots and in-going biases*, *foreseeing the impact portfolio*, *envisioning a performance-application roadmap*, *defining success metrics*, and *testing and selecting entry points* to the "shaping" process. Such behaviors are herein hypothesized, because although certain instances of these behaviors were indeed observed in the methodological approaches (scholarship of integration and historical case analysis), this design stage (and the implementation stage) are less likely to be observed in the current set up of the performance task. However, the scholarship of integration and historical case research provide a basis from which to generate hypothesized perspectives of these behaviors. Each of these behaviors, shown in Figure 5.21, is summarized in Table 5.11 and briefly defined in the following paragraphs.

Table 5.11 Behaviors to Craft a Strategy to Enable

Behavior	**Definition**	**Related literature**	**Unique link to enabling innovation**	**Link to crafting a strategy for the enabling innovation**	**Illustrative actions of the behavior**
Define the opportunity space	Detecting and delineating a pattern of changing trends that suggest the potential for achieving enabling impact	• Baron (2006) • Sarasvathy (2001)	Many historical enabling innovations histories began with a broad yet well defined ambitious goal	Defining opportunity spaces provides an area of focus that informs decisions in the pursuit of performance development and impact	• Stating overarching goals or visions • Articulating innovation opportunities
Foresee the impact cascade	Foreseeing the extent of the dimensions of impact (reach, significance, paradigm change) affected by an innovation	• Solis and Sinfield (2014) • Godin and Dore (2004)	Enabling innovations are characterized by their significant impact, broad reach and paradigm change; envisioning this impact up front helps frame and guide the pursuit of enabling concepts	An envisioned and iteratively revised impact cascade can inform decisions and aid in the evaluation of the enabling concept's potential	• Listing impact areas potentially addressed by an innovation • Estimating the potential reach of an innovation • Articulating possible paradigm change(s) due to an innovation
Envision a performance-application roadmap	Recognizing application spaces that could open up as the performance of a concept improves	• Sinfield (2008)	As the performance of an idea evolves, certain application spaces will potentially open up and charting possible performance-application trajectories up front can help uncover possible paths of least resistance toward enabling impact	Roadmaps that chart lily pads toward an enabling innovation can help simultaneously unfold performance, impact, and worldviews until capabilities for application across contexts are achieved	• Creating initial forecasts of performance development and broad impact spaces • Identifying the relationship between performance development and the aperture of new possible impact spaces

Table 5.11 Continued

Behavior	Definition	Related literature	Unique link to enabling innovation	Link to crafting a strategy for the enabling innovation	Illustrative actions of the behavior
Define success metrics over time	Identifying metrics by which the success of an idea can be evaluated at various stages because success changes as the innovation evolves	• Anthony et al. (2008) • Body and Kane (2013) • OECD (2010) • Godin and Dore (2004)	Different metrics can be defined at various points in the breakthrough stage, enabling window, and progressive cascade	Metrics provide means to evaluate the success of an idea with enabling potential	• Listing success metrics for each stage, context, desired performance, and desired impact • Identifying data sources and evaluation procedures to carry out measurements
Identify blind spots and in-going biases	Becoming aware of biases in judgment and theme areas that are too uncertain to be fully characterized/understood but might affect an opportunity space	• Anthony et al. (2008) • Kahenman et al. (1982) • Kahneman (2013)	Enabling ideas inherently involve knowledge gaps that are likely being missed due to biases in judgment, lack of experience, or the sheer novelty of an idea	The knowledge gaps and uncertainty in enabling innovations likely cause any developed strategy to have a set of blind spots and in-going biases that should be (at a minimum) acknowledged	• Creating a list of assumptions and unknown factors • Creating lists of personal biases • Structuring assumptions and defining possible blind spots and gaps
Test and select entry points	Determining possible starting points in problem and solution development	• Dorst and Cross (2001) • Anthony et al. (2008) • Adner (2012) • Norman and Verganti (2014)	Enabling innovations encompass a broad set of issues (e.g., paradigm, ecosystem) with multiple entry point possibilities that can influence the potential for success	Multiple entry points to shaping the design of an enabling concept exist (e.g., problem space, solution space, ecosystem, analogies), which call for an exploration of the benefits and drawbacks of such entry points, to illuminate the most viable paths forward	• Listing possible entry points (e.g., ecosystem, problem, solution, stakeholders) • Assessing paths of least resistance to impact and momentum for each entry point • Take long, medium, and short term perspectives

Often times, opportunities for enabling innovation are not immediately apparent or perceived as such, but emerge from *defining an opportunity space* in explicit ways, with no artificial ties to a context, and leaving room for emergent behavior. The history of the laser and GPS exemplify how these opportunity spaces can be delineated. The laser, for instance, had its origins in studying the ways by which microwave spectroscopy could lead to useful technologies, as outlined by Charles Townes: "I had myself been stubbornly pursuing shorter and shorter wavelengths. Because they interacted more strongly with atoms and molecules, I was confident they would lead us to even more rewarding spectroscopy" (Townes, 1999, p. 54). In the case of GPS, the opportunity space came from creating methods to track a satellite's orbit from data after being able to track Sputnik's orbit: "…from that time forward, we focused increasingly on quantifying the Doppler data and inferring the satellite's orbit from the data." (Guier and Weiffenbach, 1998, p. 15). Although these innovations and their impact are unlikely to be fully envisioned at the breakthrough stage, in innovation challenges, there remains an opportunity to be proactive in trying to envision and articulate promising opportunity spaces to be explored (and mapping such spaces onto the enabling innovation trajectory model of breakthrough, enabling window, or progressive cascade). Frameworks such as "goals and bounds" (Anthony et al., 2008; Sinfield and Anthony, 2006), adapted to the unique characteristics of the enabling innovation model (e.g., impact cascade, ecosystem interactions, paradigm change, problem-solution variations) can likely be helpful in delineating promising opportunity spaces.

The envisioning stage of the enabling thinking framework also implies creating a definition of success particularly by *creating success metrics*. These metrics provide guidelines to evaluate the success and progress/traction of a concept. While new metrics should be allowed to emerge as an opportunity space is further defined, an initial conception of such metrics can help assess ideas/concepts. This list of metrics can adapt and incorporate impact elements/areas (e.g., Solis and Sinfield, 2014), innovation metrics (e.g., Anthony et al., 2008), financial metrics (e.g., Body and Kane, 2013), societal metrics (e.g., OECD, 2010), and/or science and technology metrics (e.g., Godin and Dore, 2004). In the performance task, several participants defined the metric by which "a significant increase in the adoption of electric vehicles" could be evaluated. While these metrics varied widely (for example, Max defined his target EV increase as 1 million, Mike as 230,000 vehicles, Sam defined success as perceiving a change in culture, and some participants did not explicitly define a goal), they (implicitly and in some cases explicitly) provided guidelines for the actions and design approach that followed.

Given the link between performance improvements and possibilities for application spaces, crafting a strategy for the enabling window also requires *envisioning a performance-application roadmap*, i.e., recognizing that application/impact spaces could open up as the performance of a concept improves. This roadmap can outline initial choices to advance select performance capabilities while achieving impact and gaining resources to fuel a solution. Even though subsequent design process stages and the emergent behavior resulting from such stages will "shape" enabling concepts, this initial vision of possible development trajectories can strategically guide the pursuit of enabling innovations, and can prove particularly helpful in identifying contexts for early trial.

To embed learning and change into a strategy for the enabling window, there is a need to explicitly *identify blind spots and in-going biases* of the strategy-making process. This behavior is herein defined as becoming explicitly aware of possible themes of hidden assumptions and judgment biases while developing a nascent enabling concept. Enabling concepts inherently involve relatively large gaps in knowledge, and a likely large number of hidden assumptions, which call for being expansive in creating a strategy for such concepts, by creating explicit inventories of possible blind spots and biases. Many types of assumptions and biases (e.g., see Anthony et al., 2008; Ariely, 2000, 2008; or Kahneman, 2013) exist and some will be more relevant than others in a given context (e.g., an industry-related challenge, a non-profit domain challenge, or a government challenge).

Foreseeing the impact cascade of an innovation implies envisioning the possible dimensions of impact (reach, significance, paradigm change) of an enabling concept at an early stage because designing for this end result likely will influence one's approach. The ability (or inability) to create such a vision, particularly at early stages of an innovation's development, can hint at guidelines for its subsequent pursuit. Effectively, if one is able to list multiple impact spaces where an idea can potentially play role, can estimate broad reach among individuals, groups, and society in comprehensive impact areas, and can articulate possible paradigm changes that result from an innovation, then its path forward will likely differ than if its potential for reach is relatively narrow, with select significance, and relying on an established paradigm. While not all historical enabling innovations have envisioned their outcomes up front, being proactive about creating this vision has influenced the shaping of select historical enabling innovations. As examples, the Air Force's initial conception of GPS was envisioned for both civilian and military applications (in contrast with the Navy's, which was originally envisioned only for military applications) (Bray, 2014). Similarly, even early conceptions of the laser (more specifically, the maser) and applications of microwave spectroscopy were tied to impact spaces, such as time tracking, communications, and science (Townes, 1999). Further, in the performance task, several participants attempted to envision the impact (or the desired impact) of their ideas up front. Sam, for instance, identified impact areas to be addressed and argued for the need of creating cultural change, in addition, to technical and economic change:

> *"So I guess one of the things I would do is – and if you think about the technical pieces – but there are cultural pieces, too. And so it's going to take people who are – who come from different backgrounds. And I would look for experts around this – these different pieces of technical, cultural, social structure, implementation. And clearly, apparently, according to this model, we've got a variety of academics and industry executives who are interested in this. So using those people to identify individuals who can then either do research, have research done, or present research they've already done around these cultural and technical kinds of pieces. There's another side of this, too, and that's the economics. Clearly, we've supported the internal*

> *combustion engine with lots of price supports. I mean, building the road system, building the infrastructure. I mean, look at saving the auto industry in the recent downturn as another example. You've got to do those things. So there's an economic piece of this, too, that's I think important, and you would need experts there as well, that look at what are the economic incentives."*

With these components in mind, one can *test and select entry points* to the design process, which refers to determining possible starting points in problem and solution development. Multiple entry points to "shaping" a design exist, for instance, examining the problem space, the solution space, co-evolving problem and solution, creating solution conjectures, analyzing ecosystems, or searching for analogies. As a consequence, a preliminary exploration of possible entry points can generate valuable insights that highlight an enabling path forward. In the performance task, participants didn't acknowledge this entry-point behavior explicitly, but analysis of the collection of performance tasks revealed a broad array of approaches. For example, Drew began by examining the ecosystem, Ken began by examining vehicles, and Mike by studying barriers to adoption. Testing and selecting entry points, however, refers to the notion of iteratively deciding between entry points. Don for example, started by examining barriers to adoption, and then moved to examining performance dimensions in solutions. None of these approaches are right or wrong, but an exploration of different entry points into the design process can generate insights on possible starting points that might be more promising.

5.14 Cross Behavior Synthesis

As a transition to the chapter summary (see Figure 5.22), the aforementioned behaviors and key discussion points are synthesized in the table in Appendix G. Such a table collects all behaviors in the framework, their definitions and unique links to enabling innovation, as well as select insights from the analysis of each individual behavior. Such insights are herein positioned as *hypotheses* that need to be further validated in future studies.

However, such insights likely provide a useful starting point for the use of the enabling thinking framework in practical setting as well as for future research regarding the patterns and behaviors outlined herein.

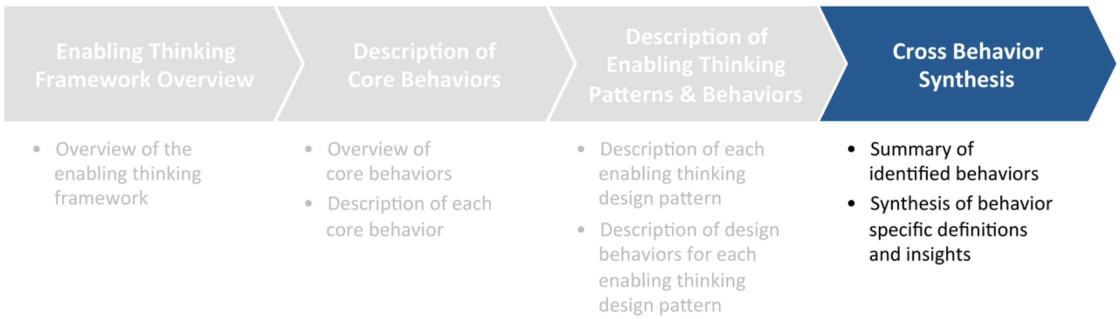


Figure 5.22 Chapter Roadmap: Cross Behavior Synthesis

5.15 Chapter Summary

Overall, the enabling thinking framework described in this chapter provides an organized perspective on an end-to-end design process that is tied to the characteristics of the enabling innovation model. The chapter began with a description of the organization of the framework and a description of its differentiating features in terms of its organization, uniqueness of patterns and behaviors, and uniqueness in terms of ties to an innovation archetype as an end goal. This design process is comprised of patterns for each stage, sets of stage-specific behaviors, and a set of core behaviors, all linked to the end goal of achieving enabling innovation. This unique goal-orientation accounts for the characteristics of enabling innovations; effectively, a set of envisioned outcomes (impact ripples), changes in paradigm, multiple problem variants/spaces (need/job categories), multiple ecosystems, many architectural forms (solution variants), and headroom for improvement.

Each pattern and behavior was then described triangulating evidence from all three approaches employed in this study: scholarship of integration, thematic analysis of historical research, and verbal protocol analysis of a performance task. To develop this framework, a subset of patterns and behaviors, such as questioning paradigms, idea network, linking diverse problem and solution spaces through associative thinking, or evaluating tradeoffs were re-framed (relative to views in existing literature) to better address the characteristics of the enabling innovation model. Other patterns and behaviors, for example, spotting opportunities in flawed paradigms, noticing, diverging-structuring-converging, empathizing and mental modeling, or characterizing impact contexts, however, are unique and newly introduced to the literature and body of knowledge through the framework described herein. The framework has implications for the study and pursuit of innovation. The following chapter provides a synthesis of findings and the implications of both the enabling innovation model and the enabling thinking framework for research, teaching and learning, and practice.

CHAPTER 6. SYNTHESIS OF FINDINGS AND IMPLICATIONS

6.1 Synthesis of Findings

The research described in this dissertation has three main findings that concisely summarize its contributions to the body of knowledge:

1) Based on their impact and departing from classifications that focus on novelty, this work creates a unique classification of innovations that differentiates between *enabling* and *progressive* innovations; breakthroughs, as defined in this work, are not innovations, but represent the type of knowledge advances that can become the foundation of an enabling concept.
2) Three distinct stages have been defined herein to characterize the development trajectory of enabling innovations: the *stage of breakthroughs*, the *enabling window*, and the *progressive cascade*; of these stages, the enabling window has (to the best of the author's knowledge) not been researched even though as described in this work it is likely critically important given that in this stage key early decisions shape the pursuit of enabling innovations and influence their reach, significance, and paradigm change.
3) The pursuit of enabling innovations requires a set of distinct patterns of thought and action, called *enabling thinking*, compared to those typically employed to pursue progressive innovation; language for these patterns is created in this study and such patterns are organized in a unique end-to-end framework that has enabling innovation as an explicit end goal.

This chapter examines the derivative insights and implications of these contributions. For each of these three main contributions, a synthesis of insights is provided in the following sections. Following, implications for the research, teaching and learning, and practice domains are discussed. The chapter concludes with a discussion of the limitations of the study, related opportunities for future work, and a brief summary of the study.

6.1.1 *Synthesis of Insights Related to the Enabling-Progressive Classification*

First, creating a classification of innovations as enabling and progressive resulted in new language, and a set of insights (described in detail throughout Chapters 2 and 3 of this dissertation), that can be useful in characterizing innovations:

- The enabling innovation model classifies innovations based on their impact over time, which, to the author's best knowledge, represents a unique characterization of innovations. This framing departs from prior innovation schools of thought, which tend to classify innovations based on their novelty and/or differentiation relative to predecessors.
- Classifying innovations by their impact requires a concise impact definition, and this research creates language to characterize impact, starting with its definition – the degree to which an innovation alters the way societal stakeholders live and act.
- Impact can be further decomposed into three key dimensions: *reach*, *significance*, and *paradigm change.* Reach refers to the number of individuals, groups, and societal segments affected by an innovation. Significance refers to the magnitude of change caused by the innovation across measures of quality of life, including health, economics, environment, and culture. (A matrix of reach and impact was created to describe impact areas for each level of reach and each measure of significance.) Moreover, paradigm change conveys the degree to which an innovation alters the worldview of implicit or explicit norms that guide current thought and action in a particular domain

- Enabling innovations exploit a new or different paradigm and have broad reach and comprehensive significance that often cascades into multiple societal benefits in economics, environment, health, culture. Enabling innovations go beyond science, technology, or engineering, because new conceptual ways of thinking about challenges can be just as powerful as new technology-based solutions
- Progressive innovations also facilitate impact, but typically in select aspects of in economics, environment, health, or culture and in more focused ways, i.e., with relatively lower reach, limited cascading effect, and based on a working paradigm.
- Both types of innovation are necessary and complementary. It is anticipated that components of progressive innovations can likely/typically be traced back to one or more enabling innovations
- Identification and proactive shaping of enabling innovations can be achieved by examining concepts across a set of key categories: a) envisioned impact cascade, b) worldview change, c) affected ecosystems, d) problem categories, e) solution architectures, and f) headroom. For each category, a set of key questions was created to guide this identification process.

6.1.2 *Synthesis of Insights Related to the Enabling Innovation Model Trajectory*

Second, the impact trajectory of an enabling innovation over time goes through different stages – the stage of breakthroughs, the enabling, window, and the progressive cascade – according to an innovation's position in the impact curve (as shown in Figure 3.6). This enabling innovation model suggests that a handful of concepts underpin a tremendous amount of impact and potential for societal advance. In addition, this model of innovation suggests that the *choices* for decision makers and stakeholders at each stage of the model are different and can influence the shaping process of enabling innovations. This model trajectory served as a foundation to generate the following language and set of insights:

- The stage of breakthroughs consists of the pursuit of discoveries and inventions, often guided by an overarching goal (although not necessarily), that represent fundamental knowledge advances and potential for a new paradigm, but little to no impact. Because of this lack of impact, breakthroughs, as defined in this model, are not innovations but represent fundamental discoveries or inventions that significantly depart from current practice and create an opportunity for a new paradigm. The outcome of the breakthrough stage is knowledge, and this knowledge rarely comes in a single event; instead, breakthroughs often come in sequences of knowledge-generating episodes. In this stage, the goal is to "break through" critical barriers to fundamental discovery or invention that has underlying potential for significant impact and the positioning of a new paradigm opportunity.
- The enabling window represents the window of opportunity between the breakthrough stage and progressive cascade in which generational enablers, i.e., lily pads or stepping stones to a grander, more significant goal (an enabling innovation), can be pursued. This stage has a unique set of challenges and opportunities that are not often discussed throughout the literature and that involve co-evolving the development of a solution, a nascent paradigm, and the generation of impact. More specifically, challenges in the enabling window include ambiguity in application spaces, artificial ties to contexts, performance/capability limitations combined with presumption of additional performance "requirements," resource constraints, ecosystem readiness, and sociological and psychological paradigm forces. Moreover, opportunities in the enabling window revolve around the early decisions that can influence the development of an enabler. These choices/decisions create a an array of possibilities regarding application contexts, advancement of select performance dimensions, garnering resources to advance a solution/capabilities of a solution, retaining interest in a concept, and exploiting a potential new paradigm. Of particular importance is the opportunity to identify and pursue lily pads in

contexts that consider the current state of a solution (with current benefits and tradeoffs) as “good enough.” These lily pads can advance select performance dimensions and garner interest and resources for continued development.

- Once an enabling innovation is primed to drive its characteristic pattern of impact, an enabling innovation moves out of the enabling window and enters the stage of the progressive cascade. In the progressive cascade, *platform innovations* represent the first product of the impact cascade when an enabling innovation is applied to a new family of problems, which creates a path for a stream of progressive innovations. In the stage of platforms an important choice is the selection of new “meta problems” or “families of problems” (or need categories) in which an enabling innovation could play a role, thus creating a path for a stream of progressive innovations to develop. In the stage of progressive innovation a choice of innovation strategies, approaches, and archetypes can drive progressive impact (what we herein term designing for models of innovation) such as “disruption,” “modularity,” “human centered design,” and “lean startup.”

6.1.3 *Synthesis of insights related to the Framework to Design for Enabling Innovation*

Third, as a consequence of the differences across these distinct innovation impact stages, the patterns of thought and action to pursue enabling innovations, synthesized here as the *enabling thinking* framework, represent goal-oriented variations from generic design patterns, such as in the “informed design” framework. This framework creates language and generates insights regarding the following aspects of such patterns:

- Levels of practice from beginner to informed to enabling are defined for each stage of a design process model building on prior work; namely, problem definition, gathering information, generate alternatives, analysis/modeling, evaluation/selection, communication, and implementation. Two additional design process stages relevant to achieving enabling innovation are newly added in this framework, envisioning (creating a strategy) and path definition (implementation planning/design).

- For each of the aforementioned design stages, patterns for the enabling level of practice are characterized to match the characteristics of enabling innovation as an end goal. Further, each of the aforementioned patterns of enabling thinking can be decomposed into stage specific behaviors. Some of these behaviors are unique to the enabling thinking framework, while others have been discussed in the literature but not in the context of enabling innovation and its characteristics as an end goal.
- A set of "core" behaviors likely underpins the above mentioned enabling thinking patterns, because such behaviors seem to be employed across multiple different stages of the design process. These "core" behaviors include: prioritizing efforts according to the innovation end goal, breaking ambiguous ideas into definite parts, separating norms from rules, diverging-structuring-converging, employing multiple perspectives, exploring variations systematically, distilling the core of an idea from its context, synthesizing insights, and iterating and reflecting.
- Envisioning activities transition from skipping visioning (beginner), to creating a design brief (informed), to crafting a strategy for the enabling innovation (enabling). Relevant enabling thinking behaviors include defining the opportunity space, identifying blind spots and in-going biases, foreseeing the impact cascade, envisioning the performance-application roadmap, defining success metrics over time, and testing and selecting entry points.
- Problem definition activities transition from solving problems to framing problems to framing the flaw in the paradigm. Relevant enabling thinking behaviors include structuring ambiguity, questioning a paradigm, and spotting opportunities in flaws.
- Gathering information activities transition from skipping research to doing research to seeing all technical, economic, systemic, sociological, and psychological forces. Relevant enabling thinking behaviors include observing

diverse circumstances proactively, noticing forces at play, and creating empathy-based mental models.

- Generating alternatives transitions from having scarce ideas to generating ideas fluently to broadening idea spaces by making connections between generalized first principles. Relevant enabling thinking behaviors include interacting with new schools of thought, exploring morphological combinations, and linking core ideas to diverse problem and solution spaces.
- Analysis activities transition from modeling superficial issues to modeling deep issues to addressing host ecosystems holistically. Relevant enabling thinking behaviors include mapping ecosystem elements, modeling future ecosystem states, reconfiguring ecosystem nodes, links and exchanges, and porpoising.
- Evaluation and selection transition from ignoring tradeoffs to balancing tradeoffs to rethinking performance and connecting to early impact contexts. Relevant enabling thinking behaviors include identifying dimensions of performance and headroom, characterizing application contexts, mapping accepted and counterintuitive tradeoff combinations, and matching lily pad contexts with tradeoffs and headroom.
- Communication activities transition from ignoring communication, to transferring information, to persuading to facilitate acceptance or use. Relevant enabling thinking behaviors include telling stories to paint a vision, conveying counterintuitive insights, creating win-win partnerships, and driving habit conversion.
- Path definition activities transition from ignoring the design of implementation, to creating a deliberate strategy, and to creating an emergent strategy that unfolds performance and impact. Relevant enabling thinking behaviors include envisioning multiple impact pathways, identifying learning metrics and assumptions, and creating learning experiments.
- Implementation activities transition from running confounded experiments, to running valid experiments, to deploying an emergent strategy to discover the

enabling path. Relevant enabling thinking behaviors include experimenting for smart failure, selecting paths that can earn and learn, leveraging unexpected opportunities, differentiating when to stop from when to persist, and adapting based on learning.

- Variations in these behaviors can likely also help drive other types of innovation (e.g., tradeoffs in disruptive innovation, morphological variants in business model innovation, rethinking ecosystem nodes and links in modular and interdependent innovation).

In summary, the comprehensive nature of the enabling innovation model and enabling thinking framework is unique because it can likely help drive both framing and pursuit of a specific type of innovation end goal, and is anchored in a mix of prior research and theories and empirical data. These insights suggest a set of implications for research agendas on innovation and innovative thinking, teaching and learning to innovate, and the pursuit of innovation throughout multiple societal endeavors. Such implications are discussed in the following sections.

6.2 Implications for Research

The primary implication of this research is the creation of language to describe innovations by their impact and of patterns of thought and action to pursue enabling innovations, which co-exists with and aims to unify multiple schools of thought. Derivative implications of this study for the innovation body of knowledge are herein discussed from the perspective of: 1) research on characterizing innovation; 2) research on designing for models of innovation; 3) research on educating to innovate; and 4) engineering research.

6.2.1 *Implications for Characterizing Innovation*

One overarching goal of this research is to create language and a framework that can begin to unify ideas around the theme of "big," "significant," or "high impact" innovation. Many terms have been historically used to describe this type of innovation, often in confounded ways, i.e., using terms that were originally defined with a different meaning to describe high impact innovation. Radical innovation, for instance, was originally characterized in the literature as a step change in underlying technological performance (Ettlie et al., 1984), yet such a term is often used with additional connotations; for example, Dahlin and Behrens (2005) define "radical" as novel, unique, and with an impact on future technology. Similarly, the term "disruptive" is often employed in multiple contexts without consideration of its original meaning (Lepore, 2014). Disruptive innovations, however, are likely not high impact innovations because they "introduce a very different package of attributes from the one mainstream customers historically value, and often perform far worse along one or two dimensions that are particularly important to those customers" (Bower and Christensen, 1995, p. 45). Effectively, disruptive innovations use existing concepts/technologies, reconfigure a set of dimensions of performance, apply such innovations in new contexts, and are thus not new nor do they drive the impact cascade or a fundamental paradigm change that characterizes high impact. Other terms frequently employed to refer to high impact innovation in cofounded ways include "revolutionary," and "breakthrough." However, each of these terms has its own meaning and a given set of defining characteristics. These terms all effectively focus on significant changes in one or more aspects of an innovation, but not specifically on their outcomes and the enabling-progressive taxonomy helps complement and perhaps unify these ideas by differentiating innovations by their impact.

The classification of innovations as enabling and progressive also complements and potentially provides a unifying model for the current body of literature on innovation archetypes and taxonomies (see Table 6.1). Overall, the enabling-progressive model of innovation can potentially be employed as a "meta-classification" that encapsulates/encompasses many other taxonomies that are time–dependent and context-dependent. Because of the focus on impact outcomes and not on novelty, what is considered enabling or progressive is likely to retain such a classification over time, while classifications such as radical-incremental (e.g., Ettlie et al., 1984), modular-interdependent (e.g., Baldwin and Clark, 2000), or disruptive-sustaining (e.g., Christensen, 1997) will vary over time or as different contexts of application are considered. For example, an innovation can be enabling *and,* at some point in its history, disruptive, and at other points in its history sustaining, but the enabling-progressive nature of an innovation likely does not fade. Effectively, over time enabling innovations can be pursued using disruptive or sustaining strategies throughout their trajectory, using disruptive strategies (e.g., performance tradeoffs, asymmetry of motivation) in contexts in which "good enough" performance tradeoffs can be an advantage relative to other concepts and sustaining strategies in contexts in which the performance dimensions of an innovation should be sustained, but the enabling nature of an innovation will likely remain the same. Similarly, even though many historical cases of enabling innovation were at some point considered radical advances in technology, the radical nature of an innovation can fade over time – and in some cases it may not need to involve technology at all especially when an innovation is conceptual – but the enabling-progressive classification likely remains. For instance, without specifically referring to the term enabling, Drucker (1986, p.31) argued that "[t]he hospital, in its modern form a social innovation of the Enlightment of the eighteenth century, has had greater impact on healthcare than many advances in medicine", implicitly making an argument about the long lasting, enabling nature of this innovation. In summary, the enabling-progressive classification can co-exist with the aforementioned archetypes, possibly unifies and provides a top-layer classification for such archetypes, and thus enhances the set of available classifications to more comprehensively characterize innovation.

Table 6.1 An Updated Perspective of Innovation Archetypes

Area of change	Innovation archetype	Definition
Impact	Enabling	Innovations with broad reach, and comprehensive significance that drive a fundamental paradigm change and an impact cascade
	Progressive	Innovations with narrow reach, and select significance that exploit an established paradigm in focused applications
Form	Product	New products or changes in established products
	Process	New processes used in the generation of products
	Service	New or improved service concept
	Business model	New approaches to develop and deliver an offering
	Management	New management methodologies/practices
Underlying performance	Incremental	Minor departures from current practice
	Radical	Significant departures from current practice
Systems	Core	Changes to primary elements of a dominant design
	Peripheral	Changes to secondary elements of a dominant design
	Modular	Changes to system components without affecting system linkages
	Architectural	Changes to system linkages without affecting system components
	Interdependent	Changes to system components and linkages
End user perspective	Incremental sustaining	Sustains predecessor performance dimensions with small changes
	Radical sustaining	Sustains predecessor performance dimensions with significant step changes
	Disruptive	Trades off performance dimensions in the pursuit of simplicity, accessibility, convenience, or affordability
	Competence-enhancing	Enhances the value or applicability of a firm's competence
	Competence-destroying	Reduces or destroys a firm's existing competences or capabilities, rendering them obsolete
Business/ economic effects	Performance-improving	Replaces old products with new and better models
	Efficiency	Help companies make and sell mature (and established) products and services to their same set of customers
	Market making	Transform complicated and/or costly products so radically that they create a new consumers or markets

The enabling innovation model is fundamentally different from many isolated constructs discussed in numerous schools of thought, such as "enabling technology" (Utterback, 1994), "general purpose technology" (Helpman, 1998), "combinatorial innovation" (e.g., MacAfee and Brynjolfsson, 2014) and "paradigm-changing innovation" (Ahuja et al., 2014). As an example, the term enabling technologies refers to technologies that help support process improvement and a shift from process to product innovation (e.g., float glass production helps focus on developing new types of glass) (Utterback, 1994; Maine and Garsey, 2006). For DARPA (2010), enabling technologies are those which cannot stand alone and must be applied to perform a function. Enabling innovations, however, are more comprehensive than enabling technologies. The enabling innovation concept described herein does not focus on technologies but on any type of innovation, and shifts its emphasis to generating (i.e., enabling) an impact cascade (and not simply other technologies). With a perhaps slightly more related but also fundamentally different term, "generic purpose technologies (GPT)" are defined as those which share four characteristics: wide scope for improvement, broad range of uses, potential for use in a variety of products and processes, and strong complementarities with other technologies (David and Wright, 1999), which are similar to a subset of the characteristics of enabling innovations. The model described herein, however, adds to these and also focuses on innovations and not technologies, and defines characteristics beyond those identified for GPTs (e.g., paradigm change, separation of problem-solution issues such as multiple problem spaces vs. multiple solution architectures, focus beyond products and processes, impact cascade, affected ecosystems). Overall, the enabling innovation model is more comprehensive and applicable to a broader array of domains than the aforementioned constructs.

The enabling innovation model can also be positioned within the body of research that provides macro level perspectives of technoeconomic and sociotechnical paradigm changes (e.g., Dosi, 1988; Perez, 2003; Geels and Schoot, 2007). Many types of paradigms have been articulated in the literature. Dosi (1988) for example defined "technological paradigms," Perez (2003, 2009) extends this notion to "technoeconomic paradigms," and Geels and Schot (2007) created an even broader perspective of "sociotechnical transitions," which all effectively focus on technological, economic, and social macro level changes, often due to collective innovation activities (i.e., groups/streams of innovations) at the societal level. The research described herein departs from these macro level perspectives by providing a micro level perspective, i.e., the research describes a model that characterizes how paradigm changes can potentially be driven by one enabling innovation that alters societal worldviews.

Similarities and differences also exist within the body of work that describes other types of macro level changes. For example, Suarez and Oliva (2005) and Geels and Schot (2007) describe five types of change to a business climate (e.g., environment-organization changes such as economic reforms) and the societal landscape (e.g., deep cultural patterns, macro political and macro economic developments), respectively: regular (slow, linear change), hyperturbulence, specific shocks, disruptive change, and avalanches based on the frequency, amplitude, speed, and scope of a change. Avalanches for example, are defined as changes to an environment that are infrequent, but when realized have high intensity, speed, and scope, for instance, radical economic reforms in a country (Suarez and Oliva, 2005). The model described herein likely encompasses all of the aforementioned types of change, but provides a micro level, innovation-triggered perspective of the process by which impact cascades are developed (compared to describing changes to a business climate and the implications for organizations in the case of avalanches). In addition, Perez's (2003) technoeconomic paradigms construct provides an envelope concept that describes the performance trajectories of groups of individual technologies that constitute a technological revolution. The enabling innovation model complements this thinking by outlining a perspective of how each of the individual technologies/solutions that drive paradigm change unfold to enact changes in society through an "avalanche" or "cascade" of impact benefits. Overall, the work described herein elevates the technological focus of this prior work to an innovation level (inclusive of non-technological innovation), explicitly articulates perspectives of impact and links between innovation change and impact, and creates a micro-process model (focused on the innovation, as opposed to macro/policy-focused perspective) by which innovations that drive this type of change can be better understood.

This research also complements micro process perspectives of invention and innovation. The enabling innovation model explicitly separates a stage of discovery and invention (the stage of breakthroughs) from innovation (impact) stages. This stage of breakthroughs, which describes sequences of knowledge-generating events, is positioned at the intersection of Arthur's (2007, 2009) theory of the process of invention (which he defines as linking purposes with concepts/principles in sequences of events and resolving subproblems that arise recursively) and knowledge about Stokes's (1997) Bohr and Pasteur's quadrants, (i.e., quests for fundamental understanding, and for fundamental understanding *and* practical needs, respectively).

Once out of the stage of breakthroughs, this research also aligns with perspectives of the technology-push and demand-pull debate (beyond the technological focus/context in which this debate originated). When examining technologies, the enabling innovation model reinforces the argument that both push and pull approaches are necessary to achieve innovation through a match between (market) demand and (technological) solution and that competences enable individuals and organizations to match technology with market demand (Maine and Garsney, 2006; Maine et al., 2012; Di Stefano et al., 2012). In fact, these perspectives can be elevated/generalized to represent a co-evolving adaptation between a solution (regardless of its technological/non-technological nature) and (latent or explicit) societal needs/demands. The enabling innovation model also highlights different areas of emphasis for this "matching" process in the enabling window and progressive cascade, such as a matching early impact and performance tradeoffs in the enabling window, and matching solution platforms with areas of application in the progressive cascade, and adds a layer of complexity because of the often fuzzy nature of concepts in the enabling window.

In the enabling window, categories/language to describe problems and solutions are often ill-defined, performance is uncertain and there is broad headroom, making problem-solution matches more difficult to establish, and likely more important to the possible success of a concept, compared to the more defined "matching" process of the progressive cascade. This perspective aligns with work in the "dominant design" literature, i.e., designs that undergo a diverge-converge process before a core design establishes dominance in a given area of application (Abernathy and Utterback, 1978). Recent work in this school of thought has argued that prior to the emergence of a dominant design, categories and labels (Bowker and Star, 2000) for new technological solutions do not emerge in isolation, but are continually shaped by changes in technological designs through parallel processes of "linguistic recombination" and "design recombination" process that "echo" each other (see Grodal et al., 2014). For example, the mobile phone industry, for instance, was characterized by early categories such as "camera phone" and "PDA phone" before converging into "smartphone" as a "dominant category" (Grodal et al., 2014). This study also acknowledges the importance of "language" and "categorization" in the development of solutions and the establishment of a paradigm, and acknowledges a critical window in which these developments likely occur – the enabling window. More importantly, the study identifies an additional dimension of complexity, from "problem-solution-category" matching to "problem-solution-category-context" matching, because the aforementioned process of "linguistic recombination" could also be aided by a process of "linguistic generalization" that helps see connections to additional contexts of application, in a process of "context recombination," and remove artificial ties to "industries," or, in more general terms, contexts. Thus, a matching process (between solution and societal needs, categories, and contexts), as outlined in the enabling innovation model, could play a role in accelerating or slowing down the often cited changes at a landscape (macro impact level), which Geels and Schot (2007, p. 400) posit that "[they] usually take place slowly (decades)." Once in the progressive cascade, the enabling innovation serves as a building block for a different type of matching process with markets/contexts and additional complementary innovations to solve different families of problems, yet without the added complexity of establishing a new paradigm.

6.2.2 *Implications regarding Designing for Models of Innovation*

Driving enabling innovations by employing the "enabling thinking" patterns and behaviors also has implications for research in the field of design. More specifically, this research examined the relationship between the fields of innovation, design, entrepreneurship, and the research findings described herein can inform each of these fields. Some of these implications – specifically regarding the nature of design and designing for enabling innovation, design processes, design patterns and behaviors, positioning within design subdisciplines, and designing for additional models of innovation – are discussed in the following paragraphs.

One of the key implications of this work with regard to the nature of design is the notion of "designing for models of innovation," and in this work specifically, enabling innovation. More specifically, the work described herein reinforces the notion that design activities have a common set of features but that also many distinct forms of design exist (Visser, 2009), especially when the end goal of design activities is to innovate. From this perspective, there are generic aspects that are common to all design activities (e.g., Goel and Pirolli, 1992) such as taking a broad systems approach, framing problems in distinctive and personal ways, and designing from first principles (Cross, 2011; Goldschmidt and Rogers, 2013). Yet, there are also many subtle aspects of designing with a given end goal in mind, i.e., emphasizing the goal-oriented nature of design activities (Archer, 1965; Crismond and Adams, 2012). The framework described herein is goal-oriented in nature, meaning that an end goal can help guide the co-evolution of problem and solution in design activities. This research thus contributes to a unique understanding of design as a form of goal-oriented activity with innovation impact as a goal. In the framework described herein, the characteristic patterns of enabling innovations (e.g., impact cascade, paradigm change, multiple problem spaces) inform the identification of the design patterns and behaviors described in the framework thus creating a unique goal-oriented perspective of design in which innovation patterns guide design activities. The enabling thinking framework thus reinforces Norman and Verganti's (2014) call for distinct design process to achieve "big/significant" innovation (which they term "radical" innovation and posit is achieved through new technology or deep reinterpretation of the meaning of a product) compared to what they term as incremental innovation (which they posit is achieved through human centered design). As such, the enabling thinking framework illustrates how innovation archetypes (in their many forms) could guide design activities by providing patterns that can serve as boundaries for the pursuit of solutions and make a sough-after type of desired outcome explicit, thus creating new links between the innovation and design problem solving schools of thought.

Building on this perspective of designing for models of innovation, the framework described herein has multiple implications for research regarding design processes and design patterns and behaviors, especially those to envision, shape, and pursue enabling innovations as the end goal. With regard to design processes, the framework described herein explicitly articulates two additional stages to Atman et al.'s (2007) design process model: envisioning, and path definition. Many design process models begin with need identification or problem definition (see Dubberly, 2004) in the form a brief; however, the enabling thinking model calls for proactively crafting a strategy to help drive an enabling innovation through the enabling window and progressive cascade. Beyond identifying needs and defining problems, envisioning an approach early on in design activities can help define an opportunity space, goals and bounds, and create a vision for a portfolio of impact areas and the development of a performance impact roadmap. This envisioning stage can help create a proactive link to the patterns of a model of innovation that can guide designers as they engage in the different design process stages, even if revisited in iterative and nonlinear ways. This distinct stage thus creates a separation between the “envisioning,” and the “shaping” of enabling ideas. In addition, the implementation stage that is characteristic of design process models is herein divided into separate path definition (implementation design) and implementation activities. This division of the implementation stage calls for more careful articulation and more attention to the design of implementation activities in the “pursue” macro stage of design activities.

This unique design process perspective and its stages of envisioning, defining problems, gathering information, generating alternatives, analyzing, evaluating/selecting, communicating, implementation framing, and implementing were used as an anchor to organize the enabling thinking framework of patterns and behaviors. This anchor builds links between design and the enabling innovation model using an organizing structure grounded on prior design research. Often times, in attempts to characterize innovators, studies create seemingly convoluted lists, mixing behaviors (the doing aspect), cognition (the thinking aspect), and non-cognitive traits (the being aspect) of innovation with non conceptual organization. For instance, Purzer et al. (2014) list traits such as deep knowledge, active learner/curious, vision/caring, team manager/leader, and risk taker as the five critical characteristics of an engineering innovator, and Ferguson et al. (2014) identify traits such as curious, organized, engages stakeholders, and recognizes opportunities, flexible, has domain knowledge and business acumen. In other instances, conceptual models address only select aspects of a design process; for instance, Dyer et al. (2008) only create a model of behaviors for opportunity recognition. As such, this framework departs from prior models which simply identify and list innovation behaviors and creates an organized perspective of innovation behaviors. In addition, the enabling thinking framework is also end-to-end, meaning that it encompasses all design process stages.

For each design stage, the design patterns synthesized by Crismond and Adams (2012) for beginner and informed designers were contrasted with patterns that match the characteristics of enabling innovations, and decomposed into a set of previously unexplored behaviors, and/or variations from previously identified behaviors tailored to the enabling innovation model. These unique behaviors thus need to be positioned within the literature/research base.

Problem definition activities, for instance, focus on framing flaws in paradigms. This perspective of opportunity discovery/creation, is a novel perspective with which entrepreneurship researchers could further investigate the nature of entrepreneurial opportunity recognition, since it has not been characterized throughout the literature that focuses on opportunity discovery/creation (e.g., Short et al., 2009). Structure, questioning paradigms, spotting opportunities in flaws and core behaviors such as breaking ideas down, diverging-structuring-converging, and separating negotiable norms from non-negotiable rules can likely play a role that is (to date and to the author's best knowledge) unexplored in opportunity recognition.

With regard to gathering information, many schools of thought emphasize observations (e.g., Dyer et al., 2008) as key elements to acquire information and gain novel insights, yet behaviors such as "noticing" and "mental modeling" have received (to the author's best knowledge) little to no attention. The classification of information as technical, economic, systemic, sociological, and psychological is also unique and complementary to frameworks such as Anthony et al.'s (2008) functional, social, and emotional.

For alternative generation activities, unique behaviors include "diverging-structuring-converging," which can help identify logic gaps between diverging and converging processes by structuring sets of ideas, as well as "distilling core ideas from their context," which helps make links between idea spaces that are typically not associated. In analysis stages, modeling future ecosystem states is often discussed in the systems literature, but seldom in the innovation literature, and is a unique behavior described herein that could be further investigated.

Regarding evaluation and selection, "identifying and evaluating tradeoffs," departs from simply evaluating tradeoffs in current/status quo solutions to evaluating tradeoffs with simultaneous consideration of headroom, impact, and contexts of application. These additional considerations thus add another layer of complexity/choice to the analysis of tradeoffs to those typically described throughout the design and innovation literature (e.g., Kim and Mauborgne, 2005; Anthony et al., 2008). Generalizing ideas, or finding their core by distilling them from contextual influences and finding first principles thus play an important role which has not been previously highlighted in design studies that study design tradeoffs and evaluation/selection processes.

Communication departs from providing information and negotiating among multiple viewpoints of stakeholders (Mosborg et al., 2005) to proactively persuading through stories, having sensitivity in conveying counterintuitive insights, creating win-win partnerships, and nudging to drive habit conversion. Nelson and Stolterman (2003, p. 43), for example, argue that "design communication may at times include the use of rhetoric and persuasion, as is also true of science and art. But these forms of argumentation are not a part of its essential nature. Also, a good designer does not spend time convincing clients of needs and desires they have not authored. So, "selling" in a traditional marketing sense, is not fundamental to the design process." The research described herein and particularly the separation of the approaches to pursue enabling innovation from progressive innovation may make the aforementioned argument invalid if the goal is to achieve enabling innovation. In fact, further along in their discussion, Nelson and Stolterman (2003, p. 109) do acknowledge that at times rethoric and persuasion will be necessary, especially because "assessing need is very different to creating need." Thus, in the pursuit of enabling innovations, driving a new paradigm will inherently encounter resistance to change, and simply listening to "clients" might not be enough to drive an idea forward, because the problem space categories that enabling innovations often address are often latent prior to the introduction of the innovation.

With regard to path definition and implementation, the patterns and behaviors in the framework align with the historical emergent strategy school of thought and its many variations that emphasize learning over forecasting (e.g., Mintzberg and Waters, 1985; McGrath and MacMillan, 1995; Blank, 2005; Ries, 2011) as well as the effectuation model (Sarasvathy, 2001a) that emphasizes control over forecasting. Yet, path definition and implementation are positioned as taking special consideration of the characteristics of the enabling innovation model, especially during the enabling window phase, in which the simultaneous unfolding of performance, characterization, contexts of application, and impact while driving a new paradigm can become critical.

The enabling thinking model has implications for and interactions with other design schools of thought that are complementary and likely mutually beneficial. For example, in the engineering (e.g., mechanical engineering design) school of thought, many design approaches call for "backwards design" (Burgess, 2012), "morphological charts" (Linsey et al., 2012), design heuristics (Daly et al., 2012b), and/or "product dissection" (Booth et al., 2013) techniques. These methods can complement the behaviors highlighted in the enabling thinking model, helping stakeholders/decision-makers understand technical requirements of a solution (even though these approaches can likely be generalized to the non-technical realm) and discern between enabling and progressive components of a concept. The enabling innovation model and enabling thinking framework, in contrast, can help provide a "big picture" perspective to engineering-driven plans for technological evolution (e.g., Arendt et al., 2012; Yannou et al., 2013). More specifically, the model and framework provide guidelines for considering the influence of contexts of application in the success of an engineering-driven innovation (particularly in the enabling window), an area that according to Yannout et al. (2013) has not been thoroughly studied. As such, the enabling thinking framework can help understand tradeoffs and contexts of application beyond the technical realm, help depart from artificially imposed ties to a given context, and embed an innovation strategy that can potentially help drive engineered technologies forward in their development trajectory. Overall, the enabling thinking model is complementary and not in competition with research in discipline-specific design thinking schools of thought.

There is also an opportunity to further investigate the subtle differences between generic design and designing for models of innovation. Beyond enabling innovation, there is an opportunity to better understand how behaviors would vary when the sought-after form of innovation changes, and the comprehensive, end-to-end nature of the enabling thinking framework can help situate and provide an anchor to new studies. As an example, given the characteristic patterns of the disruptive innovation model, behaviors to design for this type of innovation would likely emphasize balancing benefits and tradeoffs to "good enough" levels, and the discovery of latent performance dimensions in domain-specific paradigms. Slight variations of the behaviors emphasized in the enabling thinking framework such as evaluating accepted and counterintuitive tradeoffs and employing multiple lenses would thus play an important role in identifying opportunities for and driving disruption. In another example, designing for modular innovation would likely involve re-thinking, for instance, economic value chains, and understanding opportunities to create value/impact by making aspects of ideas more modular (as opposed to interdependent). Therefore, variations of behaviors described in this framework, such as rethinking ecosystem nodes and links and breaking ambiguous ideas into tangible parts can help design for modular innovation. Ultimately, the enabling thinking framework, represents a case in point of a broader school of thought that this research aims to motivate: *designing for models of innovation*.

6.2.3 *Implications for Research on Educating to Innovate*

The enabling thinking framework/model and notion of designing for models of innovation also have implications for research in learning and educational theory building. As outlined in Crismond and Adams (2012, p. 775), "Bruer (1993) and Reigeluth (1999) distinguish between two kinds of educational theories: ones that are mainly descriptive and deal with learning and development, and others that are more prescriptive and offer guidelines on what ideas and skills should be taught (i.e., learning goals).” The enabling thinking framework is situated in the more prescriptive end of this spectrum, particularly with regard to articulating the types of ideas and skills that should be taught when the goal is to innovate in pragmatic ways. Even though the framework names the patterns of thought and action as “behaviors,” the framework does not call for a “behaviorist” perspective of learning; instead, the framework acknowledges the importance of the behaviorist, cognitive, and situated learning schools of thought (Greeno et al., 1999). The framework is more aligned with Dall’Alba’s (2007, 2009) “thinking, acting, being” theory and acknowledges the importance of the interplay between these dimensions for the pursuit of innovation, even though the “being” (or ontological) dimension of innovating (and being/becoming an innovation professional) was outside of the scope of this study.

Regarding its usefulness for future studies on educating to innovate, the enabling innovation model and enabling thinking framework can thus help situate studies that aim to further characterize innovation expertise. The model and framework can also help further understand the relationships between innovation behaviors and design outputs, and understand the role of having patterns of innovation as guidelines to a design goal.

Moreover, the design patterns and behaviors in the framework represent a gamut of learning goals to be further studied in educational research, along with teaching strategies, assessment approaches, and overall pedagogies that are relevant to learning to innovate. There is an opportunity as well to study individual or subsets of the behaviors described in the enabling thinking framework that provide empirical validation (further discussed in the limitations and future research sections). Finally, educating to innovate has implications for rethinking notions of expertise (e.g., Glasser and Chi, 1988; Chi et al., 1981), and characterizing innovation expertise and its development. In a rapidly changing world, any domain-specific expertise, although critical to advance knowledge, is threatened by the possibility that such expertise will become irrelevant and outdated in shorter time spans. Further, the already vast body of knowledge is ever expanding, making domain expertise more difficult to develop and sustain given that new fields and new connections within and across fields continue to emerge. These threats highlight the need to further understand more fundamental types of expertise that are non-domain specific and could make the adaptive expertise construct (see Hatano and Inagaki, 1984) more explicit. To achieve this, the different ways of "thinking, acting, and being" that represent expertise in areas such as learning, design, entrepreneurism, and innovation (the area of focus of this work) should likely be further characterized and studied. Rethinking notions of expertise can in turn lead a to better understanding of how to enable and empower students to navigate the ever increasing body of knowledge.

6.2.4 *Implications for Engineering Research*

Implications of this work also exist for the pursuit of engineering research, especially in the areas of research investment/allocation, research approaches, and graduate mentor-mentee relationships. The engineering research enterprise is critical to the development of many enabling innovations, and thus such implications are discussed in the following paragraphs.

Although not explicitly, funding allocation mechanisms in research agencies often classify innovation using risk-return relationships that stem from the financial world, i.e., higher risks should command a higher reward. Some agencies often call initiatives with high risk and promise of high reward "blue sky" projects, and in the context of this research such approaches correspond to the "moonshot and trickle down" enabling window approach discussed in Chapter 4 of this dissertation. The enabling lily pads approach, however, offers an alternative model to the shaping, evaluation, allocation, and pursuit of research programs that embraces research plans/projects that focus on simultaneously unfolding performance and impact in multiple (even if in counterintuitive) areas of application.

Further, the risk of what have historically been termed “blue sky” projects likely lies more in the approach to pursue rather than in an idea in and of itself, because truly enabling ideas, as defined in this work, have potential for application in multiple spaces. Being proactively flexible about areas of application can thus reduce perceived research risks (even though some research paths are indeed binary in the sense that flexibility in contexts of applications is not possible). Engaging in alternate approaches to the pursuit of research (e.g., enabling lily pads vs. moonshot and trickle down) suggests that some research risks stem more from the approach to a research endeavor rather than from the uncertainty of a research goal.

The enabling thinking framework offers an approach to think about and pursue research concepts with enabling innovation potential, and an opportunity to instill such knowledge in emerging scholars (i.e., graduate students). More specifically, the design patterns in the enabling thinking framework can guide new approaches to research projects. Such approaches can, for instance, focus on addressing flawed paradigms hidden in research schools of thought, consider systems, technical, economic, systemic, sociological, and psychological implications of projects, use “generalized language” to create connections between fields, match solution tradeoffs with contexts of application to generate impact along the way, persuade rather than transfer information, and embrace emergent research paths. More often than not, the aforementioned approaches are employed haphazardly or implicitly and there remains an opportunity to explicitly and proactively engage in the aforementioned (and likely other) approaches that enhance the research enterprise. Perhaps an opportunity to embed these philosophies into the research community is in the mentor-mentee aspects of graduate advisor – graduate student relationships. Workshops, courses, and coaching could be employed to train advisors and graduate students on how to employ “enabling thinking” in their research projects. The author and his graduate advisor, for instance, piloted a workshop called “Mentor to Innovate” that employed a preliminary version of the enabling thinking framework to instill such a philosophy in mentor-mentee pairs. The workshop employed interactive presentations and a case study discussion (see case study employed in Appendix H) with the goal of sparking discussion of these issues in graduate advisor-student pairs. Overall, the work described herein aims to spark a new type of conversation regarding alternate approaches to the funding and pursuit of research that could be informed by new ways of thinking, such as the one described herein.

6.3 Implications for Teaching and Learning

The enabling innovation model and enabling thinking framework also have multiple implications for teaching and learning at the undergraduate, graduate, and professional development levels. Teaching and learning to innovate are topics that spark interest across society yet no overarching frameworks currently exist to inform instruction; and most proxies come from teaching and learning design and/or teaching and learning entrepreneurship (often as business building). Therefore, the implications of the model and framework on teaching and learning to innovate are thus herein treated from the perspective of content, assessment, and pedagogy and the integration of these three issues in educating for innovation, as outlined in education models (e.g., Wiggins and McTighe, 2003; Fink, 2003; Felder and Brent, 2003; Streveler et al., 2011). Special emphasis is placed on the implications of making a transition from teaching and learning design to teaching and learning design for innovation (and in the case of this research, enabling innovation).

To make the content/framework developed in this research more actionable and applicable to teaching and learning activities, the behaviors to design for enabling innovation are herein broken down even further into a set of actionable principles. More specifically, each behavior was broken down into a set of key principles. These principles were developed by analyzing the collection of insights described for each behavior in Chapter 5 of this research, as shown in the "behavior decomposition charts" in Figure 6.1 and Figure 6.2 (Shape), and Figure 6.3 (Pursue). These charts synthesize hypotheses/conjectures on the key principles to proactively engage in such behaviors (and due to their conjectural nature require further validation). However, these charts represent a useful start in describing the elements of the enabling thinking framework in ways that are more actionable and more easily integrated into content, assessment, and pedagogical elements of the education system. Building on these charts, the implications of the enabling thinking framework for teaching and learning are discussed in the following paragraphs.

With regard to *content*, the patterns of the enabling innovation model (and models of innovation in general) can serve as what Wiggins and McTighe (2005) term a "big/core idea" in a "backwards design" approach to designing learning experiences that aim to teach one to innovate. Learning experiences and curriculum should make students aware that not all forms of innovation are made equal, and that even though innovation is difficult to predict, archetypical patterns can guide its pursuit. Chapter 2 in this work briefly reviewed some of these patterns throughout the literature, and the enabling innovation model described in Chapter 3 describes the patterns that can be used to identify/screen enabling innovations. Therefore, this research can inform learning goals in terms of (declarative) knowledge of innovation archetypes and (procedural) skills for the screening/ identification of innovations.

Frame the flaw in the paradigm			See all forces			Broaden idea spaces		
Structure ambiguity	Question the paradigm	Spot opportunities in flaws	Observe diverse circumstances	Notice forces at play	Create empathy-based mental models	Interact with new schools of thought	Link core ideas to diverse problem & solution spaces	Explore morphological combinations
Break ambiguity into unknowns and knowledge gaps	Ask technical, economic systems, and socio-emotional 'what if' and 'why' questions	Separate mental framing from accepted practice	Develop a basic awareness of things to look for	Consider technical, economic, systems, social and emotional forces	Map actors, objectives and circumstances	Translate domain specific ideas into generic language	Decompose problems and solutions and identify core components in target contexts	Break down a concept into its core components and attributes
Assess uncertainty and significance of knowledge gaps	Differentiate between negotiable norms and non-negotiable rules	Separate problems from solutions	Create an inventory of relevant contexts and circumstances to observe	Diverge, structure, and converge on the forces to monitor	Identify techno-economic, systemic, and socio-emotional interactions, tensions and barriers	Seek different perspectives by breaking from usual social network	Find the first principles underlying core problems and solutions	Diverge, structure, and converge possibilities for each component
Provide a tree structure to knowledge gaps by asking "why" or "how"	Probe to uncover second and third order effects	Break problems and solutions into components and attributes	Prioritize key circumstances to be observed according to the end goal	Create a working hypotheses that accounts for all forces at play	Create an empathic mental model of linkages and root causes of tensions and barriers	Push ideas across many contexts as a testing mechanism	Separate problem from circumstance using generalized descriptions	Create a comprehensive, systemic view of all combinatorial possibilities
Diverge, structure, and converge, exploring issues at varying levels of depth	Differentiate answers that satisfice from those that merit further exploration	Assess rationale for links between problems and current solutions	Recognize elements of each circumstance, context, or situation	Establish most likely conditions to be encountered in a circumstance	Assess if linkages and root causes are rules, norms or assumptions to search for hidden insights	Pull ideas from exposure to non traditional environments	Identify source ideas to connect in analogical, opposite, intersectional, and adjacent domains	Understand the morphological possibilities that are within a set of established goals and bounds
Iterate between inductive and deductive approaches to structuring	Understand when it is important to probe further and be willing to act on learning	Identify what is done by cultural norm rather than by absolute necessity	Become aware of in-going biases	Monitor and focus on unanticipated signals that deviate from most likely conditions	Play with the mental model to unfold second or third order effects that lead to new insights	Suspend judgment, reflect, and engage in objective dialogue	Identify aspects of solutions in source contexts that transfer to target context	Link and explore all combinatorial possibilities even if counterintuitive
Ensure that structure is mutually exclusive and collectively exhausted		Zoom-in on flawed norms and proactive consider different perspectives		Reflect to uncover second and third order effects of findings on hypotheses	Identify any in-going biases that may have informed the mental model	Synthesize learning from networking exercises	Decide if a solution or aspects of it are applicable, translate, and adapt	

Core Behaviors

Recognize and label patterns	Find the first principles	Break ambiguous ideas down	Employ multiple perspectives	Diverge-structure-converge	Separate norms from rules	Distill the core of ideas from their context	Explore variations systematically	Synthesize insights	Prioritize according to an innovation goal

Figure 6.1 Break Down of "Shape" Behaviors Into Actionable Principles (1/2)

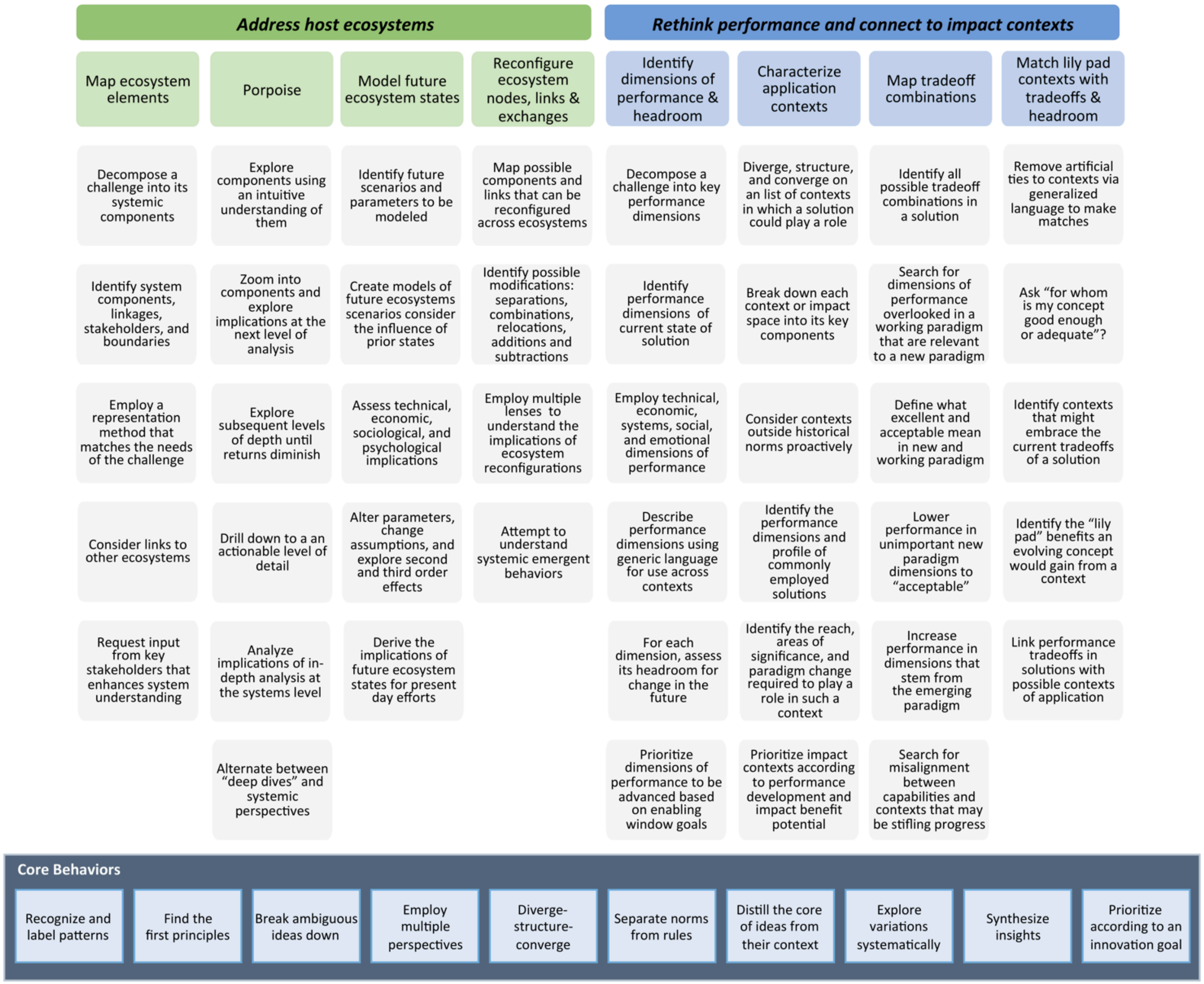


Figure 6.2 Break Down of "Shape" Behaviors Into Actionable Principles (2/2)

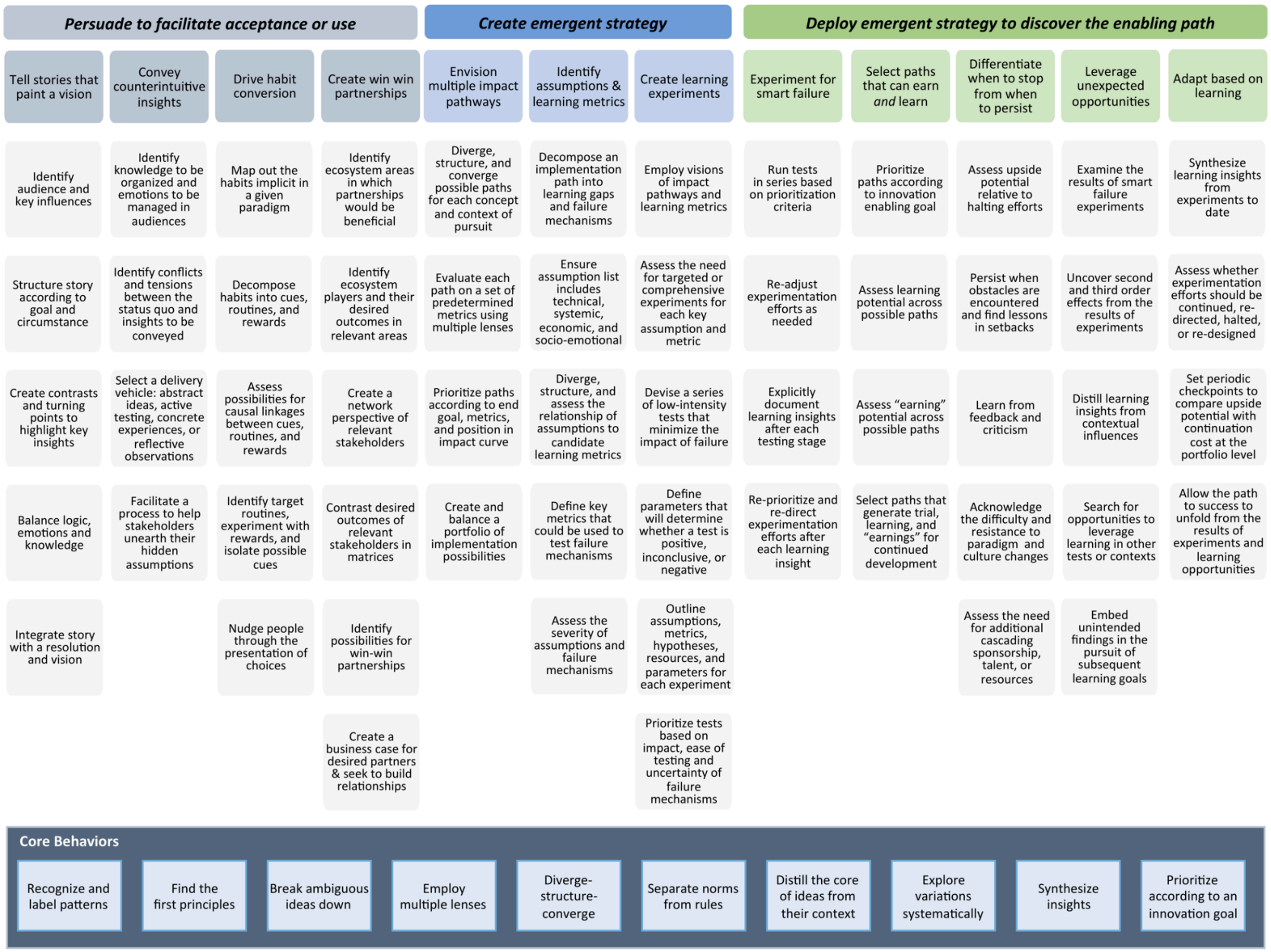


Figure 6.3 Break Down of "Pursue" Behaviors Into Actionable Key Principles

Also regarding content, the comprehensive end-to-end nature of the enabling thinking framework and its patterns/behaviors can serve as an anchor to content in teaching and learning to innovate. The framework can be used as a learning goal in educational experiences varying in scale and scope, ranging from curriculum development to individual coursework. The framework can also inform content/learning goals at different levels of granularity, meaning that learning goals can center on teaching at the framework level, at the pattern level, at the behavior level (enabling thinking and/or core behaviors), or at the principle level, as shown in Figures 6.1, 6.2, 6.3 and 6.4. As an example, one could design courses that aim to provide students with the opportunity to employ all stages of the enabling thinking framework, or could dedicate modules of a given course to a particular stage or behavior. In addition, the core behaviors identified herein are likely not only applicable to enabling thinking, but also applicable to other types of endeavors (thus their classification as "core."). As such, the set of core behaviors identified herein is likely relevant to other types of design/innovation practices, such as notions of informed design or human centered design.

By teaching specific behaviors, societal stakeholders can learn to innovate intentionally (as opposed to serendipitously). This focus on teaching design patterns and behaviors complements the broad array of tools and methods to scaffold design and innovation learning (e.g., Lidwell et al., 2010; Daly et al., 2012b; Kumar, 2012). The focus on teaching patterns and behaviors likely makes the use of such tools/methods more effective by providing a language that can be used to describe related actions.

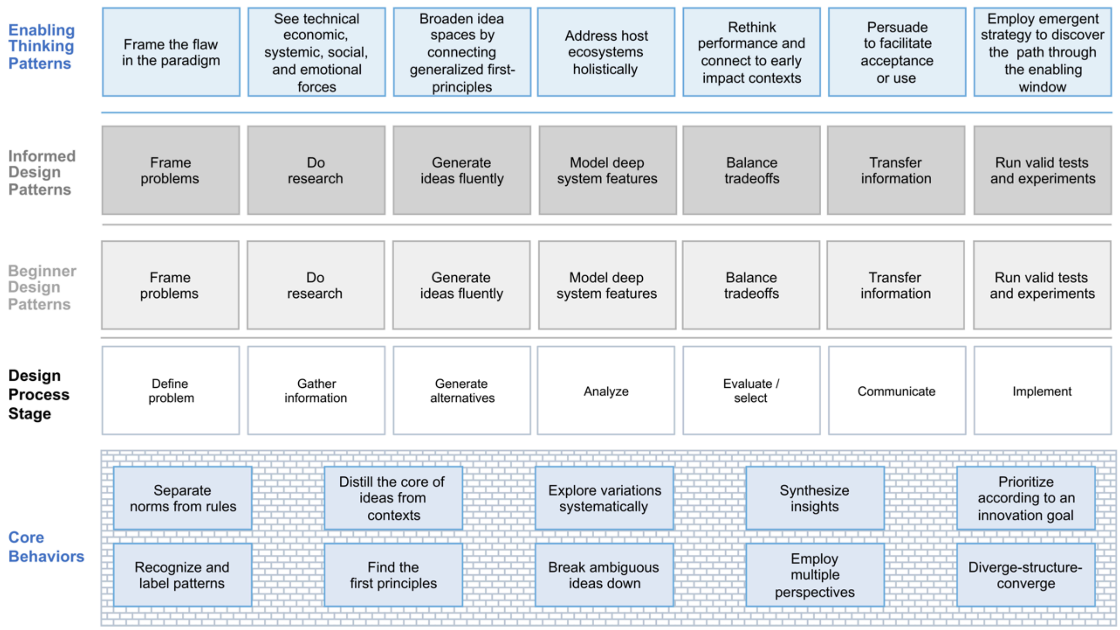


Figure 6.4 Example Levels of Practice at the Pattern Level

From an *assessment* perspective, the combination of the *enabling thinking* framework with frameworks such as *The Informed Design Teaching and Learning Matrix* (Crismond and Adams, 2012) can help inform formative and summative assessments that more clearly illustrate differences in beginner, informed, and enabling design/thinking in the classroom. This progression in levels of practice, when combined with perspectives of patterns and behaviors at the principle level and with frameworks for creating learning experiences (e.g., Wiggins and McTighe, 2005; Fink, 2003), can help create rubrics that generate evidence of student understanding (e.g., explaining, interpreting, applying, creating perspectives, empathizing, having self-knowledge). Assessments can range from informal checks and observations to tests/quizzes, exercises, and projects and performance tasks (Wiggins and McTighe, 2005). In addition to more traditional assessments (e.g., tests/quizzes and projects), one could, for instance, employ systematic observation methods (e.g., Cox and Cordray, 2008) in design meetings for a hypothetical experiential learning course to assess a given pattern or behavior in the framework. In addition, psychometric assessments and situation judgment tests can also help understand student differences and student development of behaviors and patterns described in this research especially at the cohort level and for team assembly purposes, since likely no single individual can exhibit all behaviors. The authors have begun work in this arena and illustrative samples of work in progress assessment instruments are provided in Appendix I.

In terms of *pedagogy and instruction*, even though lecture-based approaches might work for teaching the basics of models of innovation, case-based, project-based and experiential learning approaches can result in more meaningful learning experiences. Each of the enabling innovation cases identified in Table 4.2 and Appendix C can form the basis of cases that teach students about the history of enabling innovations and the intended and realized streams of decisions and patterns of thought and action that led to their realization. An example of these cases is provided in Appendix J, highlighting the history, sequence of events and thinking that led to the creation of microfinance. Beyond learning about prior innovations, pedagogical approaches can also focus discussions on current events and conceptual and technological developments, utilizing recent articles and news clips from broadly recognized news/media outlets, as frequently employed in business education. These current event discussions can help students situate their knowledge and switch from recognizing patterns in historical innovations to exercising their proactive use in understanding patterns in current events and their implications for the future. Depending on the scope of the issue to be discussed, these discussions can vary in granularity, focusing on the entire framework described herein, on a few select behaviors as "drill practices," i.e., repetitive learning activities to master/ develop a particular behavior/skill, or on gaining mastery in the identification of concepts with enabling potential using the behavior decomposition charts as guides to a learning goal. In addition, project-based learning and experiential-learning provide opportunities to further contextualize the knowledge and skills described in this research. Courses can be created in which instructors/mentors coach students in addressing a broad array of challenges from technological development, business model development, and social innovation challenges in experiential contexts, with entrepreneurs, corporations, non-profits, and governments as target clients and partners. These courses can help students bridge theory and practice, and gain first-hand experiences regarding the multidisciplinary and integrative skills to innovate on demand while simultaneously contributing to the solution of real-world problems.

Content, assessment, and pedagogy related to this study can be integrated in different ways along the educational continuum. At the *undergraduate* level, for example, the framework can inform teaching in introductory and advanced design classes (e.g., design studios, senior design projects) but can also be used to assess the development of design and innovation competencies throughout an entire curriculum. Instruction and lesson planning can target single or multiple behaviors to be embedded in desired educational outcomes, and students can be taught to recognize innovation impact in the form of patterns. The framework is also useful to coach/guide project teams in experiential learning courses (e.g., Oakes and Spencer, 2004) as it can pinpoint the level of performance (i.e., beginner, informed, enabling) at which a team is operating and suggest alternative behaviors for a more effective design process. At the *graduate* level, the framework also represents a set of target behaviors to be embedded in curricula, experiential learning courses, and/or innovation-focused courses, with direct translation to graduate research and professional practice activities. Beyond skill and competency development, these efforts can likely directly impact research activities of graduate students as they "design" solutions to their research problems. Since the outcome of research efforts often times translate to opportunities for real-world impact, the development of design behaviors for innovation is critical in graduate education. At the *professional* training and development level, the framework can inform training on design and innovation practice through workshops and professional development activities of varying duration and scope, and instruct practicing designers on the design behaviors for successful enabling innovation as well as leaders and managers on how to recognize and manage it. Designers and innovators across fields can benefit from new ways of thinking about innovation, which can inform their day-to-day professional activities.

From a policy and curriculum perspective, both the enabling innovation model and enabling thinking model/framework can inform the design of future curriculum targets and design at the macro level, providing more specific definitions and guidelines. The US government's Educate to Innovate and The National Academy of Engineering's Engineer of 2020 (NAE, 2004) initiatives, for instance, acknowledge the importance of embedding innovative attributes in the curriculum, and the research described herein can make this challenging yet important task more actionable. In entrepreneurial education contexts, for example, Lean Launchpad programs have been formally created and institutionalized and a broad array of universities. Similar programs could be created and embedded for the enabling innovation concepts described herein, thus formalizing educational approaches to teach the differences between enabling and progressive change/impact and the pursuit of innovation that seeks to establish a new paradigm.

6.4 Implications for Practice

The implications for the body of practice of the enabling innovation model and the enabling thinking framework are herein discussed. In aggregate, several key lessons for screening, prioritizing, envisioning, shaping and pursuing innovation emerge from this research (adapted from Sinfield and Solis, 2015). Such key lessons are applicable to individuals, entrepreneurs, businesses, non-profits, agencies, and governments alike:

- *Understand that not all innovation is made equal with different circumstances naturally calling for different types of innovation*. The word innovation has likely become a "catch all" phrase for new ideas, and this research calls for rethinking such a concept from the perspective of *both* novelty and impact. The classification of innovations as enabling or progressive can be a useful first step and a complementary classification to other existing taxonomies that focus on the form of a concept, the underlying technological change, the changes to existing systems, and the perceived dimensions of performance. Understanding these classifications can lead to a more precise characterization of new concepts and a more accurate match between a promising concept and potential circumstances of application. For example, in the world of mission-driven organizations, some circumstances will call for adapting solutions in the progressive domain to a given circumstance/context, while others will inherently need to enable solutions that stem from a new paradigm.

- *Embrace a broader mental model of innovation beyond new product/service development.* The model and framework described herein are applicable to the pursuit of any type of idea, such as new concepts in engineering, science, and policy activities (even if abstract/conceptual and slightly fuzzy), in addition to the types of efforts frequently associated with design and innovation such as new product design, new business model, and new service activities. As such, this research places a conscious effort on dissolving the idea that design and innovation frameworks must be associated with products or services and are thus only applicable in these domains. The enabling innovations studied in this research encompass a broad array of new concepts, new knowledge and/or new ways to address systemic issues beyond tangible products and services.

- *Rethink risk and opportunity to exploit the true potential of enabling innovations.* The notions of risk and opportunity carry a rich history of academic study, many historically-developed meanings, and cultural norms – some of which might need to be revisited for the study and pursuit of enabling innovations. For progressive innovation initiatives, current approaches to assessing risk and opportunity are likely appropriate. Yet the characteristics of enabling innovations may require perceptions of risk and opportunity that capture all the possibilities for combination and application of a concept – even if counterintuitive. In the financial field, for example, ideas are typically evaluated using asset pricing models, which aim to balance risks and rewards. As a result, because uncertainty increases when the number of possible paths to pursue is very high, enabling concepts, if artificially tied to a single context, can be perceived as high-risk high-reward. However, for concepts with enabling innovation potential, risks are likely low relative to single-stream, high-risk high-reward endeavors, given the many possibilities of application, and opportunities for large rewards that typically come with success. As a consequence, methods to evaluate risk should consider, for instance, the cost of missed opportunities to quickly achieve results in seemingly counterintuitive spaces. Rather than using single-stream methods, the notions of risk and opportunity for this type of outcome resemble a binomial option pricing lattice/tree (common in the financial field), with multiple possibilities for success and failure, which must be discovered instead of predicted. Therefore, the risk of an enabling innovation initiative will reside more in the approach proposed to pursue it. To overcome historical notions of risk, the patterns identified in this framework instead enable (and encourage) the pursuit of grander goals/ideas in ways that make such pursuits of relatively lower risk (despite any initial high risk perceptions), by ensuring that impact is generated along learning and development paths.

- *Examine "idea spaces" with a broader lens.* An enabling innovation can rapidly diffuse across multiple domains, which creates a latent need to become aware of developments in adjacent spaces not typically examined in a given context (e.g., research, business, government, non-profit). Yet, the convergence facilitated by global interaction, connectivity and digital information, around the clock business, technological advance, and the increase in entrepreneurial minds dedicated to finding opportunities likely require one to be aware of and involved in such adjacent spaces. Promising enabling concepts (in both for profit and non profit contexts) can come out of nowhere, and individuals, organizations, and societies should likely examine idea spaces broadly and beyond vanishing disciplinary boundaries in the business, research, non-profits, and government communities.

- *Use the enabling thinking philosophy to screen for potential impact early and develop strategies to explore and exploit the full potential of such concepts*. Early decisions can have (what in chaos theory is often referred to as) "butterfly effects" on the development of innovations. Making early decisions regarding new concepts employing the patterns of thought and action identified in this research may require practitioner teams to think very differently compared to status quo approaches. Very early on in a new project/initiative, teams (and leaders in such teams) can ask questions such as "who could embrace the current levels of performance of the current state of a concept/solution?" or "what could be done if our efforts achieve different levels of performance, and who might want to use that capability in such a case?" This change in thinking might lead to many possible paths, some of which may be in stark contrast with practitioners' status quo approaches. At the onset many of these paths may have a high assumption-to-knowledge ratio, but such paths can enhance the possibility of generating a cascade of impact benefits through early trial.

- *Analyze and aim to proactively influence/re-shape key elements of ecosystems*. Even though it may appear that a single stakeholder could/should drive all efforts to achieve enabling innovation, such efforts likely require multiple stakeholders. No one single stakeholder was completely responsible for developments such as the laser, X-rays, or GPS. Even owning a piece of an enabling concept in the ecosystem(s) can yield tangible impact. Stakeholders should likely aim to understand the possible roles (even if new or counterintuitive) that they can play in an ecosystem's nodes, links, and to take advantage of windows of opportunity to play a role or influence relevant ecosystem nodes and links.

- *Reduce risk through iterative experimentation and trial.* In many domains (e.g., business, government, research, non-profit), steps can be taken to manage and mitigate risk by truly testing assumptions through experiments – and going beyond simple prototyping and piloting. Active experimentation and assumption testing can take initiatives on a path of facilitated discovery that embraces smart failure as means to de-risk initiatives, and discovery emergent ways to unfold the performance and impact of enabling innovations, rather than a path of rigid, deliberate execution that may encounter unsurpassable barriers.

- *Understand that enabling innovation is just one type of innovation and that both enabling and progressive innovations are important.* Although this research focuses on enabling innovation, progressive innovations are also important because an enabling innovation would not be considered "enabling" without a progressive cascade. Effectively, enabling innovations constitute the foundation for broad impact, and more focused progressive innovations may stem from these foundations and exploit the enabling innovation's headroom through different combinations across contexts. In addition, some challenges, irrespective of domain, may simply require progressive innovations that drive disruptive, modular, interdependent, or architectural change/novelty. Thus, stakeholders across contexts should likely aim to create a balanced collection of enabling-progressive initiatives and a thoughtful matching of problems and solutions across domains – guided by archetypal patterns of innovation. Even if this work does not explicitly provide quantitative tools to analyze and balance enabling and progressive innovation portfolios (which could be pursued) it does aim to change the conversation between stakeholders considering a new concepts/initiatives.

- *Balance innovation competencies in teams.* No single individual can likely engage in the entire array of behaviors discussed in this study, yet careful attention to all aspects of an innovation process is necessary. Consequently, leaders in organizations likely need to assemble teams with balanced innovation competencies given that some individuals will have tendencies to engage in a subset of the behaviors described herein. Overall, innovation is rarely pursued individually and the careful assembly of balanced innovation teams may influence the success or failure of an initiative.

6.5 Limitations of this Research and Opportunities for Future Work

Boyer (1990) distinguishes between four types of scholarship: the scholarship of discovery, the scholarship of integration, the scholarship of teaching, and the scholarship of application. Of these forms of scholarship, this research is positioned at the intersection of discovery and integration, because it "contributes to the stock of human knowledge" (Boyer, 1990, p. 17) while simultaneously aiming to "give meaning to isolated facts, putting them in perspective" (Boyer, 1990, p. 18) with all the benefits and limitations that such a positioning entails. The following paragraphs focus on the limitations of this work, which are discussed from the perspective of the research philosophy employed, and the choices in research methodology to make and handle data. These types of limitations are discussed for both the construction of the enabling innovation model and the enabling thinking framework. The discussion of these limitations is accompanied by corresponding opportunities for future work that address these issues, and the section concludes with opportunities for future work that are unrelated to the limitations of the study.

A pragmatist research philosophy guided this study with its inherent benefits and tradeoffs. The pragmatist school of thought rejects the notion that the function of thought is to mirror reality, and argues that what matters about an argument, is understanding for whom and under what conditions it takes for it to be true; making thought a tool for solving problems. This choice in philosophy implies that the claims in this study are abductive in nature (perhaps with the exception of the historical case analysis to develop the enabling innovation model, which could be considered inductive), and more work is required to derive claims for both the enabling innovation model and enabling thinking framework that are deductive and inductive through carefully designed future studies built from these initial models.

With this in mind, this research effort proactively sought to create a pragmatic, comprehensive perspective on the topic of "big," "significant," or "high-impact" innovation, because no such umbrella perspective exists. The conscious choice of exploring this topic broadly inherently implies a tradeoff (and a limitation of this research) in terms of the breadth vs. depth of analyses, which Schön (1995, p. 28) describes as the "dilemma of rigor or relevance." This resulted in an integrative model of "enabling" vs. "progressive" innovation, an understanding of how other innovation schools of thought fit into this model, and a perspective of the competencies to pursue it. To the best of the author's knowledge, no previous model of innovation has simultaneously examined the nature and pursuit of a given type of innovation, and this breadth of scope brought as a consequence a tradeoff in depth of analysis. Future studies, however, should study the model and framework in more depth, to drive the theoretical propositions transition from descriptive to normative stage, i.e., going from simple categorization to sets of possible statements of causality (Carlile and Christensen, 2005). The enabling innovation model and enabling thinking framework should thus be further examined in subsequent research that extends the evidence base upon which is built upon, clarifies any anomalies and/or missed contradictions, enhances the qualitative richness of the model and moves the theory/framework from a normative to a descriptive stage. For example, future work can focus on increasing the number and variety of cases examined, examining cases in more detail at each stage of the model, or examining a single case in significantly more depth. In the case of the enabling thinking framework, future work can focus on subsets or individual patterns, behaviors, or even key principles instead of focusing on creating language and categorizing an end-to-end collection of these items.

In addition, an often-debated limitation of many pragmatic, multifaceted studies is the use and interpolation of different types of methods for making and handling data to make claims. There is a possibility that mixing types of data about the past and present violate underlying assumptions that govern research norms regarding the use of a given methodological approach. This study employed and mixed different types of data, which even though as described in Chapter 3 were consciously selected to meet a strategic intent (understanding impact and understanding approach), are not often interpolated throughout the literature. In the development of the enabling innovation model, a qualitative meta/thematic analysis of secondary historical research sources was combined with scholarship of integration activities that examined select aspects of the topic of "high impact" innovation. In the development of the enabling thinking framework, the same historical research sources and a separate scholarship of integration regarding design problem solving patterns and behaviors were combined with thematic analyses of verbal protocols from a performance task. To the author's best knowledge, the choices in methods and possible biases in making and handling data were explicitly documented and consistent across the analyses conducted. (i.e., content/thematic analyses guided the making and handling of all types of data). However, the lack of carefully documented research guidelines for the multifaceted approach employed in this work might result in unconscious biases and limitations for the work such as confirmation bias (i.e., seeking to confirm the model and framework developed in this study), anchoring (i.e., relying on selective pieces of information to build model and framework), or availability bias (i.e., overestimating "available" data in memory to create model and framework).

A limitation also exists with regard to "survivor bias." This type of bias refers to the focus on case studies that "survived" in a given context and overlooking cases that did not survive. Effectively, the nine historical cases analyzed in this study are prone to this type of bias with regard to the enabling innovation model and enabling thinking framework. Future studies should address this bias by proactively searching for cases that might have employed some (or perhaps all) characteristics of the enabling innovation model and/or enabling thinking framework but failed or that were pursued in two different contexts with different outcomes, which could perhaps lead to additional relevant factors not considered in this study. For instance, one could compare the development of radar across nations or continents, or contrast the US/USSR space race or atomic bomb race, which might highlight new patterns. It perhaps should be clarified, however, that given the pragmatist research philosophy of the study, the intent of the model and framework is to serve as a thinking aid and problem-solving tool rather than as a tool for prediction. Future studies that are designed to better understand the predictive capabilities of the model and framework should address these issues.

Another possible limitation of the research is the qualitative nature of the evidence employed. Both the enabling innovation model and enabling thinking framework are based upon qualitative evidence, and the use of quantitative data (which is plausible and the basis for future work) can enhance the ideas developed herein. The choice of solely using qualitative evidence was consciously made, given the departure of the basis of the enabling innovation model (impact) from prior innovation models (novelty), and the desire to qualitatively understand the characteristics of this model. For example, the link between innovations and their impact was qualitatively explored rather than quantitatively established and future studies should create metrics to more quantitatively examine the links between innovations and their impact. Ultimately, the intent in making this choice is to open-up a space for future studies (both qualitative and quantitative) that can be built upon a more thoroughly defined construct. In addition, to avoid any subjective limitations and biases of qualitative studies, many methods call for inter-coder reliability approaches yet the author consciously decided to not employ these approaches in this study. This choice was made due to the desire to build language and a categorization scheme (a la phenomenographic studies) of innovation rather than confirm previously defined propositions. Although this is a limitation of the study, the desire to build language and an evolving concept (enabling innovation) did not seem well suited for inter-coder approaches, given the rapidly changing nature of language, assumptions and propositions involved and the exploratory rather than confirmatory nature of the study. Instead, the author relied on discussions within the research team (author, major professor, and committee members) and the research and practice communities to overcome biases, refine language, and clarify constructs.

With regard to the development of the enabling thinking framework, there is a limitation regarding the validity of the organization of the traits and the progression of levels of practice. The author underwent several iterations of the labeling and placement of the behaviors across the design process model, all of which are documented and built upon an increasing understanding of the author regarding the characteristics of the model and the behaviors to design with a specific innovation outcome in mind. This study does not claim that this set of behaviors is the only one that can lead to enabling innovation – others may exist – or that their arrangement as presented herein is the most appropriate. Just like many variations of design process models exist, many variations of enabling thinking models could be created. Yet consistent with the pragmatic philosophy of the study, the framework described here provides a first attempt at building language and at visually organized representation of designing for enabling innovations that can be used for a broad array of purposes. Thus, the enabling thinking model is herein positioned as a framework, and not a theory (although subsequent validation studies could focus on specifically studying behavior configurations to transform this framework into a theory). In summary, these issues should be explored in future empirical studies.

Also with regard to the enabling thinking framework, a limitation exists due to the lack of research on "innovation expertise" and "innovation professional practice." The topic of expertise has a rich history of academic study and comprises an array of constructs and theories. Subsets of this topic have created awareness of the unique characterizations of expertise for specific domains (e.g., design expertise, entrepreneurial expertise, scientific expertise). Yet, innovation expertise is a topic that has, to date, not yet been explored. As a consequence, the selection of participants for the performance task does not come from a broadly researched school of thought regarding the characteristics of innovation experts, and instead was the result of a strategically selected sample within the pragmatic limits of the author and research team's network. Thus, as the construct of innovation expertise evolves, future studies can help empirically validate the levels of practice, behaviors, traits, and pattern recognition abilities to provide a more complete picture of this type of expert. Adding to this limitation, being a professional, for example, involves thinking, acting, *and* being. However, the framework described herein consciously chose to focus on the thinking and acting aspects of innovating. Future work, however, should explore the qualitatively different ways of being an innovator, for example through phenomenographic studies. Studies on *being* an innovator complement the work described herein and generate a richer understanding of the distinct lenses or frames of mind that guide thought and action in stakeholders and decision-makers.

In the enabling thinking framework, another limitation is the lack of consideration/study of the role of social interactions between designers and other stakeholders. Driving an enabling innovation is seldom an individual effort yet the role that these sociologically derived interactions could play was considered outside of the scope of this study and represents a likely important avenue for future work. This potential area of future work could include studying the different roles that stakeholders can play in the development of an enabling innovation over time, and the ways by which, for instance, organizational leaders can help other stakeholders see a paradigm change. Another possibility for future work includes observing teams (instead of individuals) address a societal grand challenge, which could lead to the identification of factors related to social dynamics (e.g., special types of leadership, teamwork, or social interactions) that could be an important extension of the enabling thinking framework.

Finally, this study's attempt to develop common language could have different types of boundaries (e.g., geographic, disciplinary, industry/ecosystem) that are not identified because they are outside of the scope of the study. For example, a possible limitation is the U.S. centric nature of the study. A possibility exists that findings and derivative insights could have varied if perspectives of innovation and methodological approaches from other geographic contexts (e.g., European, Latin American) were employed. Other possible boundaries to the common language developed are disciplinary in nature, and perspectives that are, for instance, anthropological and sociological could be explored in future work. Industry/ecosystem differences are also herein not discussed and perhaps also represent an opportunity for future work.

Future research should address the aforementioned issues as well as study a broad array of opportunities that are not tied to the limitations. Opportunities exist, for example, to study ways to translate the outcomes of this study into practice (i.e., research to practice issues) with regard to teaching, learning, and professional practice. Research on psychometric instruments can assess individuals and cohorts for a broad array of purposes (e.g., curriculum and assessment, professional development, and team assembly because likely no single individual can display all of the behaviors in the framework). An opportunity also exists to explore the relationship of these behaviors to cognitive functions and other psychological constructs such as imagination. The author and his advisor's research group are currently working to address these issues (both limitations and opportunities for future work).

6.6 Summary and Conclusion

This research focused on understanding high impact innovation, herein characterized as enabling innovation, and the design and problem solving patterns and behaviors that can lead to its pursuit. Prior efforts to characterize innovation have focused on the novelty of a given concept instead of its impact, and the efforts described herein aim to address this gap. In addition, designing for models of innovation has, to date, been an unexplored construct.

Two major multifaceted workstreams were employed in this research to better understand high impact innovations and their pursuit: one that focuses on the development of the enabling innovation model, and another that focuses on the identification and organization of supporting behaviors into a framework to design for enabling innovation as an end goal. The first workstream employed a scholarship of integration approach and a thematic analysis of secondary research sources that document the history of high impact innovations. The second workstream employed a scholarship of integration approach, thematic analysis of historical cases of high impact innovation, and verbal protocol analysis of a performance task conducted with a broad population of professionals, faculty, and students dedicated to innovation endeavors.

As a result, enabling innovations are characterized, including differences from progressive innovations, and a model trajectory of their development, characteristics for their screening, and a framework to design for this innovation model are developed. This comprehensive effort to understand enabling innovation unifies many innovation concepts and is positioned at the intersection of schools of thought such as innovation, design, management, learning, and STEM.

This unique, impact-based understanding of innovation has implications for the bodies of research, teaching and learning, and practice. The model opens up many opportunity spaces for study of enabling innovations and the most appropriate pathways to its pursuit, can inform teaching and learning endeavors regarding innovation and design skills, and influence the practice of innovation across the business, non-profit, government agency, and government domains by shifting perspectives of innovation from novelty-focused to impact focused and providing guiding philosophies to more predictably drive this type of innovation.

In summary, in a world in which economic, environmental, health, and cultural challenges are becoming increasingly complex, with new “grand challenges” emerging more frequently, the pursuit of seemingly incremental ideas may be an unfathomable path to follow. Accelerated low-risk pursuit of enabling innovations – especially considering the patterns of thought and action that match the characteristics of enabling outcome – could enhance society’s chances of long-term success and prosperity. Because of this, societal actors should re-evaluate how we think about, invest in, and pursue initiatives – and truly *rethink* innovation with the end goal of driving high impact innovation on demand.

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APPENDICES

Appendix A Brief Synthesis of Select Literature related to Impact (Not Exhaustive)

Researchers/ authors (year)	**Research setting (if applicable)**	**Analysis performed**	**Findings and recommendations**	**Shortcomings and issues not considered (related to impact)**
Abernathy and Clarke (1985)	Identifies a new way to assess the "competitive significance" of an innovation	Theoretical paper that employs innovations in the automobile industry as cases	Identifies competence-enhancing innovations as those that enhance the value or applicability of a firm's competence. Also identifies competence-destroying innovations as those that diminish or render obsolete a firm's competence.	The impact effects of an innovation go beyond firm competences and/or organizational interactions
Godin and Dore (2004)	Provides a framework to assess the contributions of science to society	Reviews prior literature and highlights economic indicators that dominate the literature that discuss science's contributions to society. Develops an impact typology covering 11 dimensions. Discusses challenges for social scientists and statisticians interested in measuring the impact of science.	Identifies 11 dimensions in which science can impact society (each with corresponding subcategories): science, technology, economy, culture, society, policy, organization, health, environment, symbolic, training	Innovations are broader than science. Link between innovation and science or innovation and impact is not specific (the focus of the paper is the link between science and impact)

Researchers/ authors (year)	Research setting (if applicable)	Analysis performed	Findings and recommendations	Shortcomings and issues not considered (related to impact)
Feland et al. (2004)	Describes frameworks used in an academic program to "enable consistent innovation."	Describes frameworks employed to create and guide curricular efforts in a design/innovation program. No empirical analysis conducted.	Identify a number of design and innovation frameworks (e.g., Rogers [1962] diffusion of innovation, comprehensive design engineering, Geoffrey Moore's crossing the chasm, and product development funnels. Among the frameworks identified is an innovation impact map with three axes: quality of life impact, number of entities impacted, and impact ring.	No testing of the impact map concept using cases or data. No decomposition or detailed description/ explanation of the impact map axes. Lack of consideration of the time dimension in the perspective of impact and the evolution of innovation impact over time.
OECD (2011)	Report prepared by the OECD. The report aims to identify key topics essential to well-being (e.g., material living conditions, quality of life, education, environment, health, life satisfaction, work-life balance). Each topic is built on specific statistical indicators.	Creates a qualitative framework to measure well-being and selects indicators based on international standards of measurement: policy relevance, quality of underlying data, comparability of concepts and survey questions used, and frequency of compilation	Creates a framework for measuring well-being. Identifies a comprehensive list of themes related to well-being and indicators for the areas of: income and wealth, jobs and earnings, housing conditions, health, work-life balance, education and skills, social connections, civic engagement and governance, environmental quality, personal security, and subjective well-being.	No explicit link to innovation and the impact that innovations can have on societal well-being.

Researchers/ authors (year)	Research setting (if applicable)	Analysis performed	Findings and recommendations	Shortcomings and issues not considered (related to impact)
Christensen and van Bever (2014)	Explores the connection between slow growth in the US economy and corporate reluctance to invest in what the researchers term "market creating" innovations.	"Crowdsourced" research insights using an online platform. Examines capital availability and financial metrics.	Define three types of innovations that are related to economic growth: efficiency, performance-improving, and market-creating innovations. These types of innovations have relatively different effects on the economy.	No direct measure of innovation impact. Economic effects are only one dimension of innovation impact. Market-creating innovation do not account for markets-creating innovations (innovations that create multiple markets, such as the types of innovations that are the focus of this dissertation).
Manyika et al. (2013)	Identify the economic implications of what the author's term "disruptive technologies" (e.g, autonomous vehicles, advanced robotics, cloud technology, internet of things, energy storage)	Conducted economic analysis for a select group of promising technologies, ranging from its impact on GDP, jobs, specific economic sectors	Identify a set of implications of the aforementioned technologies for individuals, businesses, and economies/governments such as (from an economic perspective): changes in patterns of consumption, changes in quality of life, changes to the nature of work, creation of opportunities for entrepreneurs, creation of new products and services, shifts in surplus from producers to consumers, changes to organizational structures, economic growth or productivity, comparative advantage changes, employment, and regulatory challenges	The term disruptive is used in a different connotation than its academic roots. Most effects described for these technologies are economic in nature (with the exception of the broadly defined quality of life).

Appendix B Sample List of Historical Cases Screened (Not Exhaustive)

- Automobile
- Aviation/air planes
- Steam engine
- Haber-Bosch process for agriculture
- Transistor
- Computer
- Vaccines
- Printing press
- Lasers
- Steel (mass production)
- Tractors/mechanization of agriculture
- Anesthesia
- GPS
- Radar
- Laser
- Satellites
- Portland cement
- Reinforced concrete
- Highway systems
- Polymerase chain reaction
- Dynamite/explosives
- Finite element method
- Assembly line
- Insurance
- Banking
- Microfinance
- Crowdsourcing
- Cotton gin
- Glass
- Light bulb
- Electric dynamo
- Antibiotics
- Internet search algorithms
- Internal combustion engine
- Petroleum catalysis processes
- Synthetic fibers
- Surfactants
- Fluoropolymers
- Fiber optics
- Jet engine
- Gas turbines
- Hydraulic press
- Elevators
- X-rays
- CT Scan
- MRIs
- Pneumatic tires
- Hydraulic cranes
- Pasteurization
- Transformers
- Refrigeration
- Synthetic rubber
- Photography
- Atomic clocks
- Circuits
- Algorithms
- LEDs
- Computer aided design (CAD)
- C programming language
- Cell phones
- Smartphones
- Paint
- Water pumps

Appendix C Select Historical Case Summaries

Brief History of the Laser[1]

Laser is an acronym for "light amplification through stimulated emission of radiation." These light emitting devices rely on fundamental ways that radiation interacts with molecules, atoms, and electrons. A wave of electromagnetic energy of a given frequency moving through a substance with more molecules in excited states than in ground (low) energy states will pick up rather than lose energy. When light enters a device with such characteristics, it gives energy to the atoms, prepares them for stimulated emission, and a coherent beam of radiation emerges through a partially transparent mirror at one end of the device.

Conceptually/theoretically, light amplification had its origins in the work of Max Planck and Albert Einstein. The work of Einstein in the early 1900s specifically proposed that "photons could stimulate emission identical photons from [other] excited atoms" (Hecht, 2010). Experimentally, the breakthrough for the laser came from the invention of the maser (the laser's microwave predecessor, which stands for "microwave amplification by stimulated emission of radiation") by Charles Townes. The maser was developed after a series of conceptual and experimental breakthroughs based on Townes' goal of developing useful technologies from microwave spectroscopy and his constant desire to work at shorter wavelengths compared to predecessor technologies. The laser was originally conceived as an optical maser in 1957. After a multi-lab race to build the first laser, Theodore Maiman built the first laser using a synthetic ruby at the Hughes Research Laboratory in California in 1960.

In the early 1960s, many improvements to the functionality of lasers came through new inventions that advanced performance, varied laser architecture, and pursued applications in contexts that embraced the tradeoffs of the then early-stage device. For example, shortly after the demonstration of the ruby laser, IBM's Thomas J. Watson Research Center demonstrated an uranium four-stage solid state laser, followed thereafter by the first helium-neon (HeNe) continuous wave laser. Within the first five years after the first laser demonstration, commercial companies started to appear. More laser variants were demonstrated in laboratories as well, such as neodymium glass (Nd) and ytrrium aluminum garnet (YAG), gallium-arsenide, and gallium-arsenide-phosphide (GaAsP) (the basis of CD/DVD devices) lasers. Other variants continued to appear, such as CO_2 lasers (broadly used in cutting and surgery), dye lasers, chemical lasers, Nd-YAD

[1] Key sources for this brief history include:
- Townes (1999)
- Hecht (2005, 2010)
- Bromberg (1991)
- Bertolotti (2004)

lasers (used in Lasik and skin surgery), and a few years later in the early 1970's, excimer lasers, quantum well lasers (conceptually developed), and semiconductor lasers appeared.

Alternatives to continuous pulsing also appeared within five years of the first laser demonstration. Q-switching (in the 1960s), also known as "giant pulse formation," which allows the production of light pulses with extremely high (e.g., gigawatt) peak power, was demonstrated. This facilitated uses that demanded high energy, such as laser-based metal cutting. Mode-locking (in 1963) and phase-locking (in 1965), which were critical foundations for advances that were to come in telecommunications.

First commercial applications seemed to be for various forms of cutting/etching material (e.g., surgery) and measurements (e.g., lidar). Advances in communications were dependent on other, non-laser related advances, such as fiber optics in the 1970s and 1980s, and CDs/DVDs, which were not realized until the late 1970's and beyond. Similarly, barcode scanners started to be used in stores in the mid to late 1970s. Laser variants and new applications continue to be explored today. Scientific applications are now broad with uses across an array of engineering, science, and technology laboratories. Lasers are also embedded in now culturally ubiquitous devices, for example, in laser pointers for presentations. New laser-based technologies and applications continued to be discovered and invented.

Brief History of Unit Operations[2]

The concept of unit operations, common in the field of chemical engineering, and developed by American engineers Arthur D. Little and William H. Walker, emphasizes the unity and common structure among seemingly unique operations. This way of thinking about processes seems to have consolidated chemical engineering as a discipline in the early 1900's, and triggered revolutionary advances in chemicals and pharmaceuticals, and is a foundational philosophy that has been employed in many fields (e.g., chemical manufacturing, food process engineering). As such, the notion of a unit operation rapidly affected industries such as chemicals, petroleum refining, rubber, leather, coal, food-processing, sugar refining, explosives, ceramics, glass, paper, pulp, cement and metallurgy (Rosenberg, 1998).

In Arthur D. Little's words the concept involves: "Any chemical process, on whatever scale conducted, may be resolved into a coordinated series of what may be termed 'unit actions,' as pulverizing, mixing, heating, roasting, absorbing, condensing, lixiviating,

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[2] Key sources for this brief case history include:

- Rosenberg (1998)
- Little (1933)
- Flavell-While (2011)

precipitating, crystallizing, filtering, dissolving, electrolyzing, and son. The number of these basic unit operations is not very large and relatively few of them are involved in any particular process" (Little, 1933; Rosenberg, 1998; Flavell-While, 2011). In this concept, for instance, the principles to separate two liquids (e.g., alcohol from water or gasoline from diesel) are assumed to be the same as long as the separation basis is the generation of vapor of a different composition from the liquid. Therefore, these separation processes can be analyzed together as a "unit operation" (e.g., distillation in the aforementioned application).

The concept of unit of operations seems to have emerged at the Massachusetts Institute of Technology (MIT). According to Rosenberg (1998), the early history of chemical engineering dates to approximately 1898 and mostly consisted of lectures led by Lewis Mills Norton of a course titled "chemical engineering," which described the commercial manufacture of chemicals in industry. The course, however, offered little treatment of the mechanical engineering aspects of the design of large-scale process plants. The course was, for the most part, an industrial chemistry course. Consistent with this philosophy/paradigm, industrial chemists of the day were primarily concerned with carefully managing a large number of chemical products and "the sequences of steps, from beginning to end, for the production of individual products" (Rosenberg, 1998).

In 1915, the unifying concept of unit operations was presented "in a report to MIT's Corporation as support for the establishment of a School of Chemical Engineering Practice" (Rosenberg, 1998). The unit operations concept called attention to a critical few distinctive processes that seemed to underpin the seemingly unique number of chemical manufacturing activities employed across multiple industries. A. D. Little, a professor at MIT (but also an early day management consultant) looked at a large number of vertical sequences that described the manufacturing steps of individual chemical products and looked across such sequences to draw together the small number of common elements in each of them, which he then termed "unit operations/actions."

The introduction of the concept of unit of operations helped establish research priorities and a pedagogical agenda for chemical engineering as well as helped establish the first chemical engineering department at MIT. This change, however, did not happen immediately. From its inception, the concept experienced a set of evolutionary changes, including making the theoretical foundations of unit operations highly quantifiable and establishing a set of principles to analyze chemical processes. This implied that, in the early years, chemical engineers sought to more deeply understand each operation, its mathematical foundations, and the principles to reduce the cost of each process.

In the post World War II years, the discipline of chemical engineering experienced growth based on advances in the unit operations approach. The concept was applied to numerous industrial applications and eventually was reduced to specialized unit operations processes applied to areas such as fluid flow, heat transfer, mass transfer, thermodynamic, and mechanical processes.

Brief History of Crowdsourcing[3]

Crowdsourcing can be defined as the process of obtaining resources, services, ideas or content from a large number of contributors rather than from a traditional single or relatively small number of sources – and in its relatively modern form from an online community. At its most fundamental level, it involves the division of efforts/labor across a broad array of sources (people or a "crowd") to achieve a given set of objectives. These objectives range from, for instance, dividing labor for tasks such as finding ideas to problems in science (e.g., research in molecular structures, search for planets and galaxies), finding resources for an investment (e.g., fundraising from the crowd), searching for answers to common questions (e.g., question and answer websites), or even finding a missing person. This term can thus be applied to a broad array of activities and has many architectural forms.

Although the term has its modern origins in the use of the Internet to democratize approaches to different challenges, early applications of this approach date as far as the 1800's, in which the Oxford English Dictionary launched a call for volunteers to make contributions and thus identify all words in the English language with example quotations. Other early day approaches to crowdsourcing can be traced to French competitions for achievements in science and medicine known as the Montyon prizes, named after the philanthropist that endowed the fund, Jean Baptiste Antoine Auget de Montyon (e.g., making an industrial process less unhealthy, achieving technical improvements). More recently, and still in the pre-Internet era, Tim and Nina Zagat established a guide bearing their name that rated restaurants based on collections of reviews by diners. In their first survey, the Zagat's only surveyed their friends, but the rating grew to be recognized internationally.

The modern use of the term, however, dates the early to mid 2000's and since then the term is often associated to the use of the Internet to achieve a given goal by outsourcing it to the crowd. One the early uses of the web to solve a problem through the crowd was developed by the company iStockphoto, which in the early 2000's evolved from a free image-sharing group to platform for amateur photography that met the needs of people searching for stock photos. In this same decade, a major pharmaceutical company funded a startup that developed a platform to allow the global scientific community to solve R&D problems for major global corporations.

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[3] Key sources for this brief history include:

- Surowiecki (2005)
- Brabham (2013)

This problem-solving and thinking philosophy of thinking has since been applied to many additional contexts, for example, in crowdfunding platforms, and citizen science initiatives. Overall, crowdsourcing has allowed to solve problems related to (but not limited to): knowledge discovery and management in which crowds find and assemble information, employ distributed human intelligence in which crowds process or analyze information in ways that computers (of a given era) cannot easily do, broadcast information search queries that mobilize crowds in search for solutions to problems, and creative production in which organizations challenge crowds to design solutions that are subjective or dependent on public support, crowdfunding in which an organization or idea can reach financial/monetary fundraising goals through the contributions of smalls amounts from a large number of people. Ultimately, this innovation seems to stem from the change in paradigm/worldview that, across all its different variants/forms, work should be commissioned to specific group as opposed to coming from an undefined (and public) group of people (i.e., the crowd)

Brief History of Anesthesia

(See Chapter 4)

Brief History of X-Rays

(See Chapter 4)

Brief History of Microfinance

(See Appendix I)

Appendix D IRB Approval Form

PURDUE
UNIVERSITY

HUMAN RESEARCH PROTECTION PROGRAM
INSTITUTIONAL REVIEW BOARDS

To:	JOSEPH SINFIELD CIVL 1235
From:	JEANNIE DICLEMENTI, Chair Social Science IRB
Date:	02/11/2014
Committee Action:	**Approval**
IRB Action Date	02/11/2014
IRB Protocol #	1312014320
Study Title	Understanding Behaviors and Thought Processes for High-Impact Innovation
Expiration Date	02/10/2015

Following review by the Institutional Review Board (IRB), the above-referenced protocol has been approved. This approval permits you to recruit subjects up to the number indicated on the application form and to conduct the research as it is approved. The IRB-stamped and dated consent, assent, and/or information form(s) approved for this protocol are enclosed. Please make copies from these document(s) both for subjects to sign should they choose to enroll in your study and for subjects to keep for their records. Information forms should not be signed. Researchers should keep all consent/assent forms for a period no less than three (3) years following closure of the protocol.

Revisions/Amendments: If you wish to change any aspect of this study, please submit the requested changes to the IRB using the appropriate form. IRB approval must be obtained before implementing any changes unless the change is to remove an immediate hazard to subjects in which case the IRB should be immediately informed following the change.

Continuing Review: It is the Principal Investigator's responsibility to obtain continuing review and approval for this protocol prior to the expiration date noted above. Please allow sufficient time for continued review and approval. No research activity of any sort may continue beyond the expiration date. Failure to receive approval for continuation before the expiration date will result in the approval's expiration on the expiration date. Data collected following the expiration date is unapproved research and cannot be used for research purposes including reporting or publishing as research data.

Unanticipated Problems/Adverse Events: Researchers must report unanticipated problems and/or adverse events to the IRB. If the problem/adverse event is serious, or is expected but occurs with unexpected severity or frequency, or the problem/even is unanticipated, it must be reported to the IRB within 48 hours of learning of the event and a written report submitted within five (5) business days. All other problems/events should be reported at the time of Continuing Review.

We wish you good luck with your work. Please retain copy of this letter for your records.

Ernest C. Young Hall, 10th Floor - 155 S. Grant St. - West Lafayette, IN 47907-2114 - (765) 494-5942 - Fax: (765) 494-9911

PURDUE UNIVERSITY

HUMAN RESEARCH PROTECTION PROGRAM
INSTITUTIONAL REVIEW BOARDS

To:	JOSEPH SINFIELD CIVL 1235
From:	JEANNIE DICLEMENTI, Chair Social Science IRB
Date:	01/26/2015
Committee Action:	**Renewal**
IRB Action Date	01/24/2015
IRB Protocol #	1312014320
Study Title	Understanding Behaviors and Thought Processes for High-Impact Innovation
Expiration Date	01/23/2016

Following review by the Institutional Review Board (IRB), the above-referenced protocol has been approved. This approval permits you to recruit subjects up to the number indicated on the application form and to conduct the research as it is approved. The IRB-stamped and dated consent, assent, and/or information form(s) approved for this protocol are enclosed. Please make copies from these document(s) both for subjects to sign should they choose to enroll in your study and for subjects to keep for their records. Information forms should not be signed. Researchers should keep all consent/assent forms for a period no less than three (3) years following closure of the protocol.

Revisions/Amendments: If you wish to change any aspect of this study, please submit the requested changes to the IRB using the appropriate form. IRB approval must be obtained before implementing any changes unless the change is to remove an immediate hazard to subjects in which case the IRB should be immediately informed following the change.

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We wish you good luck with your work. Please retain copy of this letter for your records.

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Appendix E Select Narrative Summaries

Performance Task Participant: Don

Don started the performance task by trying to (in his own words) "trying to get some kind of rough categorization and bouncing around kind of as things come up but having a place to slot them, so I can start to see sort of what the structure will be and then likely, after I have an initial list, I'll kind of step back and see a more logical or consistent way to arrange [things]." He tried to diverge and structure on alternatives to EV use (e.g., public transportation, carpooling, cars, telecommuting) and circumstances of. EV use (e.g., urban environments, commuting, air travel).

Don then shifted to thinking about performance dimensions. His goal in doing this was (in his own words) to "map out the performance dimensions somebody would care about and then how EVs stack up with some of the alternatives that are outlined here. And see if that's a way of identifying a gap in terms of their performance tradeoffs with the competition and maybe suggesting some potential levers that could be pulled." Don then spent some thinking reflecting about this approach. He stated that a lot of thoughts were coming into his mind, which he proceeded to write down. For example, he stated that there were a lot of EVs on the market and that some have been more successful than others. He wondered if looking at the case studies/histories of these vehicles would reveal anything. But decided not to do this due to the time constraints of the study/ performance task.

Don then reverted to the performance dimensions analysis. He drew a map with categories: good enough, delightful, overshot and mapped a few performance dimensions. Some of these dimensions were fuel economy, horsepower, utility, seating, trunk, comfort, and cost. He stopped and broke down cost into lifetime cost, vehicle operating cost. He continued to list dimensions such as image, range. He then talked about customer segmentation. In particular, Don was concerned with matching a performance map to a particular customer (commuter, environmentally conscious) and type of vehicle (e.g., all electric, hybrid).

Don then synthesized his insights into the performance chart comparing vehicles. Throughout the exercise, he kept going back to the types of vehicles and customers, stating that this match between customer and type of vehicle is really important for this problem, highlighting that if you generalize this "pairing" you might "wash out" interesting details. For customer-car combination he discussed pros and cons and noticed that most drivers do not get a payback from current EVs because they don't drive enough, highlight that the big issue seems to be cost. He argued that given the timeframe for the solution (5 years), technological advances might be difficult and a key "lever" to focus on is cost while simultaneously mitigating people's concerns.

Don then mentioned some possible solutions that addressed these issues. Government sponsored effort into battery technology, government mandates (e.g., rebates). Education campaigns. Subsidies for EV batteries. Subsidies to the development of charging network. Research on high speed charging. Don then stepped back and mentioned that one of the problems with increasing EV adoption is that there is no clarity on the goal to be achieved. "Is it energy independence? Is it environmental impact?"

His recommendation for this 90-minute exercise was an overall assessment of the effectiveness of existing programs. He recommended a sequence of studies that innovation consultants typically use which would likely lead to a better answer. He would like to understand the type of impact desired, a more in depth analysis of the barriers to adoption today, including the people that do not adopt, the circumstances of use, and tangible objectives and constraints. Overall his recommendation was a structured approach for actually studying why this type of vehicle is not being adopted.

Performance Task Participant: Ken

Ken co-evolved the problem and solution throughout the performance task. He focused on understanding the constraints and dimensions of the problem in great depth/detail, to understand what possible levers he could pull in the solution space in order to enact change within the given time frame (five years). Ken proactively focused on separating circumstances of use or need (e.g., commuting versus leisure trips) to be able to imagine new vehicles that would do a better job at that particular circumstance. Effectively, he seemed to be trying to personalize driving experiences. Although he acknowledged multiple circumstances of use or need, given the time constraints of the performance task (90 minutes) he decided to focus on commuters since he assumed this group would have a greater impact on EV adoption. His choice for this self-imposed constraint was to allow himself to think more broadly about this aspect of the challenge. To do this, Ken empathized with hypothetical personas or end user profiles and envisioned hypothetical "journeys" and functional, social, and emotional objectives of these personas. His stated goal was to imagine new ways in which electric vehicles could be used (that would have an advantage) and not to only seek to replace gasoline vehicles with electric. Based on this exercise, Ken started to envision alternatives by exploring tradeoffs and making analogies to other problem-solution spaces including IT infrastructure, cloud and virtualization software services, and web browsing software. He envisioned a new, smaller type of vehicle and a new type of low operating expense, car-sharing business model that could drive EV adoption. Ken also explored the role of different stakeholders in making this model work, including end users, the government, and intermediaries, and examined how value chains would change based on this new model. He also explored the details and implications of this new model and acknowledged that 90 minutes is likely not enough time to determine whether this new model would be feasible.

Performance Task Participant: Max

Max focused on user, vehicle and system characteristics to formulate a flexible roadmap that focuses on smart failure. He started by identifying and empathizing with four hypothetical types of end user profiles: power/torque-driven, cost conscious, green and utility-focused. Similar to Ken's empathy effort, he identified needs and objectives of these profiles/ personas. Max also more concretely defined his goal, and analyzed how each of these segments could contribute to achieving such an adoption end goal, albeit while acknowledging that in reality all segments likely need to adopt EVs to have a maximum impact (although along different timelines). Then, he proceeded to analyze barriers or "inhibitors" (as he termed them), to the adoption of EVs by his primary target group: cost-conscious end users. He focused on identifying the consequences of his decisions, which revealed latent barriers to EV adoption in structured ways, as well as changes and tradeoffs that he could make to better address these barriers. For example, he acknowledged how partnerships with gas stations could address infrastructure issues if the right business model that considers all stakeholders is developed. He envisioned the simultaneous development of infrastructure and the advancement of battery technology, trying to understand how each would affect the other in systemic ways in the near and long term future. Once he outlined possible details of a business case, he expressed the need to communicate these in the right ways to stakeholders to gain buy-in through well-crafted business cases/stories and product mock-ups that nudge leaders to adopt his recommendation. Max then moved into implementation details, which focused on creating a roadmap that generationally improves his solution in three phases. He termed these phases: acquisition, enhancement, and growth, outlining key partnerships for each stage, new segments to be pursued at each phase. Max also explained how "intelligent" failure and adaptation efforts along the way would be at the center of implementation. Finally, he described the capabilities of a team that would be required to carry out these activities.

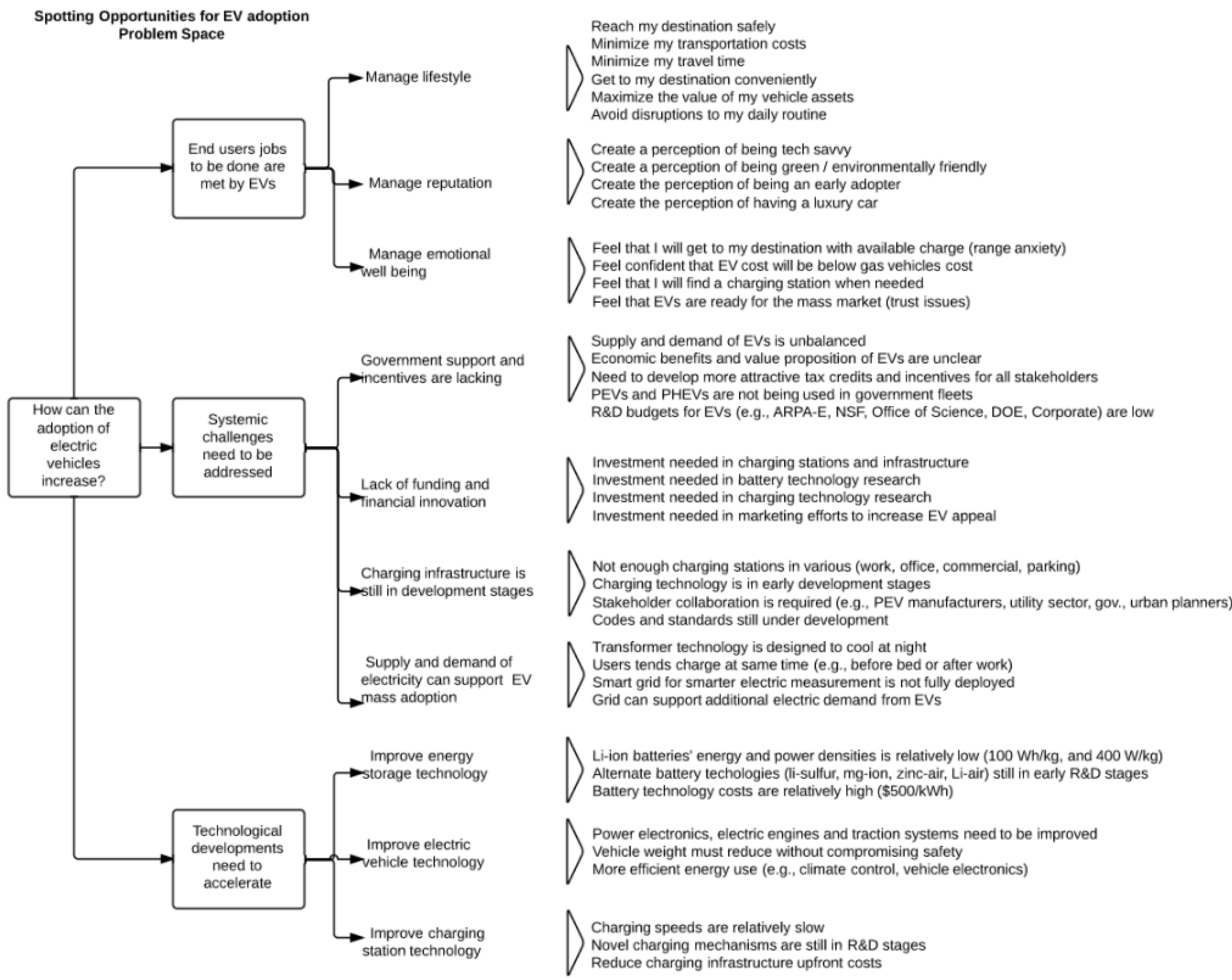
Performance Task Participant: Dan

Dan approached the design challenge at a very high level (with very little detail). His strategy consisted of transitioning from the problem to the solution space with relatively little iteration between such spaces, and no clear vision/strategy on how to tackle this "grand challenge" type of problem. Dan began the performance task by identifying challenges to the adoption of electric vehicles, which he described as: 1) price, 2) cost, 3) manufacturing and R&D, 4) transportation habits of end users, and 5) the relatively limited importance that some end users seem to give to environmental concerns. These challenges where first hypothesized and then confirmed through an online information gathering process. He then proceeded to identify relevant stakeholders: end users, the government, and manufacturers. With these considerations in mind, Dan laid out a high-level plan for three phases; namely, awareness, execution, and broad scale expansion. His plan also highlighted risks to be considered. Ultimately, his ideas remained very high-level (i.e., with very little detail) and included: government penalties, incentives, and investment in infrastructure, and manufacturer R&D investments.

Performance Task Participant: Susan

Susan started her performance task by thinking about the problem, who the stakeholders were, and listing the types of information that she would like to collect in order to come up with ideas. This list of information types revolved around the benefits and limitations of the different types of EVs and what things in electric vehicles get people excited and what they might not know about. She proceeded to get online and read about why Americans don't drive electric cars and identified concerns such as winter performance, home charging concerns and immediately jumped into an idea of a cost structure where home chargers are built into the cost of the car. Her process there onwards consisted of iterations of gathering information, reflecting upon such information and thinking how such information altered her conception of a solution space. She then discussed how chargers in worksites might be helpful and how there is need for more charging infrastructure. Susan then moved to a solution space and started acknowledging/ discussion that what is likely needed is a public campaign and increasing the number of infrastructure and charging stations available. She then started inquiring regarding charging mechanisms for different types of vehicles and whether such mechanisms are standardized. Susan went back to her initial solution and restated her "hypothesis" of how convenience and public awareness seem to be the important things that are coming up from her information gathering / research process. She then discussed range anxiety and the need to overcome it as part of her campaign. Her information search then led her to understand that EVs have fewer parts and likely require less maintenance – which she noted as another thing to highlight in her campaign. After a few more minutes searching for information she went back to the original prompt to make sure she was addressing the EV challenge/performance task. She then decided that her usual approach would be to search for information and get more informed while she reflected and synthesized ideas, but that for time purposes she would switch to generating a recommendation. Susan then started to discuss ways to increase public opinion, increase convenience, and convince people that EVs are financially viable. Her ideas included a mandate that all EVs use the same type of charging station and a government subsidy specifically for charging stations to remove the home charging station cash outlay of EV buyers. Susan then discussed the details of her public campaign and emphasized that the objective is to show that charging stations are generally available. Susan then called for more infrastructure, beyond the home chargers, for the people to perceive that the campaign is conveying accurate information. She also mentioned that if she were doing this beyond the performance task she would go out and talk to people about their perceptions of electric cars and making sure she is talking to diverse groups (e.g., renters, home owners). In her debrief she mentioned that this is her usual approach: start with a relatively vague problem, "read, read, and read," talk to people, "search for the flaws," work with a group to formulate a problem more specifically, and then try to read interdisciplinary research to draw on as many ideas to solve the problem. She mentioned that she likes to work on the fringes of what's known and come up with an inventive solution to a problem.

Appendix F Exploration of Performance Task: (a) Problem Space, and (b) Solution Space



(a)

Flawed Paradigm	Functional, Social and Emotional	Broaden Problem-Solution Spaces	Address Systems of Systems	Rethink Dimensions of Performance	Connect to Early Trial Contexts	Persuade to Facilitate Use	Discover path to success
• The top of the market is the ideal entry segment (e.g., Tesla Model S) • The bottom of the market is the ideal entry segment (e.g., Nissan Leaf) • Li-ion is the battery technology to focus efforts on • EV-fuel is the plug-in hybrid combination to focus on (e.g., use EV-fuel cell) • Private passenger vehicles should be point of entry (e.g., fleet, public transport)	• Improve batteries • Reduce prices and costs • Balance supply and and demand of EVs • Explore new, lighter weight materials • Explore inductive charging • Increase social desirability of EVs • Increase emotional desirability of EVs • Reduce safety concerns (e.g., fire) • Create technology that facilitates EV network effects (social)	• Understand other technological examples that have had adoption issues • Understand historical issues in the adoption of hybrid vehicles • Import concepts from other forms of energy storage • Import concepts from aircraft design • Import concepts from other transportation forms (e.g., electro magnetic trains) • Incorporate other energy sources in addition to fuel and electric (e.g., solar) • Improve pavement technology • Support EV startups instead of established car manufacturers • Explore car sharing options	• Invest heavily in charging stations • Invest heavily in energy storage research • Invest in smart grid research • Increase regulations on fuel-based vehicles • Increase incentives (e.g., tax, discounts) for EV adoption • Explore alternate business models (e.g., asset light models, battery swapping, vehicle swapping) • Increase parking benefits and regulations • Create EV only lanes • Address potential political issues (e.g., car manufacturer lobbying) • Enable public-private investment mechanisms and instruments for EVs • Explore partnerships with car sharing companies	• Reduce price • Increase range • Increase convenience • Increase variety (e.g., vehicle types) • Reduce charging time • Increase parking benefits • Reduce travel time • Reduce passengers per vehicle • Increase passengers per vehicle • Change materials • Enable Car sharing	• Trial new technology in aircrafts, bicycles, or motorcycles • Trial novel technology in generic energy storage applications (e.g., backup power plants) • Trial new technology in developing countries • Trial new technology in consumer electronics	• Create marketing campaigns to create awareness • Create marketing campaigns to facilitate consideration • Create marketing campaigns that motivate purchase • Create marketing campaigns to reduce range anxiety • Facilitate network effects for EVs • Raise a sense of urgency for the reduction of CO_2 emissions	• Test and learn in select markets (e.g., large cities) • Test and learn in emerging markets (e.g., China, India, Brazil) • Conduct small scale policy experiments • Conduct small scale grid capacity experiments • Conduct small scale startup experiments (e.g., Zip Cars business model)

(b)

Note on Appendix F: These problem-solution explorations by the author were conducted prior to observing participant performance tasks and concurrent with the development of early stage versions of the enabling thinking framework

Appendix G Cross Behavior Synthesis and Hypothesized Key Behavior Principles

Pattern	Behavior	Definition	Unique link to enabling innovation	Hypothesized principles
Frame the flaw in the paradigm	Structure ambiguity	Providing logic to ambiguous, complex, and ill-structured problem and solution spaces	Enabling innovations often participate in multiple complex systems with a relatively high number of nodes and links that are ill-defined (which eventually translate to reach and impact), and structured perspectives of ambiguity can help one provide logic to ill-defined paradigms	• Break ambiguity into unknowns and knowledge gaps • Assess uncertainty and significance of knowledge gaps • Provide a tree structure to knowledge gaps by asking "why" or "how" • Diverge, structure, and converge exploring issues at varying levels of depth • Iterate between inductive and deductive approaches to structuring • Ensure that structure is mutually exclusive and collectively exhausted
	Question the paradigm	Asking "why" and "what if" questions that reveal a paradigm's hidden assumptions	Many schools of thought call for asking root-cause questions to innovate, but few (to the author's best knowledge) explicitly focus on questioning fundamental paradigm assumptions when high-impact is a desired result	• Ask technical, economic systems, and socio-emotional 'what if' and 'why' questions • Differentiate between negotiable norms and non-negotiable rules • Probe to uncover second and third order effects • Differentiate answers that satisfice from those that merit further exploration • Understand when it is important to probe further and be willing to act on learning
	Spot opportunities in flaws	Recognizing opportunities in flawed yet latent assumptions that underpin paradigms	While the notion of opportunity is common entrepreneurial contexts, finding opportunities to innovate with enabling impact (reach, significance, paradigm change) by searching for hidden paradigm flaws is unique	• Separate mental framing from accepted practice • Separate problems from solutions • Break problems and solutions into components and attributes • Assess rationale for links between problems and current solutions • Identify what is done by cultural norm rather than by absolute necessity • Zoom-in on flawed norms and proactive consider different perspectives

Pattern	Behavior	Definition	Unique link to enabling innovation	Hypothesized principles
See all technical, economic, systemic, sociological, and psychological forces	Observe diverse circumstances proactively	Engaging in constant observation across diverse circumstances to inform and observe hypotheses	Observing diverse circumstances can help one gain exposure to a more comprehensive set of issues that could affect innovation efforts	• Develop a basic awareness of things to look for • Create an inventory of relevant contexts and circumstances to observe • Prioritize key circumstances to be observed according to the end goal • Recognize elements of each circumstance, context, or situation • Become aware of in-going biases
	Notice forces at play	Perceiving proactively all possible significant influences in a given situation based on hypotheses, prior experiences, frameworks, changes, or unanticipated patterns	Noticing tacit or unexpected forces related to enabling innovations often requires some degree of perceptual sensitivity to identify any factors that might play a role in the success of an innovation	• Consider technical, economic, systems, social and emotional forces • Diverge, structure, and converge on the forces to monitor • Create a working hypotheses that accounts for all forces at play • Establish most likely conditions to be encountered in a circumstance • Monitor and focus on unanticipated signals that deviate from most likely conditions • Reflect to uncover second and third order effects of findings on hypotheses
	Create empathy-based mental models	Creating mental models that account for the behavior of technical, economic, systems, sociological, or psychological phenomena from self, other, cognitive, or affective immersive experiences	Mental models that are empathy-based can unearth forces that will likely be ignored without interactions and exploration of such models	• Map actors, objectives and circumstances • Identify techno-economic, systemic, and socio-emotional interactions, tensions and barriers • Create an empathy-based mental model of linkages and root causes of tensions and barriers • Assess if linkages and root causes are rules, norms or assumptions to search for hidden insights • Play with the mental model to unfold second or third order effects that lead to new insights • Identify any in-going biases that may have informed the mental model

Pattern	Behavior	Definition	Unique link to enabling innovation	Hypothesized principles
Broaden idea spaces by connecting generalized first-principles	Interact with new schools of thought	Obtaining and testing ideas through many types of interactions across counterintuitive contexts or at the intersection of fields	Critical insights for enabling innovations may likely stem from contexts not originally considered as relevant to an enabler thus calling for proactive interactions across an expansive set of contexts and through distinct channels (e.g., social/verbal, written)	• Translate domain specific ideas into generic language • Seek different perspectives by breaking from usual social network • Push ideas across many contexts as a testing mechanism • Pull ideas from exposure to non traditional environments • Suspend judgment, reflect, and engage in objective dialogue • Synthesize learning from networking exercises
	Link core ideas to diverse problem and solution spaces	Finding cause-effect patterns in problem and solution spaces by noticing trends that are seemingly unconnected	Ideas with enabling innovation potential are likely transferable across multiple diverse problem and solution spaces as generalized first principles	• Decompose problems and solutions and identify core components in target contexts • Find the first principles underlying core problems and solutions • Separate problem from circumstance using generalized descriptions • Identify source ideas to connect in analogical, opposite, intersectional, and adjacent domains • Identify aspects of solutions in source contexts that transfer to target context • Decide if a solution or aspects of it are applicable, translate, and adapt
	Explore morphological combinations	Exploring all possible idea variants that result from combinations in the identified features/ aspects of problem and solution spaces	Enabling innovations are inherently combinatorial and complementary to other ideas and a broader examination of morphological possibilities (including broader systems issues) can amplify a concept's cascade potential	• Break down a concept into its core components and attributes • Diverge, structure, and converge possibilities for each component • Create a comprehensive, systemic view of all combinatorial possibilities • Understand the morphological possibilities that are within a set of established goals and bounds • Link and explore all combinatorial possibilities even if counterintuitive

Pattern	Behavior	Definition	Unique link to enabling innovation	Hypothesized principles
Addressing host ecosystems holistically	Map ecosystem elements	Mapping system elements to understand its interactions at different levels of analysis	Barriers and opportunities for enabling innovation often stem from interactions with select ecosystem components	• Decompose a challenge into its systemic components • Identify system components, linkages, stakeholders, and boundaries • Employ a representation method that matches the needs of the challenge • Consider links to other ecosystems • Request input from key stakeholders that enhances system understanding
	Model future ecosystem states	Understanding future possible ecosystem scenarios and the implications of such scenarios for present-day innovation efforts	The introduction of a potential enabling innovation will likely drive ecosystem changes and thus anticipating such changes can help embed elements into a solution that address future barriers and/or needs	• Identify future scenarios and parameters to be modeled • Create models of future ecosystems scenarios consider the influence of prior states • Assess technical, economic, sociological, and psychological implications • Alter parameters, change assumptions, and explore second and third order effects • Derive the implications of future ecosystem states for present day efforts
	Reconfigure ecosystem nodes, links, and exchanges	Designing solution components that have potential to influence the configuration of ecosystem components/ nodes and links	An enabling innovation that proactively embeds aspects in a solution that employ system nodes and links as levers can enhance its impact	• Map possible components and links that can be reconfigured across ecosystems • Identify possible modifications: separations, combinations, relocations, additions and subtractions • Employ multiple lenses to understand the implications of ecosystem reconfigurations • Attempt to understand systemic emergent behaviors

Pattern	Behavior	Definition	Unique link to enabling innovation	Hypothesized principles
	Porpoise	Knowing when first, second, and third order effects are important	Alternating between first principles and system perspectives can help identify logic gaps in shaping an enabling innovation	• Explore components using an intuitive understanding of them • Zoom into components and explore implications at the next level of analysis • Explore subsequent levels of depth until returns diminish • Drill down to a an actionable level of detail • Analyze implications of in-depth analysis at the systems level • Alternate between "deep dives" and systemic perspectives •
Rethink performance and connect to early impact contexts	Identify dimensions of performance and headroom	Creating a mutually exclusive and collectively exhaustive perspective of technical, economic, psychological, an sociological dimensions of performance	Enabling innovations can be characterized using a set of evolving performance dimensions and an indication of headroom for performance improvement	• Decompose a challenge into key performance dimensions • Identify performance dimensions of current state of solution • Employ technical, economic, systems, social, and emotional dimensions of performance • Describe performance dimensions using generic language for use across contexts • For each dimension, assess its headroom for change in the future • Prioritize dimensions of performance to be advanced based on enabling window goals

Pattern	Behavior	Definition	Unique link to enabling innovation	Hypothesized principles
	Characterize application contexts	Creating a perspective of the reach, significance, and paradigm change that can be pursued and the performance requirements in a given context	Enabling innovations often participate in multiple ecosystems and application contexts within ecosystems, which should be understood when introducing a solution	• Diverge, structure, and converge on an list of contexts in which a solution could play a role • Break down each context or impact space into its key components • Consider contexts outside historical norms proactively • Identify the performance dimensions and profile of commonly employed solutions • Identify the reach, areas of significance, and paradigm change required to play a role in such a context • Prioritize impact contexts according to performance development and impact benefit potential
	Map accepted and counterintuitive tradeoff combinations	Evaluating possible variations in dimensions of performance in an idea, even those that might be considered counterintuitive	Enabling innovations often need to reconfigure their tradeoffs/capabilities in the path toward achieving a "base" set of capabilities which facilitate an impact cascade and paradigm change.	• Identify all possible tradeoff combinations in a solution • Search for dimensions of performance overlooked in a working paradigm that are relevant to a new paradigm • Define what excellent and acceptable mean in new and working paradigm • Lower performance in unimportant new paradigm dimensions to "acceptable" • Increase performance in dimensions that stem from the emerging paradigm • Search for misalignment between capabilities and contexts that may be stifling progress

Pattern	Behavior	Definition	Unique link to enabling innovation	Hypothesized principles
	Match lily pad contexts with tradeoffs and headroom	Connecting solution to contexts that embrace a given set of tradeoffs, even if outside of traditional expectations/ boundaries, to accelerate impact	Stepping stones to a grander goal can be pursued in lily pad contexts that embrace the current state of a given solution, generate early impact, advance select performance dimensions, retain interest, and help unfold a new paradigm	• Remove artificial ties to contexts via generalized language to make matches • Ask "for whom is my concept good enough or adequate"? • Identify contexts that might embrace the current tradeoffs of a solution • Identify the "lily pad" benefits an evolving concept would gain from a context • Link performance tradeoffs in solutions with possible contexts of application
Persuade to facilitate acceptance or use	Tell stories that paint a vision	Communicating persuasively to build buy-in for ideas	Enabling innovations drive a change in paradigm and storytelling techniques can persuade paradigm adoption	• Identify audience and key influences • Structure story according to goal and circumstance • Create contrasts and turning points to highlight key insights • Balance logic, emotions and knowledge • Integrate story with a resolution and vision
	Convey counterintuitive insights	Conveying ideas that deviate from those typically encountered in a given context in tailored/ perceptive ways	Enabling innovations challenge a working paradigm which may trigger resistance from advocates of such a working paradigm	• Identify knowledge to be organized and emotions to be managed in audiences • Identify conflicts and tensions between the status quo and insights to be conveyed • Select a delivery vehicle: abstract ideas, active testing, concrete experiences, or reflective observations • Facilitate a process to help stakeholders unearth their hidden assumptions

Pattern	Behavior	Definition	Unique link to enabling innovation	Hypothesized principles
	Drive habit conversion	Influencing/nudging decisions through the presentation of choices	The paradigm change that accompanies enabling innovation often involves transitions in habits and/or cultural norms	• Map out the habits implicit in a given paradigm • Decompose habits into cues, routines, and rewards • Assess possibilities for causal linkages between cues, routines, and rewards • Identify target routines, experiment with rewards, and isolate possible cues • Nudge people through the presentation of choices
	Create win-win partnerships	Building relationships with ecosystem stakeholders that can influence the success of an idea	Enabling innovations often involve ecosystem level changes, which are unlikely to be achieved by a single stakeholder	• Identify ecosystem areas in which partnerships would be beneficial • Identify ecosystem players and their desired outcomes in relevant areas • Create a network perspective of relevant stakeholders • Contrast desired outcomes of relevant stakeholders in matrices • Identify possibilities for win-win partnerships • Create a business case for desired partners & seek to build relationships
Create an emergent strategy to unfold performance and impact	Envision multiple impact pathways	Mapping many possible pathways to idea success given the uncertainty that is inherent in ideas with enabling potential	Because of the new paradigm and the novelty in a breakthrough idea, multiple possible paths to generate impact exist compared to the possible paths in progressive innovation in which a paradigm is already established	• Diverge, structure, and converge possible paths for each concept and context of pursuit • Evaluate each path on a set of predetermined metrics using multiple lenses • Prioritize paths according to end goal, metrics, and position in impact curve • Create and balance a portfolio of implementation possibilities

Pattern	Behavior	Definition	Unique link to enabling innovation	Hypothesized principles
	Identify assumptions and learning metrics	Linking a set of assumptions inherent in an idea to a set of metrics that can be used to track the conversion of assumptions into knowledge	A new paradigm is accompanied by many assumptions that need to be explicitly documented and translated into a set of metrics that can help one track progress in driving a paradigm change	• Decompose an implementation path into learning gaps and failure mechanisms • Ensure assumption list includes technical, systemic, economic, and socio-emotional • Diverge, structure, and assess the relationship of assumptions to candidate learning metrics • Define key metrics that could be used to test failure mechanisms • Assess the severity of assumptions and failure mechanisms
	Create learning experiments	Creating a set of experiments that can be used to learn more about an idea and convert its assumptions into knowledge	The uncertainty that stems from a new paradigm and fundamental breakthroughs should be managed through learning experiments designed to help one navigate a paradigm change	• Employ visions of impact pathways and learning metrics • Assess the need for targeted or comprehensive experiments for each key assumption and metric • Devise a series of low-intensity tests that minimize the impact of failure • Define parameters that will determine whether a test is positive, inconclusive, or negative • Outline assumptions, metrics, hypotheses, resources, and parameters for each experiment • Prioritize tests based on impact, ease of testing and uncertainty of failure mechanisms
Deploy an emergent strategy to discover the enabling path	Select impact paths based on impact potential	Choosing between paths to pursue based on learning potential *and* potential to achieve/earn impact	The pursuit of enabling innovation, if employing a "lily pads" approach, should be based on application efforts to earn *and* learn (as opposed to just "investing to test and learn" in a moonshot approach)	• Prioritize paths according to the enabling innovation goal • Assess learning potential across possible paths • Assess "earning" potential across possible paths • Select paths that generate trial, learning, and "earnings" for continued development

Pattern	Behavior	Definition	Unique link to enabling innovation	Hypothesized principles
	Experiment for smart failure	Pursuing first-hand iterative learning via active experimentation	Historical enabling innovations have inherently encountered failures along the way that were eventually overcome and proactive design of enabling innovation should aim to proactively accommodate such failures in small low-risk ways that minimize consequences	• Run tests in series based on prioritization criteria • Re-adjust experimentation efforts as needed • Explicitly document learning insights after each testing stage • Re-prioritize and re-direct experimentation efforts after each learning insight
	Leverage unintended consequences	Capitalizing on unexpected occurrences that highlight new paths, goals, or ideas	Many historical innovation cases took advantage of unexpected deviations along their development paths which represents an opportunity to proactively document and capture opportunities that develop along the enabling window	• Examine the results of smart failure experiments • Uncover second and third order effects from the results of experiments • Distill learning insights from contextual influences • Search for opportunities to leverage learning in other tests or contexts • Embed unintended findings in the pursuit of subsequent learning goals
	Differentiate when to stop from when to persist through failure	Assessing whether efforts for a given concept should continue or halt	Many historical enabling innovation cases encountered multiple failures along the way, and eventually found success due to the commitment to an overarching goal	• Assess upside potential relative to halting efforts • Persist when obstacles are encountered and find lessons in setbacks • Learn from feedback and criticism • Acknowledge the difficulty and resistance to paradigm and culture changes • Assess the need for additional cascading sponsorship, talent, or resources

Pattern	Behavior	Definition	Unique link to enabling innovation	Hypothesized principles
	Adapt based on learning	Re-directing efforts from insights gained through emergent strategies	At a fundamental level, enabling innovations constitute a learning exercise in which assumptions about a promising concept are gradually transformed into knowledge, and such knowledge represents an opportunity to adapt implementation efforts in the enabling window	• Synthesize learning insights from experiments to date • Assess whether experimentation efforts should be continued, re-directed, halted, or re-designed • Set periodic checkpoints to compare upside potential with continuation cost at the portfolio level • Allow the path to success to unfold from the results of experiments and learning opportunities

Appendix H A Step-Change in Geoenvironmental Sensing Case Study

May 10, 2012

PURDUE
ENGINEERING

A Step-Change in Geoenvironmental Sensing – Part A

In Fall 2009, Michael Connery, an assistant professor of environmental engineering at Purdue University, and his graduate students were attempting to identify potential sources of funding to continue research on a portable geoenvironmental sensor. In the long-term, Prof. Connery envisioned a system of geoenvironmental sensors that was capable of quantifying environmental contaminants in-situ, with portable sensors of a relatively low cost. Geoenvironmental monitoring technologies, however, seemed to be heading in the opposite direction. Current systems (e.g., gas chromatography – mass spectroscopy, geophysical methods, remote sensing, and mobile probes) tended to have relatively high cost, high speed, high power, low portability, required extensive sample preparation time, and in certain circumstances destroyed the sample. Dr. Connery considered that a step-change in geoenvironmental monitoring research was needed. Despite his vision, Dr. Connery was undecided regarding both the development roadmap for his sensing system (in terms of potential contexts of application) and the technological tradeoffs that should be made during the first steps of research on his Raman spectroscopy based technology.

Introduction to Raman spectroscopy[1]

Raman spectroscopy is a non-invasive analytical chemistry technique with a broad array of applications in both research and industrial settings for the analysis of solids, liquids and gases. The technique provides information for the identification of molecular bonds that is analogous to a fingerprint. This highly chemical specific technique, quickly (i.e., in minutes) and with little to no sample preparation, provides rich and accurate insight into the chemical composition of a sample in a non destructive manner. In this technique, a monochromatic light source (e.g., a laser) is directed towards a test specimen with the aim of observing photon-molecule collisions, which take place on a time scale on the order of 10^{-12} seconds. The energy transferred in the photon-molecule collisions corresponds to the vibrational and rotational energy states of the target molecule bonds, and provides insight into the molecular structure of the specimen. The spectrum of scattered light (called the Raman spectrum) is specific to molecule bonds, and facilitates detection, identification and quantification in chemical analyses (see Exhibit 1 for a graphical representation of a Raman system and the Raman phenomenon).

[1] Part A of this case study is primarily based on the following sources: 1) Sinfield, J. V., Colic, O., Fagerman, D., and Monwuba, C. (2001). "A low cost time-resolved Raman spectroscopic sensing system enabling fluorescence rejection." *Applied Spectroscopy*, 64(2), 201 – 210; and 2) Williams, T., and Collette, T. (2001). "Environmental applications of Raman spectroscopy to aqueous systems." *Handbook of Raman Spectroscopy*. Chapter 17. Taylor Francis group

Freddy Solis, Chike Monwuba and Professor Joseph V. Sinfield prepared this case with the sole purpose of class discussion.

Anatomy of a spectrometer

A Raman spectroscopic system typically consists of components designed to perform the following functions (see Exhibit 2): 1) illumination of a specimen with a light source (generally a laser); 2) collection of scattered light; 3) spectral separation of collected light into various wavelengths using a monochromator; 4) light detection with either a charge-coupled device (CCD) or a photon multiplier tube (PMT); and 5) signal acquisition in which Raman scattered frequencies are compared to a library of known molecule frequencies in order to determine the composition of the tested substance. These five core functions must be tailored according to the nature of the target specimen (e.g., solid vs. liquid) and the measurement context (e.g., in situ vs. in laboratory).

Fluorescence Challenges in Raman Spectroscopy

Despite the merits of Raman spectroscopy, its use in several contexts (e.g., biology, agriculture) has been limited because Raman scattering is often obscured by a phenomenon called fluorescence. When a light source is directed towards a sample, the Raman scattering phenomena is typically followed by the release of fluorescence photons, which obscure the observation of shifts in photon scattered frequencies (see Exhibit 3). Because Raman is virtually instantaneous, Raman scattered photons can only exist during a laser pulse (with a few exceptions). In contrast, fluorescence involves the absorption of a photon by atoms within the molecular structure of target compounds, followed by the subsequent emission of lower energy fluorescence photons as atoms at an excited electronic energy state transition back to a ground state. This implies that a finite amount of time must transpire between the incidence and absorption of the excitation photons due to Raman and the emission of fluorescence photons, providing the potential to separate the two phenomena in time.

Trends in Raman spectroscopy

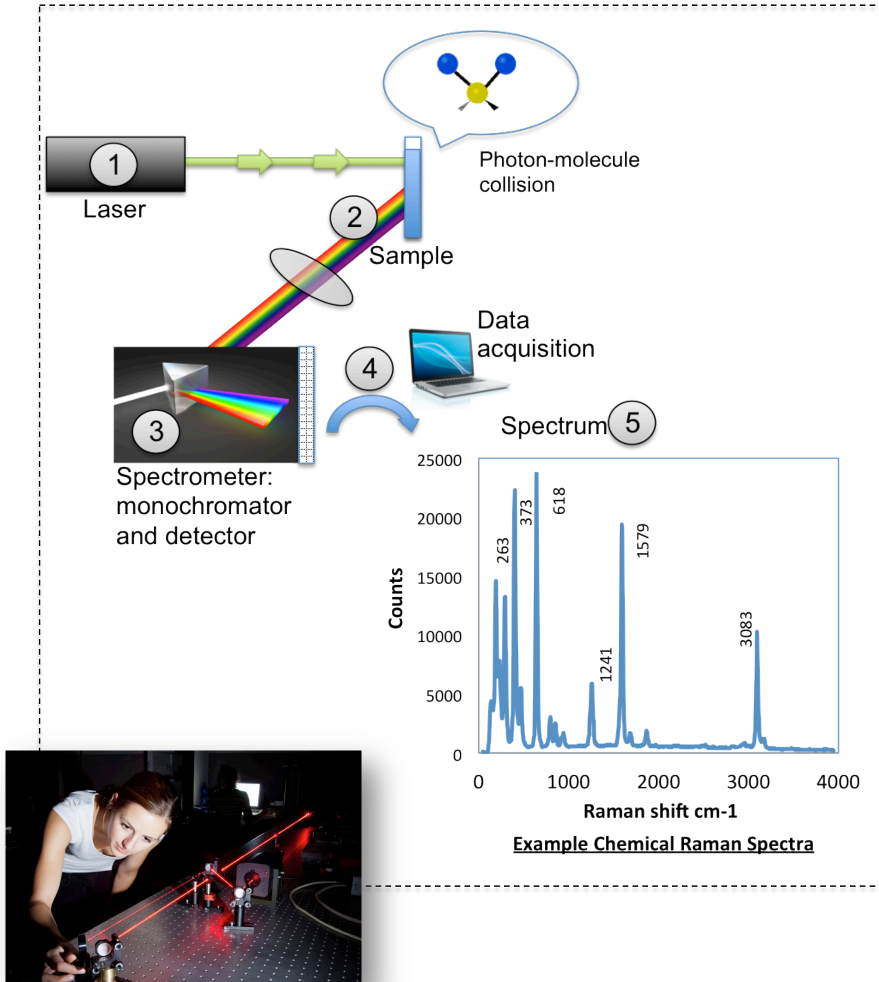
Historically, the technological trajectory of Raman spectroscopy systems has involved sustaining improvement – i.e., technological advances have aimed at improving the five core aforementioned functions of a Raman system in a mode of continuous improvement. For example, illumination intensity in spectroscopy systems has been enhanced over time to improve signal strength through the use of lasers with higher average power. Continuous wave lasers (CW) in the near/mid-infrared range have been the technology of preference to limit interference from fluorescence although at the expense of reduced sensitivity. Spectrometers have either evolved to enhance spectral resolution (i.e., to decompose light into a high resolution full spectrum) or have incorporated sophisticated fast Fourier transform capabilities (FFT) to turn raw data into rich spectra and better manage interference. Light detectors have incorporated full spectrum detection with CCD cameras, which increase the overall speed of the system (compared to the slower PMT) by enabling simultaneous collection of light at different wavelengths. Data acquisition evolved towards continuous integration and/or the incorporation of FFT signal deconvolution. These trends tended to make Raman spectroscopy systems expensive, lab-bound (non-portable), and complex.

Case Questions: Understanding opportunities for tradeoffs in Raman spectroscopy

While the technological improvements in Raman-based systems seemed like a natural progression for in-laboratory chemical analyses, Dr. Connery wanted to break the paradigm and explore moving in a different direction by focusing on the development of a portable Raman-based geoenvironmental sensing system.

1) What might be some opportunities for tradeoffs lie within Raman spectroscopy systems?
2) Where (in what situations) could advantages be leveraged but drawbacks/tradeoffs be valuable?

Exhibit 1[2] Graphical Representation of a Raman-based System

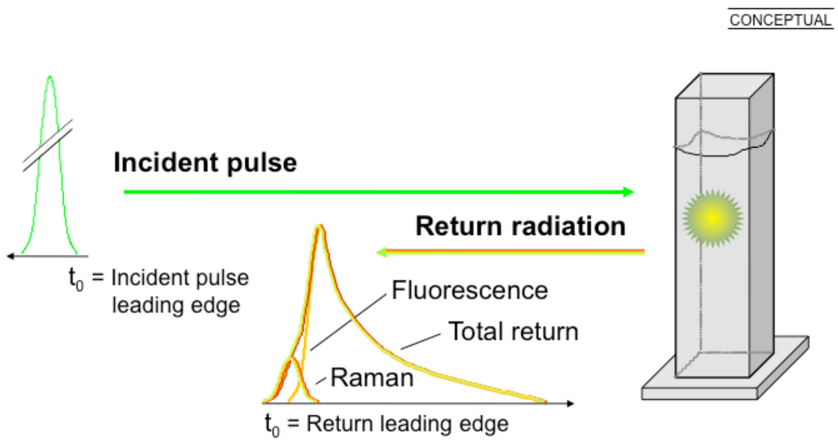


[2] Monwuba, C. and Sinfield, J.V. (2012). The effect of turbidity on Raman spectroscopic analysis of aqueous chlorinated samples. Presentation at 2012 Geo-Congress: State of the Art and Practice in Geotechnical Engineering. Oakland, CA.

Exhibit 2[3] Fundamental Raman System Components

[3] Source: Sinfield, J.V. (2010). A disruptive path to the development of a fieldable Raman spectrometer for Geoenvironmental sensing. Presentation to MIT. Boston, MA.

Exhibit 3[4] Graphical Representations of Raman and Fluorescence



[4] Source: Sinfield, J.V. (2010). A disruptive path to the development of a fieldable Raman spectrometer for Geoenvironmental sensing. Presentation to MIT. Boston, MA.

May 10, 2012

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A Step-Change in Geoenvironmental Sensing – Part B[1]

After deciding that his Raman-based geoenvironmental sensing system should tradeoff speed and resolution for size/portability and affordability, Professor Connery was attempting to define the capabilities of his technology. He knew that it was necessary to go beyond expected applications. Therefore, he wanted to explore Raman spectroscopy beyond his traditional geoenvironmental research context. He asked himself: "What role/function can this technology perform? Does it enable a new activity? Who would need/use it for this role/function?"

Dr. Connery reflected on the fundamentals of the technique: "Raman spectroscopy is an analytical technique commonly used in chemistry, as well as in a broad array of research and industrial settings for the analysis of gases, liquids and solids. The technique provides information for the identification of bonds and molecules that is analogous to a fingerprint, since vibration and rotational energy states are highly specific to chemical bonds and molecule symmetry. This chemical specific technique, quickly (i.e., in minutes) and with little to no preparation, provides rich and accurate insight into the chemical composition of a sample without destroying it. In solid-state physics, Raman spectroscopy is used to characterize materials, measure temperature, and find the crystallographic orientation of a sample. In medicine, Raman gas analyzers are used for real-time monitoring of anesthetic and respiratory gas mixtures during surgery. In historical research, Raman has been used to investigate the chemical composition of historical documents."

Case Questions

Professor Connery began to reflect on the capabilities of Raman systems at a generalized level. He wondered if he could find language that was generic enough to be understood across contexts yet specific enough to describe the capabilities of Raman. Specifically, he asked himself:

1) What are the actions/results that can be achieved with Raman spectroscopy? (Think in terms of verbs that describe what the technology enables a researcher to do.)
2) What are the objectives that can be achieved with Raman spectroscopy? (Try to qualify the verbs in identified in question 1) with appropriate adverbs/adjectives.)

[1] Part B of this case study is based on the following sources: 1) Sinfield, J. V., Colic, O., Fagerman, D., and Monwuba, C. (2001). "A low cost time-resolved Raman spectroscopic sensing system enabling fluorescence rejection." *Applied Spectroscopy*, 64(2), 201 – 210; and 2) Sinfield, J. V. (2005). "A structured approach to technology assessment." *Strategy and Innovation*, 3(5), 10-13.

May 10, 2012

A Step-Change in Geoenvironmental Sensing – Part C[1]

After reflecting on the capabilities of Raman spectroscopy, Dr. Connery stopped to think about the challenges that lied ahead for his research team. Even though Raman spectroscopy had the potential to *detect*, *identify* and *quantify* a broad array of chemical compounds, he still needed to decide on potential sources of funding for his geoenvironmental sensor. The prototype in his laboratory was (to date) only capable of detecting high concentrations of chemicals. The research funds that Dr. Connery was pursuing would serve to enable the technology to be able to identify and quantify chemical compounds with great sensitivity, with the ultimate goal of applying the technology for portable geoenvironmental sensing to monitor contaminants (see Exhibit 1).

Analogous to his experiences in industry, Prof. Connery was fully aware that the development of his sensor technology would not follow a linear path. He acknowledged that to develop the sensor he might need to pursue the initial development steps in contexts other than geoenvironmental applications, as every technology has a specific roadmap/trajectory that bridges various contexts of application. Furthermore, he was aware that limitations in one context might be perceived as benefits in another.

Professor Connery brainstormed with his graduate student team potential contexts of application. The discussion with his graduate students on the recent literature on Raman spectroscopy across a variety of fields pinpointed that despite its merits, the technique had been of limited use in contexts such as environmental analyses, biology/biochemistry, petroleum, homeland security, and defense, as well as in agriculture and food science. In contrast, the technique has been broadly employed in pharmaceuticals and manufacturing.

Case Questions

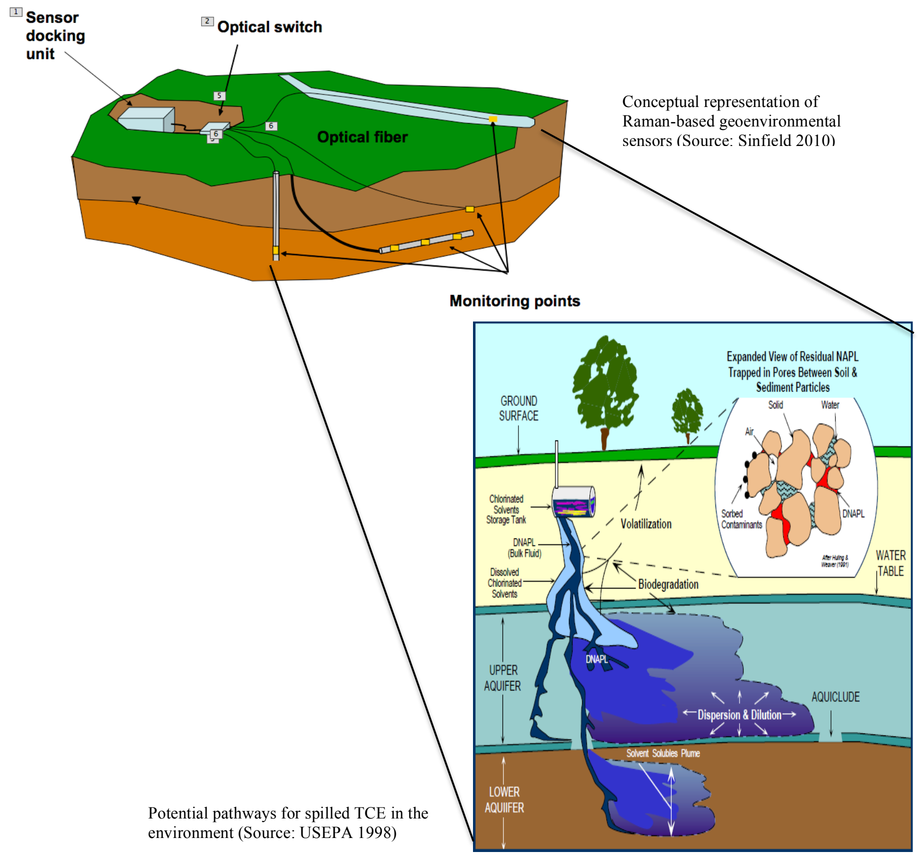
After identifying potential contexts of application, Dr. Connery began to identify potential end-users who might be interested in the roles/functions of the technology given its capabilities, objectives, and limitations in specific circumstances. Specifically, he asked himself:

1) What are potential uses of the technology in each of the contexts identified?
2) Who might embrace both the benefits and limitations of the current technology? Who needs to identify chemicals using a portable device yet only in relatively high concentrations? (Remember to think beyond narrow industry definitions.)

[1] Part C of this case study is based on the following sources: 1) Sinfield, J. V., Colic, O., Fagerman, D., and Monwuba, C. (2001). "A low cost time-resolved Raman spectroscopic sensing system enabling fluorescence rejection." *Applied Spectroscopy*, 64(2), 201 – 210; and 2) Sinfield, J. V. (2005). "A structured approach to technology assessment." *Strategy and Innovation*, 3(5), 10-13.

Freddy Solis, Chike Monwuba and Professor Joseph V. Sinfield prepared this case with the sole purpose of class discussion. Cases are not intended to serve as endorsements, sources of primary data, or illustrations of effective or ineffective approaches to engineering or management. All names and situations in this case are fictitious.

Exhibit 1[2] Vision for a Geoenvironmental Sensing System



Conceptual representation of Raman-based geoenvironmental sensors (Source: Sinfield 2010)

Potential pathways for spilled TCE in the environment (Source: USEPA 1998)

[2] Sources: 1) Sinfield, J.V. (2010). A disruptive path to the development of a fieldable Raman spectrometer for Geoenvironmental sensing. Presentation to MIT. Boston, MA; and 2) Monwuba, C. and Sinfield, J.V. (2012). The effect of turbidity on Raman spectroscopic analysis of aqueous chlorinated samples. Presentation at the 2012 Geo-Congress: State of the Art and Practice in Geotechnical Engineering. Oakland, CA.

Appendix I Sample Enabling Thinking Assessment Instrument Questions

Likert Scale Format (Not Exhaustive and Not Categorized)

- I often categorize lists of issues when planning work
- When solving problems, I often spend the majority of my time formulating procedures**
- In my projects, I tend to employ established procedures to ensure delivery of quality work**
- When solving problems, I often spend the majority of my time searching for assumptions
- I often aim to understand if the assumptions underlying my methods apply to a problem
- After generating multiple ideas, my immediate next step is typically to organize them
- After generating multiple ideas, my immediate next step is typically to select the most appropriate**
- I often communicate an argument using facts or results**
- I often communicate an argument using stories
- I often think of other fields to which my solution can be applied
- I often think of different ways in which a solution can be applied within my field
- I tend to apply solutions only to my field since my qualifications are for such a field
- I consider that imperfect solutions in one field might be perfect in another field
- I tend to do small experiments before reaching a verdict regarding a design's validity
- I prefer to simultaneously test as many assumptions as possible**

**Indicates a reverse coded question

Appendix J Microfinance as an Innovation Case Study

January 23, 2015

PURDUE
ENGINEERING

Microfinance as an innovation:
The early history of the Grameen Bank

Microfinance typically refers to the large-scale provision of small loans and deposit services to low-income people by secure, conveniently located commercial financial institutions[1]. These financial products and services enable low-income people to expand and diversify their economic activities, increase their income, and improve their self-confidence. Microfinance has existed in many forms throughout history with models spanning various time periods and locations; however, one of the earliest modern microfinance models was pioneered in Bangladesh - more specifically the Grameen Bank founded by Dr. Muhammad Yunus, 2006 Nobel Peace Prize laureate.

Improving Farming Practices in Rural Bangladesh

In 1974, Yunus, an economist by training and a professor at Chittagong University, was frustrated by economic models and their inability to explain famine in Bangladesh. This frustration motivated him to take action and investigate the issue. One of his first efforts at the microlevel was trying to help farmers in Jobra, a village nearby Chittagong (Exhibit 1), grow more food by studying methods to improve crop yields and created a project to teach farmers to plan a higher yield variety of rice. These efforts and the resulting attention from the press led to the creation of the Chittagong University Rural Development Project (CURDP), an action research initiative to help improve conditions in the area. CURDP encouraged students and volunteers to go into the village and devise ways to improve everyday life – with efforts spanning crop improvements, irrigation issues, farmers, and water supply systems.

One of these issues, water supply and its relationship to irrigation caught the attention of Yunus, who noticed while on a walk that a tube well in the region was not being used. After investigating the issue, he figured out that the government provided modern water irrigation technology to the community, but did not provide time, resources, or efforts to solve people-centered problems with the irrigation systems. Because the farmers were not trained to use the system, they often had disputes regarding its use, costs, technical breakdowns, and operations among them and with land owners, eventually leading to lack of utilization of the systems. To address this issue, Yunus proposed the creation of a cooperative, called a "three share farm" in which landowners, croppers, and himself would provide resources (land, labor, and financial resources, respectively) to generate food and have a high yield season for the area.

Freddy Solis and Professor Joseph V. Sinfield prepared this case with the sole purpose of class discussion. Cases are not intended to serve as endorsements, sources of primary data, or illustrations of effective or ineffective approaches to engineering or management.

Different Perspectives on Poverty

Yunus continued to pursue problem-solving approaches such as the "three share farm" until he noticed a flaw in his approach – i.e., his lack of focus on the poorest population. This issue stemmed from his observations of life at different farms and reflections on the distribution of wealth across farming value chains. For example, he realized that once farmers harvested rice, a different type of labor was needed to separate it. Separating rice was grueling work for very little pay. Thus, this task was often offered to the cheapest day laborers; people who otherwise would have been reduced to begging. After a quick analysis on this issue, Yunus figured out that the women who often worked on separating rice from dry straw could make four times as much if they had financial resources to buy rice from the farmers and process it themselves for future sale. The pay of the women, however, was so low that they were unable to engage in this activity and were caught in a cycle of seemingly perpetual poverty. Because of this, Yunus realized that his "three share farm" experiments made farmers wealthier but they also made the poorest even poorer.

When he realized this gap in his community improvement focus, Yunus decided to study Jobra's poverty, particularly understanding the importance of differentiating between the really poor and marginal farmers. One of the first things he noticed is that international development programs typically focused on improving the conditions of farmers and landowners. Yet in Bangladesh, half of the population was worse off than the typical farmer.

Digging deeper into his research on poverty, Yunus understood that governments and social scientists had no clear definition of "poor." Poverty definitions of the era varied and included categorizations such as "jobless people," "illiterate," "landless," "unable to feed their family," "with a given set of housing conditions," "with malnutrition" or "not sending their children to school."

Likely due to his training as an economist and inherent focus on measurement, he reflected that efforts to address poverty should reflect on a clear definition of the issue. Therefore, he created his own definition of poor according to three broad categories:

- The bottom 20% of the population (absolute poor)
- The bottom 35% of the population
- The bottom 50% of the population

Within each category, "[he] created sub classifications on the basis of region, occupation, religion, ethnicity, gender, and age,[1]" thus creating a multi-dimensional understanding of poverty that was distinctive and unambiguous.

To understand poverty to an even greater depth, Yunus began visiting the poorest households with students and colleagues and discovered cases analogous to the women who separated rice; for instance, he talked to women that made bamboo stools and discovered that they had to borrow money at relatively high interest rates (sometimes 10% per week) from lenders to be able to produce and sell their products. One woman they talked to earned 2 cents a day because of these production economics. Some people who earned so little, because of the lack of access to capital, often gave up working and resorted to begging and realized that their hopes for improvement were little according to the current economic system. Frustrated, Yunus questioned why economics are studied often at the level of millions of dollars while some deep societal economic problems were at a scale of a few cents per day. He realized that "in the world of development, if ones mixes the poor and the non-poor in a program, the non-poor will always drive out the poor, and the less poor will drive out the more poor, unless protective measures are instituted right at the beginning.[1]"

A New Banking Model

Yunus reflected on the notion of development efforts making the poor even poorer. He tried to empathize with the woman that created bamboo stools realizing that the cash cycle of borrowing at high interest rate from a trader and selling back to him did not allow her to break out of poverty and wondered if there were ways to alter this cash cycle.

The next day, Yunus called a student who often collected data for him and asked her to "make a list of people in Jobra who depended on traders and high interest lenders[1]". They learned that there were about 42 people who collectively borrowed an amount equivalent to $27 US dollars from traders. The quantity seemed absurdly low, especially for a financial institution, and it was at that moment when he realized that no financial structure was available to cater to the credit needs of the poor, and, due to the absence of financial institutions in this market, money lenders saw an opportunity to charge high interest rates.

Yunus handed the $27 dollars to his student and asked her to give the money to the 42 people, loaning it out without interest and no pressure to repay, stating that lenders could repay the money whenever they could. This was perhaps one of the first, albeit informal, instances of modern microfinance.

Yunus realized that he needed to search for ways to institutionalize his idea of lending to the poor, because no one would single-handedly be able to loan money to people all the time. He formally approached a bank manager who had previously helped him with his "three share farm" projects. The banker naturally objected on issues such as transaction costs being higher than loan amounts, the often illiterate nature of the poor having a hard time understanding terms and filling out forms (over 50% of Bangladesh's population at the time did not read and write), and the general lack of collateral held by borrowers – all elements of recognized "conventional" banking practices. Any of Yunus' attempts to work around these issues often ended in "that will not work, these are our bank's rules/policies," without a proper explanation. Effectively, the bank manager argued that every single bank in the country has a set of rules and practices and that the bank could not accommodate loans to the poor. This led Yunus to seek out conversations with individuals higher up in banking organizations who also denied his requests for loans for the poor. He realized that to make the idea of loans to the poor work, he had to move away from the banking system as a whole.

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[1] Many of the quotes and stories for this case come from two sources:
- Yunus, M. 1999. Banker to the Poor. PublicAffairs.
- Robinson, M. 2001. The Microfinance Revolution. The World Bank.

Microfinance as an innovation: The early history of the Grameen Bank

Finally, it occurred to Yunus to become the guarantor of loans for the poor and placed a request at a bank for an amount equivalent to $300 US dollars. Six months after back and forth interactions and negotiations with the bank, Yunus succeeded in taking out a loan from Janata Bank to empower the poor in Jobra. All loans had to be co-signed by Yunus. The poor did not need to go to the bank – Yunus himself would have to administer them. This was one of the first institutional instances of microfinance.

Yunus had to learn "how to run a ban" for the poor[1]" from scratch to able to distribute his loans in this "banking experiment." He investigated banking practices from conventional banks and credit cooperatives. These organizations often demanded lump sum payments at the end of a loan period, which was psychologically taxing on borrowers. Instead, Yunus instituted daily payment programs and asked for the loans to be paid back over the course of one year.

Slowly, Yunus and colleagues developed their own loan delivery and recovery mechanisms, learning along the way what worked and what didn't work. For example, they discovered that support groups were crucial to the success of the operations and psychologically helpful for applicants, so they required loan applicants to join a group of like-minded individuals within their region and/or occupation. Training and policies were provided in oral and written form to compensate for the rates of illiteracy and applicants had to pass an oral exam so the "bank" could ensure that they understood the terms. Other practices included holding group meetings in open spaces in villages to reduce corruption and inspire trust, as well as identifying ways to overcome gender bias due to cultural beliefs of the area, especially after discovering that these banking practices brought faster change to villages if loans were provided to women compared to loans provided to men. As a result of these practices, the poor had a better repayment rate than traditional banking customers.

After success in the Jobra region, the bank was formalized and named the Grameen Bank. However, higher level banking officials in Bangladesh demanded proof that the "banking for the poor" model worked beyond a single village. As such, the bank expanded into the region of Tangail. Challenges of providing scale to an idea emerged such as establishing governance mechanisms, finding qualified staff, and setting policies and procedures. Yet the bank managed to succeed and grew from 500 members in the founding location in 1979 to more than 28,000 members in 1982. The bank was first instituted as a national/governmental organization but achieved independence over the course of its history.

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Freddy Solis is a doctoral candidate in the College of Engineering at Purdue University and an MBA graduate from Purdue's Krannert School of Management. Freddy's doctoral research is in innovation models, and the doctoral work in this dissertation focuses on developing a model of innovation impact – called the enabling innovation model – and on characterizing the design and problem-solving competencies required to achieve this type of innovation. His research interests are in the areas of innovation, design, problem-solving, entrepreneurism, science, engineering and technology management and evolution, and education. While at Purdue, Freddy worked for the Minority Engineering Program as a graduate assistant, and also co-founded TEDxPurdueU – Purdue's independently organized TED event. He has professional experiences in the construction, consulting, and education spaces. Freddy is a native from Mexico, and also holds B.S. and M.S. degrees in Civil Engineering from the Universidad Autónoma de Yucatán and Purdue, respectively.