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Designing for Big X: Characterizing Design for Major Challenges*

FREDDY SOLIS and JOSEPH V. SINFIELD
Purdue University, 550 Stadium Mall Dr, West Lafayette, IN 47907, USA. E-mail: fsolis@purdue.edu, jvs@purdue.edu

This paper codifies a form of expertise that is tailored to framing and addressing the classes of complex, multifaceted, multistakeholder challenges affecting organizations and society, here termed "major challenges". This type of expertise tends to be elusive because of the divergent schools of thought used to characterize major challenges, the seemingly serendipitous nature of the innovations needed to respond to these challenges, and the tacit and situated nature of the design knowledge and practices required to frame and address them. We develop a framework for this qualitatively distinct type of design—termed "Design for Big X". Our framework codifies a set of conceptual shifts in patterns of thought and action aligned with the properties of major challenges, relative to generic design practices. The framework provides new constructs for research on innovative thinking and the cultivation of talent in educational institutions and organizations working to address major challenges.

Keywords: innovation, systems; major challenge; design behavior; design pattern

1. Introduction

Innovation leaders at organizations and institutions have been encouraging talent to pursue important unresolved problems through bold ideas and less conventional approaches [1]. Whether creating economic growth in challenging conditions [2], ensuring equitable provision of clean water [3], driving the creation of new-to-the-world technologies that improve treatment of infectious disease [4], restoring and improving infrastructure [5], managing changes in population dynamics [6], or powering agriculture via clean energy [2], this type of problem is testing the limits of our existing approaches to problem exploration, design, and innovation [7]. Examination of the schools of thought that have studied this class of challenge, such as complexity science [8], systems-of-systems [9], wicked problems [10], sociotechnical systems [11, 12], grand challenges [5, 13] and ecosystems [14, 15], reveal that they share characteristics studied across the fields of systems, innovation, and design. These intersections suggest that a framework to harness the expertise likely required to address these types of challenges—hereafter collectively referred to as "major challenges" because they represent a problem or goal that is complex, multifaceted, multi-stakeholder, multi-domain, highly uncertain and significant—could be developed by integrating key contributions from such fields.

With pattern recognition [16], reflective practice [17], and intuitive judgment [18] being hallmarks of expertise, herein we argue that if the talent (i.e., the human capital) aiming to address major challenges understands them as unique patterns of problem framing, solution design, and system response they could be more systematically approached and potentially addressed. Achieving this understanding, however, implies codifying the qualitatively distinct patterns of thought and action that may be required to develop competency in framing, addressing, and potentially achieving high-impact outcomes in complex environments. As we look beyond the "Engineer of 2020" [19], there remains an opportunity to harness these qualitative differences in competency/expertise and employ them as a foundation for future engineering education research and practice specifically related to major challenges. Even if elusive, other tacit and situated forms of expertise related to design [17, 20, 21] have been broadly studied and successfully codified. Hence, techniques typically used to study elusive forms of expertise can help codify the nuances and map the space related to designing for major challenges.

In this paper, we unpack a framework that elicits the qualitatively different patterns of thought and action involved in designing for major challenges [7, 22]. These patterns were identified from a multifaceted research design, motivated by Boyer's scholarship of integration [23, 24], that applied thematic analysis to three distinct data sources: (1) literature across diverse fields such as systems, innovation, and design; (2) historical cases on the actions/behaviors of stakeholders involved in the development high impact innovation (e.g., lasers, GPS, X-rays, microfinance); and (3) verbal protocols of 20 performance tasks focused on addressing a representative major challenge (the adoption of electric vehicles). Each method provided a unique perspec-

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tive of the challenge of innovation in complex environments: research, history, and practice; however, it is the integration of these methods that yielded unique design insights for major challenges.

The framework (see Fig. 1) consists of three clusters (envision, shape, and pursue), comprised by multiple design patterns for major challenge situations. Herein, design patterns represent thematic collections of design behaviors [20] and behaviors refer to discrete, observable design activities [25]. Nine design patterns for major challenges, organized by design process stage, emerged from the research: (1) defining a vision and strategic intent using innovation motifs; (2) framing flaws in paradigms; (3) exploring technical, economic, systemic, sociological, and psychological forces systematically, (4) connecting de-contextualized first principles to new contexts, (5) assessing and shaping ecosystems holistically, (6) rethinking solution performance, and agglomeration, and connecting to early impact contexts, (7) persuading to facilitate acceptance or use, (8) designing effectual and emergent paths to unfold performance and impact, and (9) deploying learning experiments to discover the path to impact [7, 22]. These patterns are anchored in a design process model and highlight shifts in thought and action that engineers of the future will likely need to employ given the increasing frequency with which they will encounter major challenges. The framework we present creates new links between the disciplines of systems, innovation, and design. For instance, ecosystem reconfiguration perspectives, often necessary when addressing major challenges, are not typically linked to individual-level design behaviors; similarly, the study of innovation is seldom anchored at the design behavior level of analysis and vice versa.

Our discussion of these topics is organized as follows. We first create a perspective of major challenges based on their systems, innovation, and design properties, examining how these schools of thought provide theoretical foundations for the study of related expertise. We then describe the integration approach employed to codify our framework. A discussion of the key components of the framework follows, utilizing evidence from our data sources to illustrate critical expertise differences relative to generic design practices. We conclude with implications, limitations, and future study possibilities for engineering education and beyond.

2. Theoretical foundations for the study of major challenges

Codifying design patterns relevant for talent attempting to address major challenges requires a perspective on this class of challenge in and of itself. While such challenges are indeed daunting, when deconstructed into their problem space and solution space components, they seem to parallel issues studied in the fields of systems, innovation, and design. Because of this, in the following pages, we review key insights from these schools of thought that, if connected, can inform our understanding of what we herein term major challenges.

2.1 Complex, multifaceted, multiscale, multistakeholder problem spaces

A first component in addressing major challenges entails characterizing their problem spaces. As defined herein, major challenges are situated at the intersection of schools of thought, such as systems of systems [9, 26], complexity science [27–29], grand challenges [1, 5, 13], wicked problems [10], ecosystems [14, 30], and sociotechnical systems [11, 12].

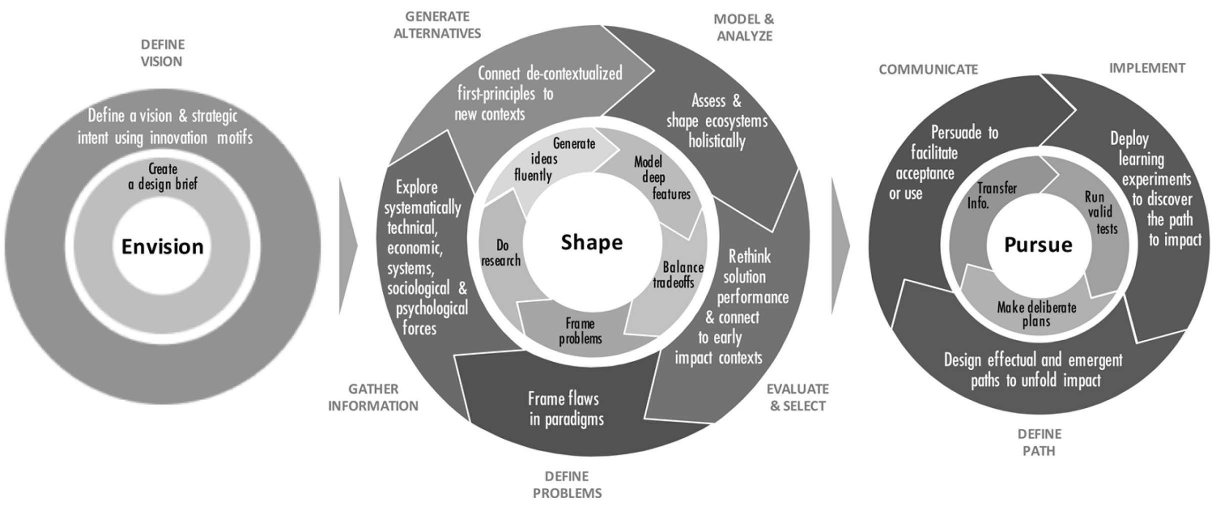

Fig. 1. A Framework to Design for Major Challenges [7].

These schools of thought provide insight into the cross-disciplinary, multifaceted, ill-structured, and high-assumption problem space patterns that talent must be aware of in major challenge scenarios.

Within major challenges, a broad array of systems with technical, economic, social, and psychological implications interact, and the number of variables and interrelationships that must be accounted for is relatively large (e.g., the number of multifaceted issues in addressing agricultural challenges in developing economies). These challenges are also ambiguously bounded, do not operate in equilibrium, and prior states often influence present states (e.g., population dynamics influence aging population challenges). Further, system behaviors at different scales tend to be emergent [31] and system changes generate network effects that produce change in interdependent elements [32] (e.g., cascading failures in city infrastructure). Elements capable of interacting with each other and the environment display organizing principles beyond the simple integration of individual elements [33] (e.g., securing cyberspace). These interactions are non-linear and near-decomposable, implying that such issues are often not reducible to separate subsystems [34]. Beyond this, the issues faced in this type of challenge have a sociotechnical nature with multiple levels, disciplines, perspectives, goals, and constraints that can often be incompatible and ill-structured [11, 12].

2.2 Innovation patterns and solution spaces

A second component in major challenges entails characterizing the solution spaces that may address them. In this regard, the innovation as an outcome school of thought [22, 35, 36] provides insight into the nature of solution spaces that may be applicable to major challenges. Awareness of the abstract characteristics and patterns in innovation solution spaces may help map the types of competencies that talent may employ when designing for major challenges.

Many framings of innovation as an outcome exist and can be employed to characterize solution spaces, as multiple researchers have theorized organizing constructs to classify innovations, for example, by their form and magnitude [36] and by their type of novelty, differentiation, and impact [7, 22, 35, 37]. Constructs such as product, process [38], service [39], and business model innovation [40] describe possibilities for solution forms. Constructs and concepts related to radical and incremental innovations [41, 42] can be used to describe the magnitude of changes in solution performance. Concepts related to modular and interdependent innovations contrast the organizing structure of system-level solution components [43–45], while disruptive and sustaining innovations can be used to contrast solutions on the basis of end-user perceptions of value [46]. Additionally, constructs such as general purpose technologies [47, 48], market-creating innovations [49], and enabling innovations [22, 35, 37] provide insight into the types of outcomes/impact for which talent aiming to design for major challenges can strive. While this review of innovation archetypes is not exhaustive (for a more exhaustive review see [22, 37]), major challenges will likely require several solutions in each of these innovation spaces. Talent could therefore benefit from learning to characterize and design for solutions that strive for a specific innovation pattern.

2.3 Co-evolution through design

A third component—one that connects problem and solution spaces for major challenges—is the field of design. For any challenge, including major challenges, problems and solutions are iteratively framed, shaped, and introduced into practice via design processes [50]. Conceptions of design processes (i.e., the number and nature of design stages) vary widely throughout the literature [51–53], but typically include stages to frame problems, synthesize solutions, and communicate and implement such solutions [51, 54, 55], with non-linear transitions between stages [56] that occur opportunistically and iteratively [21] given the ill-structured nature of design challenges [57–59].

Some argue that design activities vary according to the nature of end goals, using the phrase ''design for x'', where ''x'' represents a goal. If a specific type of outcome is desired or appropriate given the characteristics of a major challenge, then design behaviors are likely to be more effective if they are tailored toward such a type of outcome. Hence, proactive cultivation of design behaviors for framing and addressing major challenges inherently requires codifying this qualitatively distinct level of design practice. Inspired by studies on learning progressions [60, 61], here, levels of design practice describe conjectural models of increasingly sophisticated design behavior and highlight how a sequencing of skills and ideas of practice unfold over time. In design learning, levels of practice have been studied by highlighting hierarchies in progression from novice to expert [62] or levels of practice pathways [63]. Yet definitions of these levels of practice vary greatly [20] and are studied at a ''generic'' level, meaning that they are typically not tied to a specific type of problem or solution space. As a result, models of innovation expertise and design for major challenges that depart from generic design competencies and codify approaches for co-evolving major challenges, have, to date, been underexplored.

With the above in mind, we highlight qualitative differences in design patterns that are likely required when addressing major challenges, building on connections between the fields of systems, innovation, and design. Developing language that captures these variations in design behavior can inform talent development efforts for institutions and organizations, and can be employed in research, teaching, learning, and practice.

3. Methodology

To develop the framework, we employed a multi-faceted research design grounded in Boyer's [23] construct of a "scholarship of integration." In contrast to the emphasis of the scholarship of discovery on what is yet to be known and found, the scholarship of integration (SOI) emphasizes the connectedness, meaning, and interpretation of scholarly byproducts. Such connections and interpretations place specialties in a larger context, open new research directions, strengthen research-to-practice cycles, and are use-inspired in nature [24]. The aim of SOI is not to make definitive discovery claims, but generative integration claims that outline how novel connections between fields, emerging ideas, and worldviews, converge into strongly informed hypotheses or frameworks for new or interesting cross-disciplinary research directions [24]. The link of SOI to major challenges is that insights related to designing for this type of challenge may come from integrating knowledge from many disciplines and approaches. For more on SOI, the reader is referred to Boyer [23], Solis et al. [24], Crismond and Adams [20], and Bartunek [64].

3.1 Research streams

We iteratively integrated insights from three research streams (Fig. 2): (1) a thematic synthesis/ integration of research from disciplines related to major challenges; (2) a search for themes in historical research regarding the development of 7 high-impact innovations with properties on par with major challenges; and (3) analysis of 20 verbal protocols of a performance task in which professionals with diverse backgrounds worked to address a representative major challenge. We employed thematic analysis [65–67] as a common tool to analyze data because our goal was to search for common patterns/themes across our research streams. These three research streams are highly complementary: observing documented instances of behavior in historical research complements verbal protocol analyses in which behaviors can only be "seen/observed" from the lens of the present, while a research synthesis anchors findings to existing literature.

The synthesis of research across literature related to systems, innovation, and design was our starting point to identify patterns of thought and action, even though the synthesis activity continued throughout the study to anchor emerging observed patterns in bodies of knowledge. Literature related to systems, innovation, and design, spanning fields such as management, economics, entrepreneurship, engineering, science, technological evolution, psychology, complexity, education, and design was analyzed. We identified and translated latent design problem-solving, systems thinking, and innovation themes (in the form of behaviors and patterns of thought and action) into elements of the framework. Inspired by studies that have spanned disciplinary boundaries, advanced scholarly activities, and translated research to practice [20, 64, 68–73], our aim was to conduct a thematic/integrative synthesis that, using an emergent approach, codifies an elusive phenomenon (design patterns and behaviors for major challenges).

The analysis of historical cases involved searching for evidence of design patterns and behaviors in historical research, thus establishing links between behavior and demonstrated impact. These links between behavior and demonstrated impact suggest that the patterns of thought and action we uncovered played a role, in intended or unintended ways, in the development of historical innovations that addressed challenges and generated impact on par with what we herein consider major challenges. We purposely selected seven innovation cases: radar, laser, x-rays, global positioning systems (GPS), anesthesia, antisepsis, and microfinance. We strategically selected these cases to show that high impact solutions can take many forms and may be artifacts or concepts, technological or non-technological, medical or financial, and can result from serendipity (unexpected insight) or intentional/ systematic pursuit. We used published secondary historical research as data sources. A subset of these sources consists of first-hand accounts (e.g., narratives, interviews) from/with stakeholders directly involved in the development of the innovation (e.g., Townes and the laser [74], or Yunus and microfinance [75]). Other sources consisted of rich investigations of the cases with a relatively large number of documented references (e.g., anesthesia [76], x-rays [77]), typically developed by historians of science or science journalists. We followed Scott [78] for source quality determination.

Verbal protocol analysis (VPA), a method in which subjects think aloud as they perform tasks, was employed to make patterns of thought and action, often hidden in a final artifact/solution,

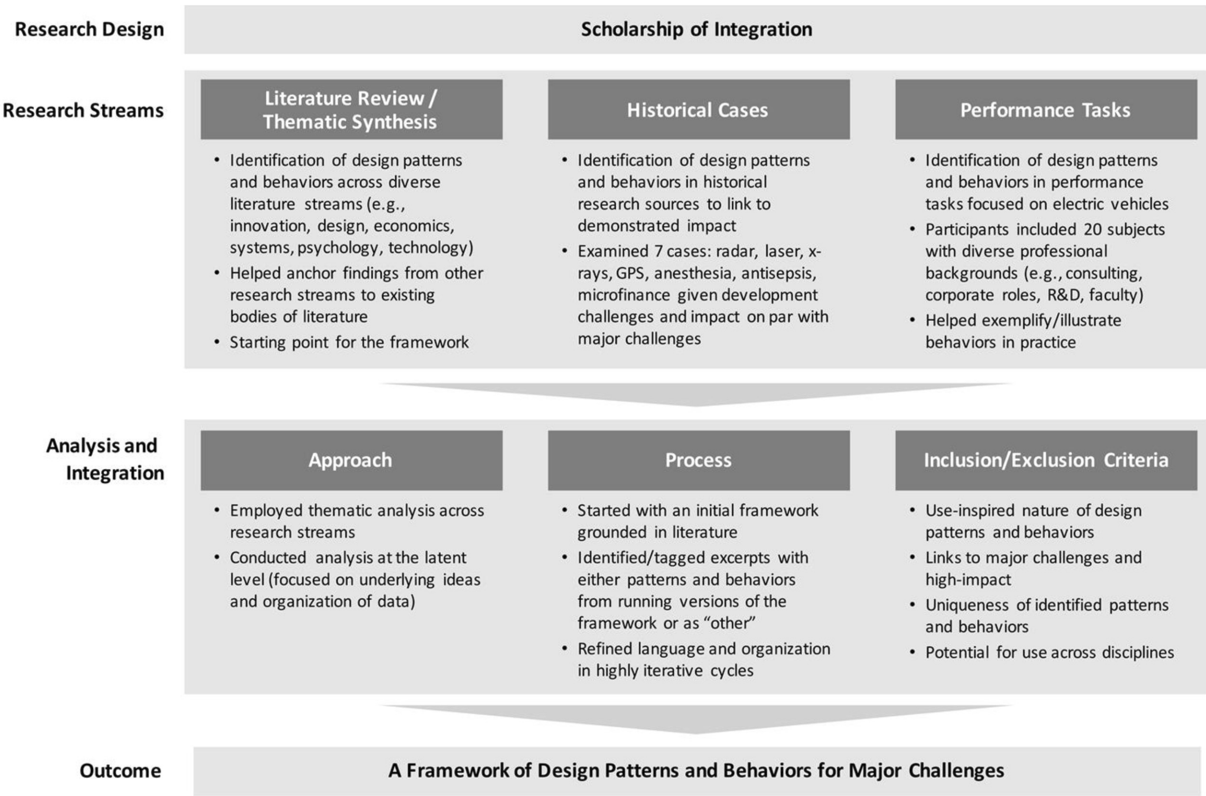

Fig. 2. Methodology.

more explicit. (For more on VPA, see [79–81].) VPA was used to generate rich descriptions of design behaviors/patterns, with a special emphasis on characterizing and searching for example instances of designing for major challenges. We asked participants to engage in a design task centered on increasing the adoption of electric vehicles (EVs), shown in Fig. 3. We selected this topic because it is representative of major challenges: (a) no solution is available and no single insight will address the problem; (b) the challenge is inclusive of engineering, design, science, management, systems, and broader societal issues, and (c) perspectives from more than one stakeholder category are required to address the challenge. We purposely selected 20 subjects with diverse professional roles and backgrounds through snowball sampling (Fig. 3). We sought participants from roles in which their day to day professional activities prompt them to innovate on demand. We conducted the tasks in person or via video conferencing, set a two-hour duration (90 minutes for the task, 30 minutes for semi structured interview debriefs on their approach) and allowed the use of a monitored computer for information gathering.

3.2 Data analysis and integration

Due to our aim of developing language that can be employed to characterize design for major challenges, we employed thematic analysis [65, 66] at the latent level (i.e., focused on underlying ideas and their conceptual organization) [82] across the three research streams to identify and organize themes into a framework. In this study, themes represent design behaviors that aggregate into thematic patterns of thought and action.

Our starting point was an early conception of the framework developed by the authors, grounded/inspired by a cross-disciplinary research synthesis across design, innovation, and systems. From this starting version, guided by a set of theme inclusion/exclusion parameters, we iteratively identified and tagged excerpts across the three research streams using running versions of the framework, per the process in Fig. 2. All tagged excerpts were assigned a design process stage (or more than one, if applicable) and we adapted Atman et al.'s design process [54, 83, 84] for use as an anchor due to its granular division of the design process into discrete stages. Tagged excerpts were also assigned either a design behavior and pattern of thought and action (if appropriate), or tag of "other" for further analysis. We reviewed all instances tagged as "other", searching for underlying themes not considered in running versions of the framework. A subset of behaviors that were tagged/assigned with multiple design stages emerged through this process, which we labeled as "core" behaviors. Overall, the process

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.

(a)

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

(b)

Fig. 3. (a) Performance Task; and (b) Performance Task Participants.

to integrate insights was highly iterative, aiming to identify a wide array of behaviors and aggregate them into design patterns, with integration efforts proceeding in parallel across all research streams, until returns diminished. To ensure research quality, we employed strategies described by Walther et al. [85].

4. Design patterns for major challenges

In this section, we unpack the framework to design for major challenges (see Fig. 4). From our data and methodology emerged nine thematic differences in patterns of thought and action relative to generic models of design. Each pattern is comprised of a set of identified behaviors and is anchored to an end-to-end conception of a design process consisting of the stages of: envisioning, problem definition, information gathering, alternative generation, modeling and analysis, evaluation and selection, communication, path definition, and implementation. These stages were grouped into three clusters: envisioning, shaping, and pursuing. In addition to stage-specific behaviors, we also identified a set of unique behaviors that were identified as relevant to multiple design stages, which we labeled as "core.".

For each cluster and design stage, the following sections describe shifts in design pattern and associated behaviors for major challenge situations. We first describe the shift and define the behaviors we identified, and then provide select illustrative examples from our data, utilizing excerpts from the different research streams (i.e., excerpts from historical cases, direct quotes from VPA participants, and links to existing theories and research). Since the study was designed with integration in mind, our goal is not to provide an in-depth justification of each behavior identified (which would be beyond the scope and space limitations of this paper), but to map the space of patterns of thought and action and behaviors related to major challenges. Following the description of stage-specific patterns and behaviors, we describe and define the behaviors we identified as core and illustrate how these behaviors are likely relevant to multiple design stages.

5. Envisioning high impact ideas

5.1 *From design briefs to defining strategic intents using innovation motifs*

For the visioning stage of design, the first thematic shift that emerged is the contrast between defining a vision and strategic intent for a long-term opportunity space and creating design briefs [7, 22]. In major challenges, opportunities for high-impact innovation might not be immediately perceived but tend to emerge from explicitly defining a vision for a long-term opportunity space, often with no artificial ties to a solution, context, or application, to leave room for emergent behavior. Our data suggests that articulating this vision entails more than the typical focus on short/medium term objectives, constraints, or performance characteristics of design briefs

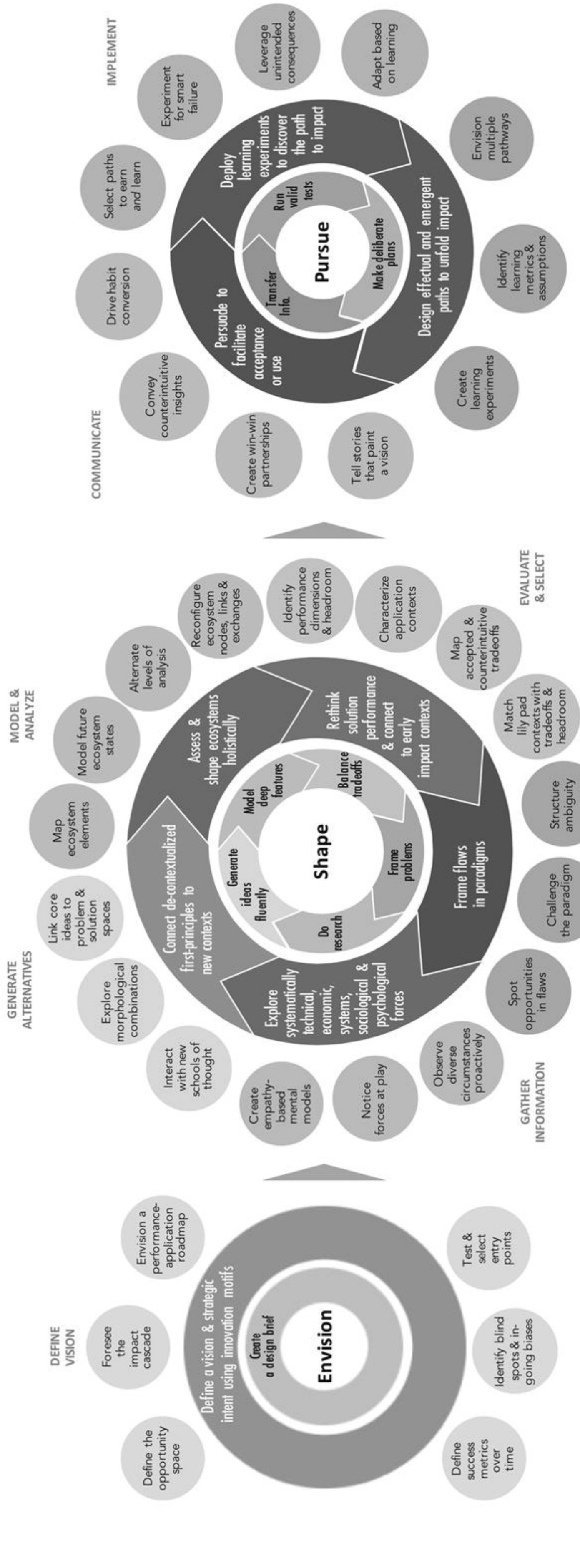

Fig. 4. Patterns and Behaviors to Design for Major Challenges.

Table 1. Defining a Vision and Strategic Intent for Long Term Opportunity Spaces

Behavior	Definition
Defining opportunity spaces	Detecting and delineating a pattern of changing trends that suggest the potential for achieving high-impact in a major challenge
Foreseeing the impact cascade	Foreseeing the extent of impact that an innovation(s) could have on a major challenge
Testing and selecting entry points	Determining possible starting points in problem and solution development
Identifying blind spots and in-going biases	Becoming aware of biases in judgment that are too uncertain to be fully characterized/understood but might affect an opportunity space
Creating success metrics over time	Identifying metrics by which the success of an idea can be evaluated at various stages because success changes as an innovation evolves
Envisioning a performance-application roadmap	Recognizing application spaces that could open up to address a major challenge as the performance of a concept improves

(e.g., see [86]) to include a focus on long-term opportunity spaces. Relevant behaviors to define this type of vision identified in our work are defined in Table 1.

Historical examination of high-impact cases revealed that, for instance, for GPS, the opportunity space came from a vision to possibly track objects on earth with satellites, which was spurred after the creation of methods to track Russian satellite Sputnik by manipulating its radio signals [87]. These visions, however, are not only relevant to technologies. In the conceptual domain, the microfinance movement did not begin with the intention of addressing financial issues for the poor, but as a broad effort to understand and reduce famine in Bangladesh, which encompassed exploration of irrigation issues, farming ecosystems, and helping the poorest segments of the population [75]. Overall, actors/stakeholders in these cases identified a long-term vision but were not constrained by it and were able to foresee the impact that would be generated if successful. They also tended to test and select multiple entry points (e.g., the technology, the end-user, the ecosystem) to a given challenge.

In the VPA, we also observed this envisioning pattern and multiple related behaviors because our prompt was purposely ambiguous, which forced participants to define what "significant increase in EVs" meant to them. Some participants immediately attempted to quantify what a significant increase in EV adoption meant to them; for example, Mike defined it as doubling today's adoption, and Max set a target of 1 million EVs. Others, defined the opportunity space more broadly, in a similar fashion to the historical cases. Victor, for example, defined very concisely his opportunity space as a transition in habits:

> ". . . what we're trying to do is transition people's habits from moving gas vehicles to all electric"

Similarly, Ken defined the EV opportunity space as making transportation as easy as possible:

> ". . . it's not just about transporting a person and 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"

After defining a vision, some participants spent time testing and selecting entry points, via thought experiments, to the shaping cluster of patterns and behaviors for problem and solution spaces. Don, for example first briefly examined systemic barriers to EV adoption and then moved to examining performance dimensions in solutions as possible entry points. Kate also began by examining barriers and then moved to issues with end users. Drew began by examining ecosystems, while Ken began examining vehicles but moved beyond this focus to examine long-term systemic changes as a possible entry point. Effectively, while conceptions of design processes typically begin with a problem definition stage, the sheer complexity of major challenges increases the importance of having a vision.

6. Shaping high impact ideas

In the shaping cluster of the framework we describe the process of moving from a long-term vision to shaping problems and solutions for major challenges. Here, we unpack perspectives of designing for major challenges for five design stages in Fig. 4: problem definition, information gathering, alternative generation, modeling and analysis, and evaluation and selection.

6.1 From framing isolated problems to framing flaws in paradigms

For problem definition, research suggests that the way a problem is framed inherently constrains the set of solutions one can develop [88–93]. Because major challenges tend to have significant ecosystem and paradigm components compared to other types of problems, our data suggests a shift from framing isolated problems in generic forms of design to framing flaws in paradigms in major challenge situations. We define paradigms as the status quo norms and assumptions that govern the framing of a problem and the nature of commonly employed solutions in a given domain; flawed paradigms thus refer to the often negotiable yet latent assumptions governing such norms [7, 22]. It is often in finding opportunities to address the hidden assumptions underlying flawed paradigms where the spark for addressing major challenges has been ignited, with literature implicitly suggesting that this pattern occurs across domains such as economics [94], science [95], and technology [96–98]. Doing so entails questioning the validity of old assumptions and frameworks [88, 99], and unearthing not only what we know, but also what we don't know because it is inherent in cultural and historical traditions, or at the outer limits of the body of knowledge. Relevant behaviors for this type of problem framing that were identified in our work are defined in Table 2.

This pattern and relevant behaviors emerged in our exploration of historical cases. Stakeholders driving the early anesthesia movement, for instance, addressed the hidden assumption that pain in acute circumstances, such as surgery, was a normal part of life [100, 101]. Advancing the concept of the laser required re-examination of assumptions of thermal equilibrium underlying the 2nd law of thermodynamics [74]. Microfinance challenged flawed assumptions in banking systems; one of the leaders of the movement, Muhammad Yunus, for example, recalls a conversation with a banking manager in which he questions such systems [75]:

> "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?"

In the analysis of our EV sessions, differences in approach were observed for participants that simply listed problems with EVs and those that more profoundly examined transportation paradigms to search for hidden assumptions. As examples, Sam, Ken, Susan, and Henry questioned underlying assumptions regarding consumers' use of automobiles in transportation systems:

> "So increase EV adoption, five years. Okay? I think I start by thinking about the history of the automobile in the US, and the history of the automobile worldwide, and ask the questions about societal use of the automobile. . ." (Sam)
>
> "Most cars are designed to be compromises between travel patterns. So the important question that arises is how can you change that?" (Ken)
>
> "So how can you make people's lives less time-consuming and I come back to the charger station. . . they aren't widespread like gas stations and so how can we make charging stations convenient? Are they available at the grocery store while you're shopping, just trying to find ways to make life easier because life is complicated." (Susan)
>
> "Are there opportunities to create new types of relationships between people and their cars?" (Henry)

Our data suggests that framing interconnected assumptions in paradigms—to then attempt to address them—can help unearth new challenges and possibilities, thus constituting a qualitatively different design pattern than framing isolated problems. This type of framing implies that hidden ecosystem and paradigm assumptions must be made visible in order to be addressed.

6.2 *From focused research to systematic multiscale, and multifaceted exploration*

With regard to information gathering, a pattern emerged from our data suggesting that major challenges require systematic exploration of technical, economic, systemic, sociological, and psychological forces that may act upon problem and solution spaces. Because ideas with high-impact potential for major challenge situations face multiple types of resistance, doing research on focused issues is valuable but likely insufficient, especially as the number of categories of issues that need to be understood begins to increase. In this type of situation, perspective taking [102–105], i.e., adopting other view-

Table 2. Framing Flaws in Paradigms

Behavior	Definition
Structuring ambiguity	Providing structure to ambiguous, complex, and ill-structured problem and solution spaces
Challenging a paradigm	Asking "why" and "what if" questions that reveal a paradigm's hidden assumptions
Spotting opportunities in flaws	Recognizing opportunities in flawed yet latent assumptions that underpin paradigms

points, seems inherent to information gathering, especially when it occurs systematically. By systematic, we mean an exploration that purposely examines intuitive and counterintuitive facets of an issue and that is as comprehensive as possible, implying an exploration of technical, economic, systemic, sociological, and psychological issues [22]. Technical issues are herein defined as those related to a particular subject matter, art, craft, science, or technique. Economic issues are related to the processes that govern the production, distribution, and consumptions of goods and services. Systems issues refer to the collective behavior that emerges from the interaction of multiple forces, which cannot be anticipated or understood unless systems are studied holistically. Sociological issues are those related to the development, structure, and functioning of human society, and their influence on social behavior. Finally, psychological issues are those related to the mental states/functions and behaviors of stakeholders. Relevant behaviors for this type of information gathering identified in our work are defined in Table 3.

Historical cases suggest that high-impact ideas are inherently influenced by multiple types of forces (e.g., technical, economic, sociological), which will strongly influence the outcome of innovation efforts in major challenges even if not acknowledged. The adoption of X-ray technology in the medical field, for instance, encountered sociological barriers rooted in power struggles between X-ray technicians, physicians, and the nascent field of radiology [77]. Technical issues also had to be overcome, like the resolution of X-ray machines, which was addressed through Coolidge tubes and ray collimation techniques [77, 106]. In microfinance, the economics and functionality of the new banking model, and sociological and psychological issues such as group loans, repayment trust, and gender issues with female entrepreneurship had to be addressed [75]. In GPS, regulatory, systems-level forces driven by the Federal Communications Commission in the US played a role in the ubiquity of the technology [107].

In the performance tasks, a similar range of issues were raised, ranging from battery range and charging speed to economics, commuting patterns, and emotional attachment to cars—with participants acknowledging that focusing on a single issue or scale can potentially obscure other key issues. For example, Walter, Nicole, and Charles acknowledged the multiple types of forces that seems to influence EV adoption:

> "I looked at some issues that I saw with adoption of EVs. One being the higher cost to purchase the car. Shorter driving range, range anxiety, limited infrastructure, longer charging time." (Walter)

> ". . . kind of immediately, I started trying to break the problem down into buckets in my head. One was, given the different types of EVs—what are the consumer jobs to be done? So, for example, I know that there's a huge concern around range anxiety that consumers have. So just thinking about what are the barriers? But the other big thing I started thinking of was the business models, and how they may be similar and different to more traditional vehicles. The third thing, there's a huge infrastructure component I think we take for granted..." (Nicole)

> ". . .This is a pretty open-ended problem—it's not like a heat transfer problem that you've got basically one issue. This one is a bit more complicated because it's got consumer aspects, it's got engineering aspects, and it's got other flow systems to worry about, fuel, electrical energy, and so on. So my approach with these things is generally try to at least sketch the problem, lay out the puzzle pieces that you've got. It's frequently with an open-ended problem we're not going to have all the pieces right away, so that's why you try to figure out which 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. That's kind of my process, see what's interesting on the people side, on the organizational side..." (Charles)

Our data suggest that ideas that aim to address major challenges will inherently encounter multifaceted forces. Therefore, such forces should be systematically considered in a design challenge to consciously address the inertia of status quo paradigms as well as the latent, previously unencountered challenges of driving a new paradigm.

6.3 From broadening idea spaces via lateral thinking to first principles thinking

In the generation of alternatives, evidence from our multifaceted approach suggests that, in addition to lateral thinking techniques such as heuristics and analogies [108–110], broadening "idea spaces" (i.e.,

Table 3. Systematic Exploration of Technical, Economic, Systemic, Sociological and Psychological Forces

Behavior	Definition
Observing diverse circumstances proactively	Engaging in constant observation across diverse circumstances to inform and observe hypotheses
Noticing forces at play	Perceiving proactively all possible significant influences in a given situation based on hypotheses, prior experiences, frameworks, changes, or unanticipated patterns
Creating 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

idea sets) for major challenges also entails connecting decontextualized first principles to new contexts. While heuristics and analogies are indeed valuable, the possibilities for generating ideas by employing these techniques may be somewhat limited when ideas are truly new to the world and represent a significant paradigm change, making complementary approaches—such as decontextualizing and thinking from first principles—potentially valuable. The notion of a first principle is anchored in literature from physics education, in which the term is used to denote a problem-solving approach based on fundamental physical laws and abstract physics principles compared to approaches based on superficial features of a problem [111–114]; a similar argument is also made in the technology evolution school of thought [97]. In major challenge situations, broadening idea spaces by thinking from first principles is complementary to analogical reasoning, and means getting to the core of ideas to derive new possibilities by either starting from the identified core/first principle and connecting it to a new context, or by proactively changing the first principle. Although not explicitly, some literature suggests that jargon free language describing first principles without discipline-specific implications seems to be critical to thinking in first principles, as distilling ideas from contextual influences can help overcome behavioral tendencies such as functional fixedness [115] and what we herein term as application context fixedness (a tendency to inherently link ideas to a specific application context) [22]. Distilling ideas from context-driven influences or jargon can thus reveal underlying principles applicable to seemingly unrelated problem and solution spaces. Thinking about the underlying principles of ideas (e.g., describing what a technology really does without ties to a specific context) can help unearth new possibilities [116]. Relevant behaviors for this pattern in alternative generation that were identified in our work are defined in Table 4.

Historically, the laser is an example innovation that rapidly found new applications with this line of thinking. When described as a coherent energy source that can precisely ablate material, modulate electromagnetic energy, or focus energy, many domains emerge in which these first principle have value (e.g., surgery, dentistry, manufacturing, cleaning, communications) [7]. In the history of antisepsis [100, 117–119], Joseph Lister was among the first to take a "first principles" perspective of Pasteur's germ theory and find derivative insights for his studies of surgical infection.

Our EV tasks also illustrated how insights derived from first principles happen. Mike, for example, broke down the EV challenge using an adoption framework from the field of marketing (e.g., awareness, consideration, trial, purchase, retention). In the awareness category, he first made an analogy to smoking in the 1950s but then decontextualized it to find the underlying (first) principle (social shifts that start at the fringes and gradually become mainstream):

> ". . . you could create more of a negative social—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 lead users being the ones who do it, and then over time, it becomes mainstream to where it's almost embarrassing to not do it."

Overall, this pattern of thought and action highlights an alternative path to broadening idea spaces that consists of identifying the first principles of ideas and either building derivative insights, changing the first principle, or making connections to other spaces (on a first principles basis) to enable new possibilities. Such a pattern is complementary to (and not in competition with) analogical reasoning.

6.4 From modeling to assessing and shaping ecosystems

With regards to the analysis design stage, another pattern that emerged from our data entails assessing and shaping ecosystems holistically. By holistically, we mean that addressing an ecosystem inherently implies a portfolio of related solutions, as no single solution is likely to address all issues in a major challenge problem space. Our data suggests that ideas that have successfully addressed major challenges proactively incorporate elements into their design that consider how solutions interact with a system in order to tackle ecosystem-level barriers.

Table 4. Connecting Decontextualized First Principles to New Contexts

Behavior	Definition
Interacting with new schools of thought	Obtaining and testing ideas through many types of interactions across counterintuitive contexts or at the intersection of fields
Linking core ideas to diverse problem and solution spaces	Connecting de-contextualized cause-effect patterns from first principles to problem and solution spaces that are seemingly unconnected
Exploring morphological combinations	Exploring all possible idea variants that result from combinations in the identified features/aspects of problem and solution spaces

Table 5. Assessing and Shaping Ecosystems Holistically

Behavior	Definition
Mapping ecosystem elements	Mapping system elements to understand their interactions at different levels of analysis
Alternating levels of analysis	Knowing when explorations at different levels of system granularity are important
Modeling future ecosystem states	Understanding future possible ecosystem scenarios and the implications of such scenarios for present-day innovation efforts
Reconfiguring ecosystem nodes, links, and exchanges	Designing solution components that have potential to influence the configuration of ecosystem nodes/components and links

Per related literature, systemic barriers can emerge due to issues with resources, operations, policies, economics, or stakeholders [31], hidden hierarchies in complex systems [120], perceptions of complexity in problem spaces that can be simply missing logical depth [121], or lack of awareness of opportunities for ecosystem reconfiguration [14, 122, 123]. This pattern is qualitatively different than modeling features of solutions and their interactions with a system through sketches, representations, or prototypes [20] as its emphasis is on both assessing and shaping the ecosystem. Relevant behaviors for this analysis pattern that were identified in our work are defined in Table 5.

Historical examination of cases reveals that actors in the history of high-impact innovations were aware of the importance of ecosystem elements in their success. In the history of microfinance, creating loan mechanisms for the poor was a critical but insufficient element of the innovation. Other ecosystem-level elements included the creation of support groups in villages that encouraged repayment and proper use of funds, as well as policies and training adequate for areas with high illiteracy rates [75]. Efforts also included meetings in open spaces to inspire trust and reduce corruption, and the identification of ways to overcome gender bias. These practices went beyond the banking solution and were key to its success. Similarly, the use of radar in weather forecasting required developing a wide network of tracking antennas that went beyond any meteorological mathematical modeling.

Participants in our performance tasks engaged in a similar pattern in the analysis stage. For instance, Kate recognized that addressing the EV problem, a representative major challenge, goes beyond one single solution:

> "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 actually going to be enough"

In an example of how participants aimed to shape ecosystems holistically, Max discussed the importance of reconfiguring the EV ecosystem. Throughout the task, he assessed that a critical opportunity resides in building a business case for existing fuel providers, and highlighted new ecosystem stakeholder links and future ecosystem state implications that would need to be shaped to enhance the adoption of EVs:

> ". . . with that in mind as kind of a blocker of adoption, what you're hitting on is you need infrastructure beyond the vehicle, right? This is not just a question of a product that I have to design. I also need to be concerned with the infrastructure being in place to facilitate the use of that product, which complicates matters greatly. So I have to, in some way, shape or form/replicate the infrastructure that we have for combustion engines. 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 and you're just adding charging capability to existing structures. So, I'd look to partner with retail establishments, potentially, or gas and service stations."

Overall, designing for major challenges inherently involves assessing and shaping ecosystems because no single solution is likely to address all issues in the problem space. Hence, this type of design must proactively incorporate a portfolio of related solutions that address ecosystem-related barriers and proactively attempt to shape ecosystems.

6.5 *From "moonshot" to "lily pad" performance development*

In major challenges, the development of needed performance in solutions is unlikely to unfold quickly and/or in one single step change—and thus there is a need to contain risks while evaluating and selecting alternative solutions. Hence, with regards to selecting and evaluating alternatives, another pattern that emerged from our data suggests that rethinking solution performance, agglomeration, and connections to early impact contexts can lead talent, at any point in time, to find solution-context matches—which we term "lily pads" [35]—for which the current performance of a solution might be adequate because limitations in one context can be benefits in another. Thinking about lily pads entails proactive consideration of the interplay between performance tradeoffs, the evolutionary development of solutions, the agglomeration/de-agglomeration of solution components, and the need to find connections to application contexts that can achieve impact early on. This pattern of thought/action adds layers of complexity to major challenges beyond those typically highlighted in the study of design, which tends to focus on balancing tradeoffs and benefits in solutions [20, 124, 125]. Although this pattern has not been explicitly documented in the design literature, these additional layers of complexity have implicit links to technology and strategic management theories, such as dominant design [126], technology-category co-evolution [127], and technology-market matching [128, 129]. Additionally, this "lily pad" approach to solution evaluation, selection, and development is fundamentally different than pursuing advanced solutions ("moonshots") in a single application context and waiting for benefits to trickle down to other societal contexts [35]. Consequently, it challenges the often times hidden/implicit assumption that new ideas need to stay in the application context in which they were conceived. Relevant behaviors for this evaluation and selection pattern identified in our work are defined in Table 6.

In the history of X-ray technology, for instance, early applications included short stints as entertainment and shoe fitting devices in department stores, as customs inspection devices, and as a means for identification of the deceased after fire tragedies. Early X-ray technology was also more suited for use by dentists to scan teeth than by physicians to examine bones [77]. It was not until several technical, economic, and sociological barriers were addressed that physicians routinely employed X-rays in hospitals. Microfinance began as a project to diminish famine in Bangladesh, evolved to a farming improvement university-based community project, and to private loans managed by its founder, before jumping into the institutional banking domain [75]. In the case of lasers, where the technology sparked interest in many fields, 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 [130, 131].

In our performance tasks, we observed participants engage in performance-context matching decisions. As an illustrative example, we walk through Charles' evaluation of EV technology, starting with his assessment of the fundamental performance dimensions of battery technology:

> ". . . basically, an EV is a battery system or some sort of energy storage system. There's four things that impact battery life: 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. All these things have some interdependencies, too."

Charles also matched the performance of EV batteries to possible application contexts:

> ". . . you gotta find the right assets, and it might be 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 practical, because 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, 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. So if you're actually gonna try to improve acceptance, I'd be looking at how do you make it cool to drive an EV to school, for instance, where we have lots of kids who go to high school. Again, you've gotta look for places that this whole system can be a benefit or an asset."

Finally, Charles also de-agglomerated EVs to find applications for parts of ideas, even if in counterintuitive contexts (e.g., using EV batteries in military bases) or for counterintuitive purposes (facilitating quiet time in such bases)

> ". . . 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 EVs, if added to the generator set for the military, there's recent studies that show that you can turn the generators off for six hours at a time. 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 can make the command post relatively quiet for at least some blocks

Table 6. Rethinking Solution Performance and Connecting to Early Impact Contexts

Behavior	Definition
Identifying dimensions of performance and headroom	Creating a mutually exclusive and collectively exhaustive perspective of technical, economic, psychological, and sociological dimensions of performance of a solution
Mapping accepted and counterintuitive tradeoffs	Evaluating possible variations in dimensions of performance of an idea, even those that might be considered counterintuitive
Characterizing application contexts	Creating a perspective on the reach, significance, paradigm change, and longevity that can be pursued and the performance requirements in a given context
Matching lily pad contexts with tradeoffs and headroom	Creating a roadmap that connects solutions to contexts that embrace a given set of tradeoffs, even if outside of traditional expectations/boundaries, to accelerate ideas

Table 7. Persuading to Facilitate Acceptance or Use

Behavior	Definition
Telling stories to paint a vision	Communicating persuasively to build buy-in for ideas
Conveying counterintuitive insights	Conveying ideas that deviate from those typically encountered in a given context in tailored ways
Creating win-win partnerships	Building relationships with ecosystem stakeholders that can influence the success of an idea
Driving habit conversion	Influencing/nudging decisions through the presentation of choices

of time. 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 there are some other things that we can get out of this."

This pattern of thought and action recognizes that, in major challenge situations, the performance of solutions is constantly evolving and one of the critical choices in the evaluation and selection of alternatives is to identify appropriate tradeoffs necessary to maintain solution feasibility. Our data suggests that designers/talent might need to not only balance tradeoffs and benefits of solutions, but also match tradeoffs to application contexts to form lily pads where solutions can advance and achieve early impact—even if such solutions are in seemingly counterintuitive contexts or purposes. These contexts can "host" an innovation, accept its current performance/capability, generate impact, help unfold a paradigm, garner resources, and allow an idea to advance/survive.

7. Pursuing high impact ideas

In the Pursue cluster of the framework we describe the process of moving from shaping to implementing solutions for major challenges. Here, we unpack perspectives of designing for major challenges for three design stages in Fig. 4: communication, path definition (herein defined as implementation planning), and implementation.

7.1 From information transfer to persuasion

In the communication of ideas that aim to address major challenges, simply transferring information may be not be enough as altering ecosystems and driving paradigm change requires artful persuasion to facilitate acceptance or use [7, 22]. This may involve storytelling, habit conversion techniques, and means to convey counterintuitive insights [132–137]. These techniques tap emotion, empathy, and human nature, and are key to addressing the natural resistance to new ideas. Stories, for example, help paint visions and trigger emotions that enhance idea adoption [138, 139] because the marketplace for ideas "competes not only over truth but also over emotion" [138]. Relevant behaviors identified in our work for this pattern of thought and action are defined in Table 7.

In history, solutions to major challenges have been accompanied by persuasive communication. For example, the invention of lasers tapped into human emotion and storytelling given their potential to be envisioned as weapons [130, 131]. In the case of anesthesia, paradigm-related habits had to be changed over time. Doctors were habitually used to operating quickly to minimize a patient's suffering and had to adjust their behaviors for surgical procedures involving anesthesia to be more elaborate and less time pressured [100]. Similarly, surgeons had to modify behaviors to incorporate sterilization techniques with the advent of antisepsis [100].

We also observed persuasion patterns in the EV performance tasks. For example, with regards to habit conversion, Nicole isolated routine behaviors that would need to change and the consequences for failing to change such behaviors for the transition from gasoline vehicles to EVs:

". . . because people, the drivers, they have habits and it's really hard to break habits. So right now you go home, 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 EVs, there's a whole new step there, you have to plug it in. So, there's kind of this degree of habit change required . . ."

In major challenge contexts, persuading rather than simply communicating are key to addressing the natural resistance and skepticism to new ideas. Effectively, the design of solutions for major challenges must be accompanied by a plan to effectively, efficiently, and persuasively communicate their benefits—specifically if such ideas are counterintuitive—as well as a plan to proactively manage required habit and behavior changes.

7.2 From predicted and deliberate to emergent and effectual pursuit

In ideas wrought with Knightian/unclassifiable uncertainty [140], such as major challenges, implementation strategies should be designed to provide desired levels of adaptation and control [141].

Such strategies could thus blend transformative approaches (low prediction, high control) such as effectuation [142], adaptive approaches (low prediction, low control) such as emergent strategy [143, 144], as well as discovery-driven planning and real options-based techniques [145, 146], to help design implementation paths toward impact.

Two final patterns emerged from our data related to defining implementation paths and actual implementation of ideas for major challenges. In designing effectual and emergent paths to unfold the impact of ideas, implementation paths are defined by mapping and converting key assumptions necessary to achieve impact into actionable learning experiments. These strategies are then implemented by deploying learning experiments to discover the path to impact, prioritizing opportunities to earn (for resource sustainability), learn (for solution improvement), and redirect efforts in light of learning. Relevant behaviors for these implementation stages are defined in Table 8 and Table 9.

Victor, for example, stated in his performance task that for his envisioned ideas he would iterate frequently between assumptions, plans, and consequences to understand why EVs are or are not gaining ground:

> "The next step would be, okay, so here's what my plan would look like. This is how I would execute it. And then I would do another iteration through what are the assumptions, what are the plans, what's the consequences? I'd be going back and verifying my assumptions around, okay, is this really what consumers want? Because if my assumption is correct that the technology is sufficient, why aren't people evolving more quickly?"

Drew engaged in a similar process and outlined hypotheses and possible experiments. From his standpoint, increasing EV adoption is an ecosystem type of challenge and thus experiments should reveal information about how an ecosystem works (although he acknowledged that component assumptions can be as critical):

> "So, there are certain assumptions and hypotheses. The first hypothesis—let's say performance of electric car, whatever type it is, equals the traditional car. The second hypothesis will be that the battery price comes down dramatically, and that this is driven by scale. . . Then, I think the test would be pretty simple. I would probably take in the US a state—or a city, and I would say, for example, subsidize cars and charge more for fuel, and see how things evolve. I think to de-risk it, you need all the stakeholders to play together in an ecosystem. Let's start with something, and just simulate the reality as it could look like and eliminate all risk factors. Customer demand? Yes. Car manufacturers will produce? Yes. Battery manufacturers will produce? Yes. Long term interest? Yes. Of course, you can insulate or isolate some of the elements, but I don't think—you don't crack the case like that. I think because the key element—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."

Overall, the implementation of solutions in major challenges needs to be designed to accommodate their inherent degree of uncertainty. It is unlikely that all issues—such as performance limitations, uncertainty in application spaces, ecosystem level barriers, and other barriers/roadblocks—can be envisioned at the onset or discovered while shaping a solution; some will likely only emerge during implementation efforts. Hence, implementation strategies should be defined in emergent and effectual ways that facilitate the conversion of assumptions into knowledge, and prioritize opportunities to learn, generate impact, and re-direct efforts in light of learning.

Table 8. Designing Emergent and Effectual Paths to Implementation

Behavior	Definition
Envisioning multiple impact pathways	Mapping sets of possible pathways to idea success given the uncertainty that is inherent in ideas with high-impact potential
Identifying learning metrics and assumptions	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
Creating learning experiments	Creating a set of experiments that can be used to learn more about an idea and convert its assumptions into knowledge

Table 9. Deploying Learning Experiments to Discover the Path to Impact

Behavior	Definition
Selecting paths to learn and earn	Choosing between paths to pursue based on potential learning, earning, and/or achievable impact
Experimenting for smart failure	Pursuing first-hand iterative learning via active experimentation
Leveraging unexpected opportunities	Capitalizing on unexpected occurrences that highlight new paths, goals, or ideas
Adapting based on learning	Re-directing efforts from insights gained through emergent strategies

8. Core behaviors

In addition to design stage-specific behaviors, a subset of the behaviors that emerged from our data were labeled as "core" (see Fig. 5), because the data suggests that they are foundational to the framework. In the process of tagging/coding excerpts, these behaviors were identified as relevant to multiple design stages. This suggests that such behaviors (shown in Table 10) are foundational to designing for major challenges, and, likely, more broadly applicable to any type of innovation endeavor.

While providing justification for each behavior is out of scope for this paper, we herein illustrate how our data suggests that core behaviors are applicable to multiple design process stages. We employ three behaviors in our list as examples: separating negotiable norms from non-negotiable rules, distilling the core idea from its context, and diverging-structuring-converging.

For example, 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 (e.g., new perspectives of problems, information, alternatives, tradeoffs, systems, solutions, and implementation issues). In the case of anesthesia, for instance, speed 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 anesthetics [101]. In the case of microfinance, an assumption about the poor being unbankable prevailed according to conventional banking practices, when in reality what was needed was a new business model and supporting ecosystem. In the case of the laser, and more specifically, its 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 [147].

As another example, distilling the core of an idea from its context is defined as detaching context-specific language from descriptions of ideas to facilitate connections and understanding across fields. Engaging in this behavior can help talent understand the broader potential of ideas, because new ideas often get rapidly associated with a context/circumstance of use, and such associations are typically difficult to remove (i.e., they become embedded, albeit negotiable, norms). This core behavior is complementary to many patterns in the framework. Paradigm flaws, for example, can stem from associations to context-specific circumstances and the identification of such flaws can stem from removing such associations. The identification of problems and solutions can also be re-framed when circumstance-specific details are removed, facilitating, for instance, the generation of previously uncovered insights or new links between ideas.

Similarly, diverging-structuring-converging, which refers to a behavior observed in which some participants structured the results of their diverging process before converging or diverging again to assess the exhaustiveness of an idea space, can be employed in the identification of problems, generation of alternatives, analysis of systems, and evaluation and selection of solutions. This intermediate structuring step allowed participants to assess the comprehensiveness of a problem or solution space to then decide if one should continue to diverge to address blind spots, converge, or explore a different

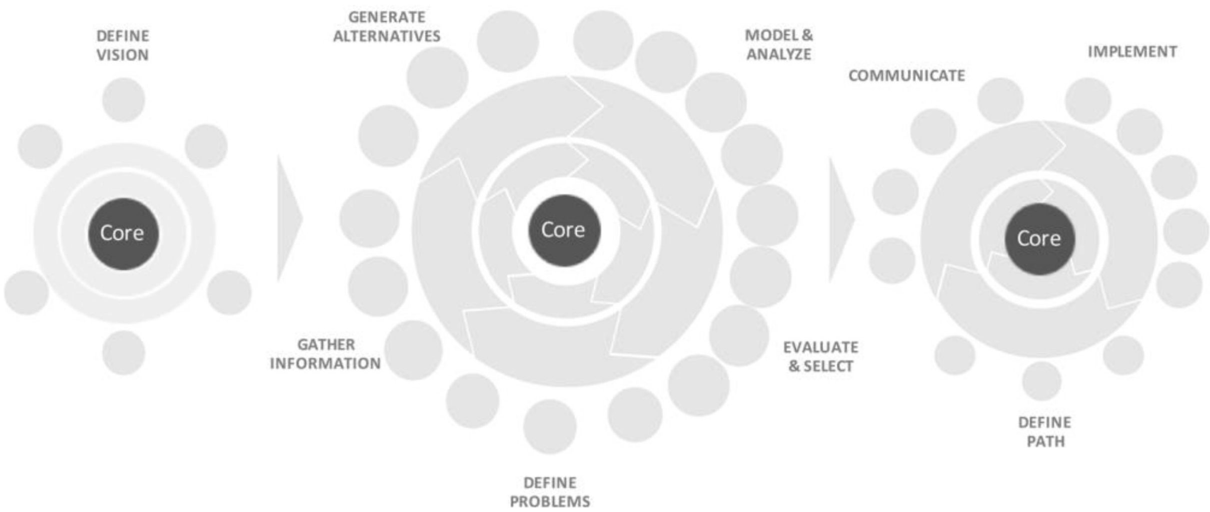

Fig. 5. Core Design Behaviors.

Table 10. Core Behaviors to Design for Major Challenges

Behavior	Definition	Link to High-Impact Solutions
Recognize and label patterns	Assigning a label to a given input stimulus value	Design can benefit from innovation pattern recognition in which new ideas can be better understood through problem and solution 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 solution	The pursuit of high-impact solutions relies on identifying critical choices to 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 more targeted solution-development actions
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	Barriers and opportunities for high-impact solutions are often hidden in norms that are the result of historical precedent, and which 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 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 solutions into an ecosystem calls for a thorough examination of multiple perspectives (e.g., technical, economic, sociological, systemic, and psychological issues)
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 problems and solutions 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 deeper levels of cause-effect relationships, to gain a more fundamental understanding and the ability to derive novel insights	Barriers and opportunities for problem-framing and solution-development are often hidden at deeper levels of cause-effect relationships that, if explored, can uncover new principles and/or insights
Synthesize insights	Integrating new dimensions of understanding to form a whole greater than the parts	The many issues surrounding problem-framing and solution-development need to be synthesized concisely and effectively for persuasion and understanding
Iterate and reflect	Utilizing strategies multiple times as needed, while keeping track of them through reflection/meaning-making	Given its inherent uncertainty, innovation is a highly iterative process that must undergo multiple iterations with a reflective practitioner mindset

opportunity as a result of the categorization process. Don, for instance, in our performance tasks, engaged in this behavior often when exploring 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. 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."

Other core behaviors in our framework were identified through a similar process. Overall, after multiple rounds of tagging and identifying excerpts and instances of behavior in our methodology, these behaviors stood out as more broadly applicable, and different, to those that our data suggested were more stage-specific, hence suggesting their separation from specific design stages.

9. Discussion

Our framework to design for major challenges has implications for two categories of stakeholders: (1) innovation and education researchers and practitioners, especially those looking to influence engineering education; and (2) practitioners in academia, industry, or non-profit endeavors, especially those looking to address major challenges. We discuss implications for each stakeholder category.

For innovation/education researchers and practitioners, our framework has implications for program/curriculum design, as well as research in learning and educational theory building across disciplines and educational stages (from undergraduate to professional settings). The framework is situated in the more prescriptive end of the descriptive-prescriptive spectrum of educational theories, particularly with regard to articulating the types of ideas and skills that should be taught when the goal is to innovate for major challenges in pragmatic ways. As a result, implications of the framework for those looking to influence engineering education include:

- *The framework codifies a set learning goals organized in an end-to-end model to be used in research.* The design patterns and behaviors in the framework represent a gamut of learning goals to be further studied in cross-disciplinary educational research, along with teaching strategies, assessment, and pedagogies that are relevant for teaching/learning to innovate for major challenges. While other efforts have attempted to map innovative competencies/behaviors, unique to this effort was the fact that an end-to-end design process model, common in design learning, was used as an anchor to organize the framework, which facilitates links between the design education and innovation literature. Some attempts to characterize problem-solving approaches for innovation have created related frameworks, but these typically mix behaviors, cognition, and non-cognitive/attitudinal traits with little to no conceptual organization. In other instances, models address only select aspects of a design process (e.g., Dyer et al.'s [148] model of opportunity recognition).
- *The framework provides an end-to-end foundation to teach students to design for major challenges.* Although more research on the patterns and behaviors is needed, the framework described herein is end-to-end and can be used as a foundation to design educational experiences (e.g., coursework, experiential learning initiatives) that teaches students the fundamentals of addressing major challenges. Students of today are the major challenge researchers and practitioners of the future and we should ensure they are prepared to face them.
- *Educating to design for major challenges implies rethinking notions of expertise.* In a rapidly changing world, any domain-specific expertise, although critical to advance knowledge, is threatened by the possibility that such expertise might become irrelevant or outdated in shorter time spans. Further the 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 trends highlight the need to further understand more fundamental types of expertise that are non-domain specific and could make the adaptive expertise construct (see [149]) more explicit. Different ways of thinking, acting, and being that represent expertise in areas such as innovation, systems, design, and entrepreneurism should likely be further characterized and studied. Rethinking notions of expertise can in turn lead to a better understanding of how to enable and empower students and practitioners to navigate the ever-increasing body of knowledge—especially in the face of challenges such as those outlined in the National Academy of Engineering's Engineer of 2020 and Grand Challenges reports [5, 19].
- *Educating to design for major challenges requires true practice of cross-disciplinarity.* Major challenges are unlikely to be solved without truly engaging with multiple disciplines (e.g., business, engineering, science, humanities). This makes it critical that we organize educational experiences and programs to not only teach students about working together across fields, but—in line with research on cross-disciplinarity—teach students to truly learn about, and intelligently engage with, other fields in meaningful ways in order to challenge and transform practice (e.g., see [150]).

For practitioners looking to address major challenges, our framework has implications for the examination and pursuit of ideas, and the evaluation/selection of teams involved in addressing these challenges. More specifically:

- *The framework can be used by practitioners to drive towards new types of solutions.* Awareness of the patterns and behaviors described herein can help practitioners drive to new types of solutions by examining and pursuing ideas with a different/broader lens. It can help practitioners be aware if they are testing multiple entry points to shaping processes for their vision, searching for flawed paradigms, systematically examining technical, economic, systemic, sociological, and psychological implications, shaping ecosystems holistically, searching for lily pads as means to make progress and reduce risk, persuading to facilitate adoption, and creating and deploying implementation plans that are emergent and effectual.
- *The framework can be used by leaders in organizations to guide their organizations/teams.* Each of the patterns and behaviors described herein can help leaders understand if stakeholders are asking the right questions about concepts/ideas with potential, in order to drive breakthroughs towards impact. It can also help them understand if their teams need training in any of these activities, to help them conceptually shift their thinking for specific stages of the design process.

- *The framework can be used by leaders in organizations to assemble teams*. The framework can be used by practitioners to view their teams under a different lens. Addressing major challenges is inherently a team-based activity, and likely a multi-organization activity. The multi-stakeholder nature of the pursuit of solutions to major challenges inherently involves group dynamics that need to be managed and represents a co-inquiry/co-shaping process of solutions towards impact. The framework can thus be used to assess whether team members have the right mindset and/or complementary strengths in the key areas of the framework—as no individual is likely to excel at all behaviors described herein.

With regard to limitations of the study, the conscious choice of broadly exploring the topic of design for major challenges inherently implies a tradeoff (and limitation) in terms of breadth vs depth of analyses, which parallels what Schön [151] describes as the dilemma of rigor vs relevance. Limitations also exist with regards to survivor bias, given the focus on case studies that "survived" in a given context, which might overlook cases that did not survive. Effectively, the historical cases analyzed in this study are prone to this type of bias although this study does not claim that engaging in all identified behaviors will result in success. This choice, however, was intentional, as our goal was to identify behaviors that have been, directly or indirectly, linked to success.

Opportunities for future work are broad. For instance, there is an opportunity to study individual behaviors, or subsets of the behaviors described herein to provide more in-depth empirical validation. In addition, future studies that use quantitative data (which is plausible and the basis for future work) can provide new insights regarding the ideas developed herein. The choice of solely using qualitative evidence in this study was consciously made given the intent of creating a model/framework with rapidly evolving new constructs that open up a space for future studies (both qualitative and quantitative), as well as our desire for greater scope/breadth. The framework, as presented herein, is considered a starting point, and, as the body of knowledge on designing for major/complex challenges increases, it will likely undergo multiple iterations to improve findings, insights, and language. Regardless, the framework to "design for Big X" is a stepping stone towards influencing the practice of innovation and design for major challenges in educational settings, as well as in business, non-profit, research and government, by providing new guiding philosophies and behaviors to more systematically pursue solutions to major challenges.

10. Conclusions

In this study, we employed a multifaceted approach to understand a qualitatively different type of design that is specific to major challenge endeavors. Such an effort integrates concepts from fields such as innovation, design, and systems, and thus opens up new pathways for the study of major challenges, as well as the study of teaching and learning aspects related to addressing them. Effectively, we simultaneously integrate and translate design, innovation, and systems research for the context of major challenges, while setting the foundation for new research streams on design and innovation, and engineering education.

The framework developed in this effort consists of a set of nine design patterns, one for each stage of the design process, which are unpacked into a set of behaviors to design for major challenges. Additionally, the framework identifies a set of behaviors labeled as "core" because they are not design stage-specific (i.e., they can be employed across design stages). The framework can be used as a foundation to further our understanding of major challenges and as a foundation for future research on the topic. It can also be used as an anchor for the design of educational experiences, as well as by practitioners who are working to frame and find solutions to these challenges. Awareness and practice of these patterns and behaviors will be valuable to individuals pursuing significant impact in the world.

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Freddy Solis is a former postdoctoral research associate at Purdue University and currently a consultant at Innosight, an innovation and strategy firm in Boston, MA. His research focuses on innovation typologies, patterns and principles, strategy in technology, industrial, and R&D contexts, as well as design and innovative thinking in the context of major challenges. Freddy holds a PhD from Purdue's College of Engineering with an emphasis on innovation and design, an MBA from Purdue's Krannert School of Management, a MSc in Civil Engineering from Purdue, and a BSc in Civil Engineering from the Universidad Autonoma de Yucatan in Mexico.

Joe Sinfield is an Associate Professor of Civil Engineering, and the founding Director of Purdue's College of Engineering Innovation and Leadership Studies Program. Dr. Sinfield's research, teaching and professional activities are concentrated in two focal areas: (1) innovation science, intrapreneurship, entrepreneurship, and engineering education, and (2) experimental methods, digital technologies, and sensor design. Sinfield has nearly two decades of experience as an advisor to senior leaders of multi-national corporations on systematic methods to identify, prioritize, and commercialize growth opportunities, design new business models, and manage strategic change. Sinfield held the position of Senior Partner at Innosight, LLC, where for 13 years he helped lead the firm from a small start-up to a global innovation strategy and investment firm that was acquired by a publically traded company. Prior to Purdue and Innosight, he was a strategy consultant for over 5 years with McKinsey & Company. Dr. Sinfield is a frequent speaker on the management principles that can be employed to more predictably drive innovation and serves on the innovation advisory boards of multiple companies, including the TPT Scientific Advisory Board of Procter & Gamble. He is the co-author of The Innovator's

Guide to Growth: Putting Disruptive Innovation to Work (Harvard Business Press, 2008), and has published broadly in the popular press, business media, and an array of peer-reviewed journals in science and engineering. Dr. Sinfield received a BS degree in civil engineering summa cum laude, from Bucknell University, Lewisburg, PA, and MS and ScD degrees in civil and environmental engineering from the Massachusetts Institute of Technology, Cambridge, MA. He also worked as a geotechnical engineer at Haley & Aldrich in Cambridge, Massachusetts early in his career.