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Upsetting the Convergence Norm: Investigating Practitioner Engagement in Divergent Thinking*

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Both divergent and convergent thinking processes are core to engineering practice. Engineers can divergently explore many potential approaches, perspectives, and solutions and then ultimately converge on one to pursue. Because convergent processes dominate engineering education and practice, engineers often struggle to diverge while solving engineering problems. Divergent thinking can support complex problem solving, innovative solutions, and engagement with diverse perspectives, but research on its use in engineering is limited to design concept generation. We interviewed 20 engineering practitioners to explore how they engaged in divergent thinking during problem-solving. We identified 17 dimensions described by practitioners as impacting their divergent thinking practices during engineering projects. Practitioners described shaping their divergent thinking engagement through personal knowledge, perspectives, and actions, and pointed to influences from organizational structures, culture, and processes. This evidence suggests an engineering culture where 'convergence is king' fails to meet the needs of engineering practice and education.

Keywords: divergent thinking; engineering practice; engineering culture; professional practitioners

1. Introduction

Divergent thinking involves exploring many potential alternative options and diverse perspectives [1, 2], while convergent thinking synthesizes information to identify a single 'correct' answer [3]. In engineering projects, both are crucial processes for solving complex problems [4, 5]. For example, engineers might divergently explore varied methodologies to resolve a technical issue, then converge on one approach to pursue further.

Engineers can struggle with divergent thinking, sticking to familiar solutions and perspectives [6–9]. Research suggests this tendency may stem from a lack of 'openness to experience' and other personality traits [10, 11]. Organizational influences, such as inadequate training, culture, environment, and workload, can also hinder divergent thinking processes on engineering projects [12].

Most research on divergent thinking in engineering focuses on generating diverse design concepts [13, 14]. Yet, divergent thinking can also apply to exploring multiple perspectives, methods, and broader systems. In order to understand ways to better support divergent thinking in engineering projects, we interviewed mechanical engineering practitioners about their experiences with divergent thinking during problem solving. Our goal was to uncover insights about how people and organizations can better support divergent thinking processes in engineering to foster innovation and achieve successful and socially engaged outcomes.

2. Background

While both divergent and convergent thinking are important aspects of creativity in engineering, there is little debate that convergent analytical skills are prioritized in education. A study of seven engineering courses aimed at fostering creativity found that instruction emphasized convergent skills like analysis and evaluation, with little coverage of divergent thinking skills like idea generation and openness to exploration [15]. Another study of over 1100 required electrical engineering courses and found less than 2% explicitly included creativity [16]. A review of engineering education literature found that divergent thinking was studied in only about a third of articles reviewed [17]. Engineering instructors and students identified ten 'maxims' of creativity, many of which align with divergent thinking, such as, "keep an open mind, ambiguity is good, encouraging risk, and search for multiple answers" [18]; however, instructors struggled to teach these principles and students felt their education lacked them.

Divergent thinking in engineering fosters creative and innovative outcomes [5, 19], preventing repro-

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duction of the same ideas. For example, a study of engineering designers' initial ideas found them likely to be already suggested by others and therefore not viewed as novel [20]. Divergent thinking helps engineers move beyond obvious ideas to original ones, and supports alternative approaches to problems beyond an obvious pathway [21]. Grant [22] described that when people are offered a binary choice, they often double down on their original perspective, but a problem with more nuanced choices, encourages open, diverging approaches. Divergent thinking can help engineers to incorporate the diverse perspectives of stakeholders in their work [23], an essential asset when navigating the social and technical relationships within engineering systems [24]. Exploring and valuing diverse perspectives is also key to supporting more inclusive and equitable engineering outcomes [25, 26].

2.1 Opportunities for Divergent Thinking in Engineering

Research on divergent thinking in engineering has focused primarily on concept generation in early design. Concept generation is a central engineering design activity [27]. To move beyond fixation on past and current ideas [28] the concept generation process often leverages tools such as Brainstorming [14, 29], Morphological Analysis [30], and Design Heuristics [31] to explore varied ideas. Extensive work has been conducted to understand divergent thinking practices and outcomes supported with the tools [32]. Although divergent thinking is central to concept generation [33], it can also benefit other areas of engineering problem solving, such as defining problems, conducting research and gathering information, identifying stakeholders, and naming potential implications.

When developing problem understanding, engineers might explore the framing and core need of a problem [34, 35], including by taking various perspectives on the problem [36, 37]. One study identified 27 different perspectives engineering students and practitioners used to explore problems, such as breaking down the primary stated need, focusing on a particular setting or scenario, or expanding the given scope [36]. Reframing the problem can be challenging, especially in contexts where employees lack power, legitimacy, and allies in support of that exploration [38].

Divergent thinking can benefit background research and information gathering by supporting the collection of many, diverse forms of information, which is important to taking on a systems perspective in understanding the problem and possible solutions [39]. Guilford [40] described divergent thinking as 'searching around or changing direction.' Engineers might 'search around' for diverse sources of information [41] that help engineers learn about various contextual factors, such as local education rates, institutional practices, and existing technology [42]. Further work is needed to understand what inhibits or facilitates engineers in exploring diverse information sources.

Understanding diverse perspectives is crucial for engineers, as their work is impacted by and impacts people [43], yet engineers have been shown to struggle to identify and manage many different perspectives [23, 44]. Stakeholder identification research in business management literature [45] and design literature [46] has pointed to the importance of seeking out many, diverse perspectives to inform decisions. Failure to account for diverse stakeholders when engineers develop technology can lead to harmful, biased outcomes, such as facial recognition technology misclassifying darker-skinned individuals [47] and at-home COVID-19 tests unusable for blind people [48]. More research is needed on how engineers explore stakeholders in their work.

Engineers must also explore the impacts of their work, including on society and the environment. One review of medical device engineering described that developing the device alone is insufficient to improve health equity; in addition, engineers must look beyond the device to engage community stakeholders and investigate contextual factors that might impact device implementation [49]. Humanitarian engineering programs stress the importance of integrating and embedding education on societal, human, and ethical impacts of engineering practice [50], and the Engineering, Social Justice and Peace effort described the need for both reason and compassion in engineering work [51]. While it is clear that engineers must broadly consider implications of their work, there is little research on how engineers can divergently explore those implications.

3. Methods

The following research question guided our study: What do practitioners report as impacting their divergent thinking during engineering problem solving?

3.1 Participants

Participants included 11 men and 9 women working at the time of the interview as engineers in the United States. Participants identified their race and/or ethnicity as white (11), Black (5), Latinx (1), Hispanic (1), Southeast Asian (1), and Guyanese (1). Their engineering practice experience ranged from 1.5 to 38 years, averaging 12.4 years

(SD = 10.7). Participants worked in engineering industries including automotive, electric vehicle, consumer products, biomedical, human factors, aerospace, commercial trucking, defense, locomotive, energy, and various research and development areas. All participants identified themselves and/or their work as within the mechanical engineering field. We selected participants in mechanical engineering to demonstrate possibilities for divergent thinking within a single field not limited to solely design experiences, but encompassing various mechanical engineering problems. This approach expands recognition of divergent thinking beyond design projects, which have been the focus of divergent thinking research. Participants were identified and recruited using the authors' professional networks, local engineering associations, and snowball sampling.

3.2 Data Collection

The first author interviewed each participant over Zoom with audio recording. Interview length ranged from 74 to 105 minutes, with an average of 86 (SD = 7) minutes. Before the interview, participants were asked to recall one specific experience during a past project where they practiced divergent thinking: "We're interested in open-ended engineering project experiences where you explored multiple options or perspectives in one or more aspects of the project." We explicitly requested they consider exploration they consider either successful or unsuccessful during a project.

The research team developed an interview protocol based on recommended practices for semi-structured interviews [52, 53], prior author experience conducting concrete experience-based interviews with practitioners, and pilot testing with practitioners not in the study. The protocol questions, sequence, and language were revised following an iterative protocol development process, as described in more depth by Clancy and colleagues [54].

During the interviews, we first asked participants to describe the "big picture" of their identified past project, along with its timeline, goals, and constraints. At the beginning of the interview, we suggested five potential areas of exploration during engineering problem-solving processes [27, 55]: problem understanding, background research and stakeholders, problem solving approaches, types of solutions, and project implications. Each participant selected which areas of divergent exploration were most relevant to their project and answered the following questions for each area: (1) What did you do? (2) How did you decide to do that? (3) What alternative options did you explore? (4) How did you know you had explored enough? (5) What alternatives did you not explore? (6) Why did you not explore those alternatives? (7) How successful were you at exploring?

These questions were described within the exploration area selected; for example, the problem-solving approaches questions were: (1) How did you go about solving the problem? (2) How did you decide this was the strategy you wanted to use? (3) What other ways did you consider solving the problem other than the strategy you use? (4) How did you know that you had considered enough possible problem-solving strategies for you to move forward with the project? (5) Thinking more broadly, are there multiple different ways the problem *could* have been approached to reach solutions that were not considered? (6) Why were those strategies not pursued within this project? (7) How successful do you think you were at exploring problem solving strategies?

Next, we asked participants to compare their selected experience to another one where they were either more or less successful at divergent thinking. This comparison helped identify factors influencing their exploration across projects. We concluded the interviews with broader questions about how participants' training, engineering experiences, personal perspectives, and engineering environments impacted their ability to explore diverse options and perspectives. We used follow-up questions in the interviews to probe for clarification, additional depth, and meaning.

3.3 Data Analysis

The first author immersed herself in the data by transcribing interviews by hand and doing multiple close readings of interviews, in accordance with recommended qualitative analysis practices [56, 57]. The research team employed a multi-pass coding strategy to analyze the data according to the research questions. In the first pass, two members of the research team identified interview excerpts that described examples where practitioners' divergent thinking was impacted, coming to consensus on identified excerpts. In the second pass, guided by recommended practices [57, 58] we inductively categorized the excerpts according to the circumstances they described, generating a preliminary list of themes impacting divergent thinking practice. For example, a participant in the aerospace industry discussed a project involving extensive stakeholder exploration. The project involved a large metal part of a fighter jet to be dipped, rotated, and pulled out of a chemical mill tank within 12 seconds to minimize hand-grinding slag from previous welding:

> "It was . . . a lot of sitting down boots on the ground, getting the right people, the stakeholders involved that are going to be involved in this process and getting

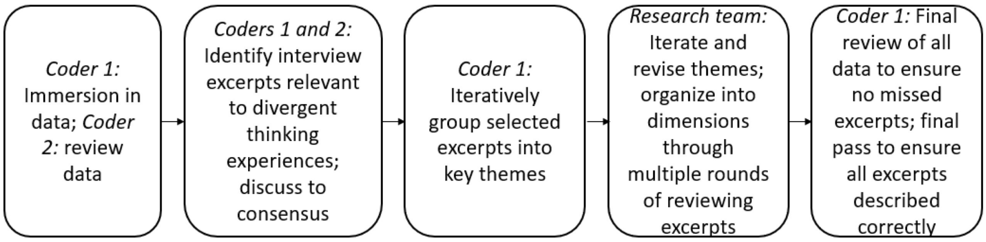

Fig. 1. Flow chart of data analysis process.

> their feedback because I have zero process for running a [chemical-mill] line . . . I would . . . go talk to somebody . . . the operators themselves go, 'If you put it on this side, then I can access this and this easier. So, when you do the design, make it here.' And make it this height because, again, they're on a platform. There's tanks and then there's the actual conveyor system above that moves that. So, the elevation that they're working on too, you don't want to reach. You have OSHA (Occupational Safety and Health Administration) requirements for overhead work, all these other things . . . I would not have understood some of those . . . issues had I not gone and just had a conversation with these people. So, through that, just with a notepad and sketching it out, I came up with some ideas and then [would] go back to the computer, fill out the details, and then go back with those people again. And I think that was key to success of this . . .We had a[n existing] check process . . . And I didn't follow that process . . . Nowhere in the process says, 'Go talk to the operator.' . . . Getting stakeholders involved really early from the concept was what made that a success.''

In this excerpt, the practitioner identified many dimensions impacting his ability to think divergently. He had minimal knowledge on the topic, prompting him to explore various stakeholders for expertise. Conversations with operators led him to consider new implications: the platform height, OSHA requirements, and operator arm reach. Sketching helped him explore potential solutions and engage further with his stakeholders. The participant described limitations of his company's process, including the convergent norms of his company that made stakeholder exploration difficult, as engineers typically are told to meet set requirements without additional exploration.

In further analysis of the meaning of excerpts identified across interviews, we perceived dimensionality in the themes. For example, agency and openness as a theme appeared in transcripts as both positive examples and negative expressions of fear, embarrassment, or failure if exploration was attempted. The description of themes was best described as dimensions where the same core theme – agency and openness – was described as both a focus for some and as ''avoided'' by others. Guided by suggested practices [58, 59], the team extensively iterated on these themes as dimensions to accurately represent practitioners' descriptions, reflecting their use as both positive and negative influences. Seventeen separable dimensions impacting divergent thinking (either positively, negatively, or both) were identified. The first author did a final close-read pass of all data to ensure all relevant excerpts were identified and described accurately. This analysis process is represented in Fig. 1.

4. Findings

In our results, we identified 17 dimensions described by participants as impacting their divergent thinking, detailed in Table 1 and with interview excerpts provided for each dimension in the Appendix.

4.1 Individual Dimensions

In this section, we discuss two prominent dimensions related to the engineers' individual knowledge, perspectives, and actions. We discuss the ways in which they as an individual either facilitated or inhibited divergent thinking practices.

4.1.1 Agency and Openness

Agency and openness towards exploration was a proliferous dimension for facilitating divergent thinking. This dimension included the individual characteristics and mindsets that prompted engineers to value and push towards divergent thinking. One participant said:

> ''To be an effective problem solver that takes a degree of humility, willingness to listen to other people's opinions and entertain their ideas, and a willingness to change your own perspective when necessary.'' (P6)

Another participant echoed the importance of humility in facilitating their divergent exploration: ''It's just like coming and saying humbly, 'I don't know how do to this but I'm willing to learn.' '' (P20).

In contrast, practitioners described how fear of embarrassing themselves prevented them from exploring broadly. One practitioner said:

> ''I didn't ask many questions . . . I was shy, and I wanted to be good at my job, but I didn't want other

Table 1. Dimensions participants described as influencing their divergent thinking. Four dimensions were described by participants only as facilitators or only as inhibitors. We added italicized descriptions to denote hypothesized themes not directly observed in the data. Example interview excerpts for each dimension are included in the Appendix

	Facilitation of Divergence	Exploration Dimension	Inhibition of Divergence
Individual	Willingness to explore unknowns	**Agency and Openness**	Fear of embarrassment and failure
	Scaffolds what/where/how to explore	**Familiarity with Topic**	Assumes more exploration is not needed
	Aware of one's own limitations	**Humble Expertise**	Fixates confidently on single path
	Lack of knowledge forces exploration	**Knowledge Limitations**	Limits knowledge of possibilities
	Willingness to explore new paths	**Risk Aversion**	Conservative decisions to avoid risk
	Mental & physical visualizations	**Tangibility**	*Absence of physical observation*
Organizational	Envisions broader system implications	**A Systems Viewpoint**	Narrow focus on separate parts
	Clear goals bound deeper exploration	**Clarity in Scope**	Ambiguity confuses exploration
	Resource (time, money, team) affordances	**Costs**	Limits from lack of resources
	Designated a process for exploring	**Designated Process**	Uncertainty prevents exploration
	Unconstrained projects open alternatives	**Existing Constraints**	Defined constraints limit alternatives
	Critical projects drive deeper exploration	**Project Importance**	Small projects do not warrant exploration
	Motivation to change and innovate	**Valuing Divergence**	Convergence incentive
Relational	Diverse perspectives offer more alternatives	**Diversity of Perspectives**	Less diverse teams converge on status quo
	Encourage and guide exploration	**Mentors and Experts**	Serve as sole decision authority
	Stakeholders' interest drives exploration	**Stakeholder Investment**	Exploration stunted from lack of interest
	Balance of egos, information, & risks	**Team Collaboration**	"Silos" limit information access

> people to think I didn't know what I was doing even though as the young engineer . . . I wanted to learn everything on my own and not sound stupid." (P17)

4.1.2 Knowledge Limitations

The most frequently observed dimension inhibiting engineers from engaging in divergent thinking was their own limited knowledge of their project topic. For example:

> "DFMEAs [Design Failure Mode and Effect Analysis] are . . . intended to catch potential problems, but that's really difficult to do in practice because you can only put in DFMEA things you already know, you know?" (P5).

DFMEAs can be a method for engineers to explore potential implications, but limited knowledge on the topic can make that exploration challenging. Multiple participants reflected on how they wished they had researched more, describing how their lack of knowledge resulted in mistakes throughout the project. One participant described challenges in opening a new plant:

> "You're launching new equipment, new warehouse, just everything's new. Even to the point where you get there and it's like, oh, we don't even have a janitor . . . It definitely would have been nicer to have people more knowledgeable, especially with how to run the machines there." (P15)

The limited knowledge of the team made exploration of solutions and processes difficult. However, in other scenarios participants perceived limited knowledge of a topic as a reason to diverge deeply into background research, stakeholder engagement, and project implications. For example:

> "Because I joined in phase four or five of total six, I didn't have all the history behind it. So, one of the important things is learn about the history, learn about what is the status, what is the changes and every time they get the information of all the trials, all the results, all the reports of the trials, and what were the main changes on every single one of the stages." (P16)

4.2 Organizational Dimensions

In this section, we discuss two prominent dimensions related to the engineers' organizational settings. We discuss the ways in which organizations either facilitated or inhibited divergent thinking practices.

4.2.1 Designated Processes For Exploration

A commonly-cited facilitator of divergent thinking was designating a process to guide divergent thinking. Some of the processes participants described employing were the Eight Disciplines Methodology [60], Five Whys Technique [61], Ishikawa Diagrams and Fishbone Diagrams [62, 63], Failure Modes and Effects Analysis [64], the House of Quality [65], Is/Is-Not studies [66], Best-of-the-Best and Worst-of-the-Worst studies [67], and the Stanford Biodesign Process [68]. Other participants cited industry regulations or internal standards as scaffolding exploration. Finally, other processes described included checking comprehensive internal databases, referring back to fundamental engineering principles, actively asking questions of teammates and other stakeholders, and digging to a root cause in order to best solve a problem. An active measure for ensuring that exploration did actually occur involved having designated 'exploratory' roles where an individual was assigned to perform it, or checkpoints planned within the project process where exploration was explicitly considered.

Many practitioners described the absence of designated processes for divergent thinking as making their jobs difficult. One practitioner described the challenges he experienced because his company did not have a clear process for sharing information across projects. Since his company did not have a way to share relevant project information early on, he struggled to understand what potential solution options might be until much later than necessary during the project:

> "In both cases that could have made more options, just having . . . a better process to find options. Or more options I guess generally available upfront rather than finding out we needed another option or needed another way to look at something down the road." (P10)

4.2.2 *Costs of Exploration*

The most frequent barrier observed was the logistics required to set up and execute exploration. For example, one participant working in biomedical design wanted to conduct broad exploration of potential hospital environments but found that challenging in the limited time available. She described how support for the costs of exploration would have been helpful:

> "If our hospital visits and interviews were set up for us because it did take some time to arrange for those things. And I think that struggle would kind of get to us sometimes . . . It was disappointing if we weren't getting small and large hospitals or like very rural and urban ones . . . If someone had set that up for us than we'd be saving some time and frustration." (P9)

4.3 *Relational Dimensions*

In this section, we discuss two prominent dimensions capturing the relationships with others in the work environment. We discuss the ways in which relationships either facilitated or inhibited divergent thinking practices.

4.3.1 *Mentors and Experts*

In some cases, having a mentor or subject-matter expert (SME) to consult facilitated deep exploration by practitioners whereas in others it halted exploration. The data indicated that mentors and SMEs were most valuable when practitioners leveraged them as checkpoints to validate exploration. When consulted, mentors helped practitioners identify areas to explore further through their own expertise. These conversations helped practitioners to 'know what they don't know,' and provided guidance for further exploration. One practitioner stated: 'Having other people on your team that have more experience than you to tell you like, "Hey, did you look at . . . did you check this? Did you check that?"' (P5)

In contrast, some practitioners perceived their in-house SME as a single source for all information. Rather than exploring multiple sources, practitioners assumed that this single expert knew everything there was to know. In some cases, practitioners identified these assumptions as a key failure in their project's success:

> "I found one person that seemed to know everything. Seemed. Keyword 'seemed' to know everything. And she caught me up to speed on everything from their old company. And I was like, this is great. I have a full understanding and I kind of dropped it . . .Very naively, I was like, this is it, this is all I had to do." (P13)

4.3.2 *Team Collaboration*

Team collaboration was also a key facilitator of divergent thinking for many participants. It allowed egos to be 'checked at the door,' facilitated a better flow of information, and supported more engagement with diverse perspectives within and outside the team. Collaboration also helped engineers feel more comfortable to take risks:

> "If you can find that harmony with people you work with, then that project is going to be easy. You might have hurdles, you might run into issues . . . but if you can get that harmony in your team, your life is much easier because now. Now you're just dealing with that problem. It's just a problem that can be solved and every problem we will eventually be solved, right?" (P17)

When supportive team collaboration was not available, engineers struggled to practice divergent thinking. "Siloed" organizational structures made it challenging for employees from different departments or teams to collaborate. One participant described the impact of this division between her team and others who might have useful advice:

> "The difficult part is like even that I have other peers in quality, you never get to work with them. Besides my training period when I was working with a guy looking for that, you never get to talk that much with them." (P16)

4.4 *Connections between Dimensions*

Some of the dimensions appeared to interact. For example, limited team collaboration caused by siloed organizational structures appeared to impact individual perspectives. When engineers were not afforded a collaborative environment, they seemed to hold a more narrow understanding of their project, which in turn limited the breadth of their exploration. One practitioner described how he did not account for a systems-level view when considering implications for the supply chain team:

> "It was an assumption that . . . once I released the drawing, supply would take it over and do their job.

> They would just handle it. It would get made and it'll go down the line. So, it was kind of a 'throw it over the wall and forget about it' type process." (P1)

In contrast, it appeared that team collaboration supported divergent thinking. One participant described the value in 'that so-called water cooler talk.' He said that having regular casual conversations with his coworkers made it 'easier to identify issues with my scope or my understanding' (P20).

Similarly, team diversity appeared to be a dimension contributing to team collaboration. One participant described:

> "Sitting down with all my teammates and looking at the problem and everyone coming up with ideas . . . having multiple people with their own set of experiences. That's the best. I mean, it's essentially diversity of thought, right? Like just having multiple points of view and having people [who] have solved other problems and bringing that experience with them." (P5)

5. Discussion

We identified 17 dimensions impacting divergent exploration, and tied their occurrence to sources within the individual engineer, the broader engineering organization, and the relationships within the work environment. These sources of support and limitation of divergent thinking during engineering projects reflect the major findings of the study.

1. *Individual engineers shape divergent thinking practice through their knowledge, perspectives, and actions*

Individuals described feeling in control of exploration efforts through their own 'metacognition' [5, 69]. For example, individuals who perceived their own knowledge as limited sometimes sought more extensive exploration to fill the gaps. In other cases, those with limited knowledge struggled to identify what to explore, and thus were limited in their efforts. Prior work similarly demonstrates that engineers' approach when questioning experts can either increase or decrease ambiguity [70], indicating that individuals can direct whether they are leveraging the activity to converge or diverge. Individual dimensions likely interact with organizational factors. A setting where divergent thinking is valued may be more likely to prompt an individual to diverge in their information gathering, while one that prioritizes convergence may prompt limited or no exploration.

Individual practitioners identified physical visualization as important to their divergent thinking, creating tangible ways to understand problems, approaches, and solutions through sketching, building, and other forms of visualization. Prototyping is an important tool in engineering design that can help to detect and minimize negative ramifications of design decisions, advance projects further, and facilitate communication [71–73]. Early-stage and low-fidelity prototyping is particularly beneficial to test out many ideas at lower cost [74]. Beyond physical models, mental visualization can help engineers 'prototype' non-tangible aspects of projects such as impacts on supply chain or stakeholders. Prior work identified that visualization can help facilitate concept generation [75], and may support other divergent thinking activities as well.

Individual engineers differed in their attitudes, perspectives, and mindsets about divergent thinking. Previous studies found divergent thinking correlates with personality descriptors such as, 'openness to experience' [10, 11, 76]. Engineers in our study reported leading with intellectual humility which has also been associated with reflective thinking, intellectual engagement, curiosity, intellectual openness, and open-minded thinking [77]. These individual characteristics have been shown to support greater knowledge acquisition, further supporting connections to divergent exploration in engineering. Our results build upon previous work by identifying how these individual qualities are reflected in specific actions and states of knowledge that impact divergent thinking practices.

Our results also identified individual engineers' aversion to risks inhibited divergent thinking, especially when working on brand-endangering or legacy products. Individuals often revert to rigid and familiar behaviors in stressful work situations [78], and in such high-stress situations, engineers may fall back on the convergence thinking dominant in engineering culture. A study of design professionals found that past experiences with failure can encourage risk-aversion and promote convergent thinking [79]. In contrast, a review of failure experiences in engineering classrooms found failure is a mechanism for uncovering key concepts and promoting reflection, and the importance of a safe climate for encountering failure [80]. As a result, engineers may benefit from greater awareness and reflection on how past experiences may impact future divergent practices.

2. *Organizational structure, culture, and processes impact engineers' ability to think divergently*

Many dimensions impacting divergent thinking related to engineering organizations' structures, processes, and cultures. When the engineering culture valued divergence, engineering teams and individuals seemed more willing to take on the perceived costs of divergence for its important longer-term benefits. In particular, some organizations supported divergent thinking through designated processes. For example, dedicated checkpoints and identification of individuals to play 'exploratory' roles provided clear expectations for divergence and offered both accountability and process to ensure exploration took place during engineering problem-solving.

Our findings on the impact of organizational structure, culture, and processes on divergent thinking align with similar findings on facilitating creativity. A review of organizational creativity found that leadership style, resources and skills, organizational climate and culture, and organization structure all impact creativity [81]. With results similar to our findings, support from leadership, positive organizational values, provided resources, and relevant training helped to facilitate creativity, and when absent, inhibited creativity among employees across a variety of workplaces and roles [12].

A specific feature of projects reported to inhibit divergent thinking in our study was time pressure, with the presence of tight deadlines working against the practice of divergence everywhere in engineering project processes. When divergence was valued by organizations, engineers devoted extra time and resources to deeply explore their project topic, and engineers prioritized engaging with diverse perspectives. When convergence was prioritized by the organization, there were fewer processes to facilitate divergence, and practitioners feared taking on the perceived risks of divergence. This suggests the importance of developing methods to estimate and build in time for exploration across stages during projects to allow for divergence in pathways and discovery of superior alternatives. As nearly all other dimensions are driven by the work organization's valuation towards divergence, the most potent way to change the practice of divergent thinking is to demonstrate its value in the engineering environment.

Organizations may find it challenging to support divergent thinking, but literature supports "Both/And" leadership or "paradoxical" leadership where leaders are asked to hold multiple, sometime conflicting, truths [82]. In the short term, Both/And leadership acknowledges that it can be valuable to have stability and avoid risk; for longer term benefits, however, innovation requires divergent thinking to question norms, push boundaries, and take risks. While our findings showed multiple supports for divergent thinking, we also found cases where practitioners and organizations lacked support and strategies for divergent thinking, revealing an opportunity for more intentional support.

3. *Workplace relationships influence divergent thinking*

While organizations often served to inhibit divergent thinking, relationships in the workplace – mentors and collaborators – were sources of support and encouragement as engineers made project decisions. In contrast to a siloed organizational structure, engineers afforded a collaborative team seemed to hold a broader perspective on their project, which in turn facilitated their exploration. It appeared that team collaboration often supported divergent thinking. One practitioner described the value in 'that so-called water cooler talk' lay in having regular casual conversations with his coworkers. This made it 'easier to identify issues with my scope or my understanding' (P20).

Similarly, team diversity appeared to contribute to divergent exploration. One practitioner made the diverse contributions among the team evident:

> "Sitting down with all my teammates and looking at the problem and everyone coming up with ideas . . . having multiple people with their own set of experiences. That's the best. I mean, it's essentially diversity of thought, right? Like just having multiple points of view and having people [who] have solved other problems and bringing that experience with them." (P5)

However, some practitioners described keeping their focus on only their immediate teams because they feared being overwhelmed by 'too many cooks in the kitchen' (P12). One practitioner prioritized 'not having so many stakeholders because then you start to get octopus arms, and you get pulled in all types of different directions' (P18).

A narrow viewpoint in some cases appeared to arise from the lack of a process to manage differing perspectives. Creating a process for seeking more diverse input outside of a project team may help connect to broader goals and make the process of collecting information more manageable.

Practitioners often reported consulting a mentor or subject-matter expert (SME) during their project work. In many cases, mentors served to encourage and guide exploration, suggesting possible paths based on their own knowledge and experiences. The SME or mentor in these cases was not conducting the exploration themselves – they were merely facilitating the exploration of the practitioner and providing one highly informed point of reference. Coworkers supported exploration by providing diverse project interests and knowledge beyond the individual, resulting in the consideration of alternative views and ideas. The collaborative team also provided balance in the assessment of information and risks, reducing some perceived uncertainty about whether exploration was sufficient. The positive views towards divergent thinking expressed by mentors and collaborators was a key source of encouragement for practitioners.

5.1 Limitations

This study included twenty engineering practitioners from varied industries in the mechanical engineering field, but we did not attempt to identify industry-specific circumstances that facilitate or inhibit divergent thinking practices. It is likely that some areas of engineering practice require and support more divergent thinking than is the norm in others. Given the small sample, the range of experience levels among practitioners did not allow for specific comparisons related to seniority, such as subject matter experts, new hires, project leads, and managers. Other differences among practitioners were also evident, such as gender, but no comparisons of individuals was planned. Data collection through virtual interviews may have limited certain aspects of reported experiences, such as the role of hands-on building and visualization. Proprietary information was also retained by participants and not collected as part of the protocol, so assessments of project outcomes was reported through subjective observations by participants. Other practices influencing exploration during projects may have been omitted by participants if specific prompts appeared unrelated. Other data collection methods such as contextual observation may provide additional insights beyond this study's self-reported experiences.

5.2 Implications

To support divergent thinking during engineering projects, engineering culture and education must challenge the status quo prioritizing convergence. Convergent analytical skills dominate engineering education and practice [15, 18, 83], making convergence the default mode and familiar 'norm' for engineers. Yet, both divergent and convergent thinking are required in engineering practice [4, 5]. Engineering organizations seeking better outcomes should identify divergence as a key value for engineering projects. Organizations would benefit from investing in infrastructure to support, document, and add accountability for divergence, and designing collaborative teams to allow the time and resources to consider alternatives before converging on a course of action.

One suggestion for engineering practice and education is to leverage each identified dimension to facilitate divergent thinking and create natural 'antidotes' to environmental inhibitors. Organizations can support leadership investment in divergent thinking, while educators can emphasize divergent thinking within curricula. A systems thinking perspective is one way to facilitate more divergent thinking about problems, stakeholders, and implications of engineering work.

Our findings suggest that naming and documenting assumptions and project constraints can counter barriers like topic familiarity, reliance on a singular expert, and fixation on one path. Engineers may not explore divergently if they assume their knowledge is sufficient, rely on an in-house expert, or believe the default convergence path is the only alternative. By interrogating these assumptions, engineers can transform barriers into facilitators of divergent practices. A study on the engineering design process of naval ships highlighted the importance of documenting assumptions [84]. Initially contentious, this process required team members to justify traditionally unquestioned methods, ultimately enabling broader design space exploration. The process of naming and documenting assumptions can help uncover the unstated or "tacit" knowledge that drives many engineering design decisions [85]. Engineering educators can incorporate a similar practice into course projects or assignments to enable broader design space exploration.

5.3 Conclusion

Both convergence and divergence are crucial in solving complex engineering problems, just as they are in human thinking more generally. Being able to trade-off divergent and flexible thinking and convergent and persistent processes is an essential engineering skill. Yet, engineers often struggle with divergent thinking, especially in engineering environments where convergence dominates. We interviewed 20 engineering practitioners about their divergent thinking experiences during professional projects. A qualitative inductive analysis revealed 17 dimensions impacting divergent thinking practices. The results offer guidance for both individual engineers and organizations on how to better support divergent exploration in engineering practice to counter the dominance of convergent thinking in engineering.

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Appendix

Table A1. Examples of interview excerpts for each dimension that impacts divergent thinking practice

Facilitation Example Protocol	Dimension	Inhibition Example Protocol
"To be an effective problem solver, that takes a degree of humility, willingness to listen to other people's opinions and entertain their ideas, and a willingness to change your own perspective when necessary." P6	*Agency and Openness*	"I was scared. I sat back and learned instead of being upfront, right? And you can't really learn if you just sit . . . well, you can learn sitting back and you can learn and you can observe people. But that's when it was so overwhelming to be on site of the customer. You have all these engineers who know what they're doing. So, I sat back." P17
"We're talking to facilities people, we're talking to general managers of the area, operations managers, [and] the actual operators because they're going to have to know how to use this when it comes in and be comfortable with it." P1	*A Systems Viewpoint*	"When you're just doing your daily task, you don't always recognize the problems that you're solving sometimes. You're looking at more of a micro level . . ." P18
"It is very, very easy to keep thinking of "what-if" scenarios and having this infinitely long set of tests that I would love to do. So having these constraints early on definitely made me satisfied that I did my due diligence and . . . I did enough." P1	*Clarity in Scope*	"It was also something where my team didn't even understand the scope of the ask. So, they couldn't even set me up in a way where we could have predicted that ask." P13
N/A	*Costs of Exploration*	"Balancing out the need to maintain a schedule and actually make a decision versus finding a perfect design. I don't know . . . perfection is kind of the side of engineering. In general, it was like, it could always be better, and I want to figure it out. But yeah, there's not really that endless time to do it." P10
"A goal of the Stanford Biodesign process, which is the method that we're supposed to use, is to try to remain unbiased. So, when we do the observations and interviews, we want to try to identify from the user's perspective what the problem is." P9	*Designated Process*	"It's not like we specifically laid out a strategy that would have been best." P3
"Sitting down with all my teammates and looking at the problem and everyone coming up with ideas or things that should be looked into that we should be considering . . . I mean, it's essentially diversity of thought, right? Like just having multiple points of view and having people [who] have solved other problems and bringing that experience with them." P5	*Diversity of Perspectives*	"People with whom you collaborate are not always widely varied in their position or in their background or in their education. Most of the time we're in solving problems with people that think a lot like us." P2
N/A	*Existing Constraints*	"In this instance for us, coming up with a completely new concept was not . . . like it was just not an option. . . If you already have something that you're starting out with, that really limits your options, and you have to work within those constraints." P5
"My advice, again, if anyone's listening, is to humble yourself. I have no problems whatsoever talking to the injection molding supplier because they are experts at injection molding and tell me how to improve the design of this part." P1	*Humble Expertise*	"I didn't explore that many. I don't know if that doesn't make it successful. But I also think like we didn't spend too much time relatively speaking just kind of like spinning our wheels and like trying to find other things. I think we found something that worked and kind of moved forward." P10
"So, a little bit of knowing already the product, being that this was my maybe fourth or fifth project. So, I already had a little bit of experience working with this product, so you already understand where are the key items to check and the main points [to] check." P16	*Familiarity with Topic*	This time around, we assumed the problem was solved. So since, since it was all, 'this is easy,' it was just, go do it, get it done. And not taking the time to do the actual due diligence." P1
"Initially, I wasn't quite sure what I was gonna do. Because at that point I had never run a test organization. Okay? So first of all, somebody show me what the equipment looks like, right? And then I started reaching out to do my research and talk with my connections. I met with my boss first and said, 'What are we talking about? What is on your mind? What does 'done' look like for you?'" P8	*Knowledge Limitations*	"So, I think like the limited knowledge in the beginning was sort of a hindrance because I learned more as I went on and became an expert in it. But at the beginning when I was making the big like project-impacting decisions and problem-solving strategies, I didn't have all the expertise that I did at the end. So if I had known more at the beginning, maybe I would have had even more creative problem-solving strategies." P11
"Being around someone who's been through it 20 plus years. Going to them and asking for their advice... they give you insight and their perspective and then they'll say, 'Oh, I would look for this here . . . That's fishy to me. Ask about this.' And then just building up that list of due diligence." P18	*Mentors and Experts*	"I think it maybe kept exploration a lot more internal because I had someone so close to me who sort of maybe was an expert in it. So I could just really use that one source to learn everything I needed to know." P11

Facilitation Example Protocol	Dimension	Inhibition Example Protocol
"So brake systems are safety critical . . . So one of the nice things about it is that you can really go deep and people want you to go deep because any risk is really bad, right? The consequences of having a bad system are potentially, I mean, you're talking about people could lose their life." P5	*Project Importance*	"We just felt like the impact of that particular problem was smaller than what we could potentially impact if we solved a different problem." P9
N/A	*Risk Aversion*	"So, for risk mitigation, we didn't have the whole world to choose from because it was new technology. It's a brand-endangering product. You don't put it into the hands of a new partner. You choose a tried and true partner. Those partners work with only certain material limitations." P2
"When they come back to you a third time for the same thing you've been working on that you didn't think had a lot of weight to it, and now they're like name dropping a vice president or a director. You're like, 'oh, okay, got it, got it. Upper-level management wants to know about this? This must be something important.'" P13	*Stakeholder Investment*	"When we presented to the leadership team, they rejected all of it and their solution was to, "well, just have a meeting with us to make sure and we'll tell you whether you can move forward or not." And we did what they said, and we continued to have the same problems...I can't explain why someone would just ignore that..." P15
"When you have a really strong functioning team, the egos are checked at the door and, and everybody just says, 'let's get it done.' And everybody's trying to get the same end result. And that definitely comes into play for a good launch versus a bad launch." P7	*Team Collaboration*	"So, a bunch of these discussions were happening between maybe two teams other than the four I described earlier. Only two teams were talking at a time and having parallel but slightly different conversations. And it took a while to realize, oh, other teams are involved in these discussions. Let's all get together and scope it together so we're completely on the same page and timelines align." P12
"Some of [the implications] are defined. Some of them I would just walk through the process. So, in an installation or an assembly – and this is why I think every engineer should, build their first prototype so that they can see all the stupid things that they did. And myself included." P6	*Tangibility*	*N/A*
"Whereas this new division, they're like, 'Hey, you're only five years into your career. Why don't you try and give a stab at this and see what you come up with. And then we'll both learn and fail from that together.'" P12	*Valuing Divergence*	"I think a lot of it was just kind of company culture. Not really wanting to understand problems fully or just like having pressure to keep costs low. So therefore, you don't spend as much money on testing and validation." P5

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