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Improvising: A Core Practice of Engineering

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Improvising: A Core Engineering Practice

Introduction

Improvising is a natural human response where individuals reflexively work through instances of uncertainty [1-2]. While improvising has been historically associated with the performing arts, it is present in every facet of the human experience, from joking with others in conversations and developing solutions under resource constraints to cooking a favorite dish with an altered recipe. Because improvising is primarily documented in the literature on performing arts (e.g., musicianship, choreography, theatre) [3-4], its critical role in engineering practice has been overlooked. Current studies in engineering education and practice refer to improvising as a means to generating creativity [5], building rapport with members of a team [6], and developing skills to manage obstacles [7-8]. Less frequently, engineering education and practice scholarship situate improvising as a general engineering or disciplinary-specific approach that can be leveraged to manage uncertainties within engineering practice [9]. For instance, when performing their work in extreme conditions (e.g., high humidity, electromagnetic interference), an engineer may have to *improvise* by manually performing onsite field measurements with a ruler if the technological equipment like a caliper is malfunctioning due to the environmental sensitivity of electronic instruments.

How did we start asking questions about improvising?

Our focus on improvising in engineering emerged from our larger project situating engineering practices within community contexts [10]. In this larger project, we identified 140+ engineering practices through a literature review of 52 manuscripts in engineering and engineering education peer-reviewed journals, such as *Journal of Engineering Education* and *Engineering Studies*. Through an iterative process involving practitioners and scholars who are experts in various engineering disciplines, including engineering education, we operationalized engineering practices identified in the literature review. Initially, we gave them a list of engineering practices with summarized definitions and then asked them to group the given practices based on the definitions and their own perception of how the practices are connected with each other.

In the iterative process, our team realized that not all of the practices were sorted or addressed by the experts to the same extent. Thus, our team decided to perform a visual network analysis using Gephi to understand which practices were most addressed by the experts and which practices were positioned as engineering bridges across contexts (e.g., community and disciplinary). To perform this analysis, our team took the selected list of 50 engineering practices grouped by the experts to examine which were the most salient to them. From the network analysis, *improvising* emerged as a key engineering practice with the most direct connections to other practices. Improvising was directly grouped with 29 other engineering practices from the provided list by experts including critical thinking, working under constraints, using heuristics, and planning ability. Improvising also had the most indirect connections, meaning that even for a practice that was not directly grouped with improvising, scholars likely grouped this practice to another practice that was, in fact, directly grouped with improvising.

In contrast with our integrative literature review [10], improvising emerged as a salient engineering practice for experts within a time-constrained sorting activity. In the literature review, improvising was only explicitly referenced in one out of the 50 peer-reviewed journal articles that met the inclusion criteria. In those manuscripts, improvisation was briefly mentioned as a process in engineering consultation but never defined or fully expanded upon [11]. Instead, the reviewed articles widely-referenced engineering practices like problem-solving, applied science and mathematics, and judgment and decision-making. These findings thus warranted a deeper investigation into improvising as a distinct engineering practice. Drawing on conversations with experts in select engineering professions and the scholarship in engineering education and practice, we define improvising in organizational behavior and document examples in the literature of improvising in chemical engineering, software engineering, and civil engineering.

Improvising in Engineering Practice

Roux-Dufort & Vidaillet define improvising in organizational practice as the simultaneous act of execution and planning drawing on lived experiences, informal social structures, and the allocation of resources [12]. In the context of organizational practice as in engineering, individuals rely on collaboration with others as well as their intuition, and circumstances to solve problems [13-14]. Solving problems in cases of improvising often involves *bricolage*, the capacity of people to combine, allocate, transform and reconfigure resources in a constrained environment, which demands some degree of spontaneity and/or urgency, such that "decisions and actions are made without formal prior analysis" or explicit thought [12]. In their practice, engineers often engage in spontaneous decision-making, a form of improvising, when allocating resources without using standard techniques (e.g., mass balances, the methodical optimization of parameters through solved differential equations, and software-supported modeling) or heuristics. For instance, during the crisis of the Apollo 13 mission when one of the oxygen tanks attached to the spacecraft exploded, NASA engineers engaged in improvising to solve the problem of CO_2 by creating a filtration system. Quickly experimenting with materials available to the crew, such as duck tape, cardstock, and socks, they produced a design of a modified LiOH canister that kept the CO_2 levels down [15-16]. Rather than a preplanned standard response to be likened to traditional engineering problem-solving, Tony England, an astronaut in one of the teams responding to the crisis, likened this process of exploring which materials in the aircraft would work to a "makeshift deal" [16]. In other words, as the example of the filtration system suggests, engineering improvising involves solving problems without codified responses in an attempt to respond to contextual factors (e.g., people and the environment) efficiently but quickly. It involves engineers performing their job in an attempt to meet the goals of the project or task at hand while pondering specific constraints such as time or location [17-19].

Improvising in engineering can be examined along a spectrum of urgency and time constraints. Commonly-known cases of improvising in engineering typically occur in situations of crises, troubleshooting, and innovation (See Table 1). Crises are "natural, accidental, or intentional event[s] that severely impact people, property, and/or the environment" [20]. Crises are the most urgent cases, requiring almost immediate interventions and bricolage to resolve the issues at hand. For example, during the COVID-19 pandemic, engineers and designers within healthcare, textile, and industrial safety sectors were tasked with producing and distributing more better-quality masks to meet community needs by reducing the risk of infection for the general public [21-22]. Separate from crises, troubleshooting can be a more moderately urgent response to situations. It typically occurs when a system is not working as intended resulting in an undesired outcome but not necessarily the destruction of environments and/or people [23-26]. For instance, if a 3D printing machine is malfunctioning resulting in 2 of 5 defective products, engineers will likely be alerted to solve the issue. Depending on the context, the response may be needed or expected over a longer period of time as compared with an emergency situation. Methodical approaches like hands-on adjustments (e.g., turning the printer off then on again) or repairs (e.g., replacing the printer's filament or updating the software) can be adopted to carefully determine the root of the problem and alleviate the situation.

Lastly, innovation typically involves the least amount of urgency, such as innovation in Research & Development (R&D). Some exceptions to this sense of urgency in innovation include "crisis innovation", which will fall under the category of crisis as it responds to a dire situation of emergency. Some examples of "crisis innovation" led by engineers include the development of low-cost incubators, "Embrace Warmers", for under-resourced communities facing crises due to wars and/or limited access to resources [27], and engineers designing blue roofs for the recovery of communities in the event of a hurricane [28]. Often operating under R&D departments within organizations or research laboratories in academia, engineers aim to create new products and solutions. Innovation may occur in closed- and open-ended conditions. In close-ended conditions, there is a clear objective or a desired target product that can be met through trial-and-error or iterative processes in engineering. An example of close-ended conditions for innovation is when Thomas Edison aimed to meet the single objective of lighting a bulb without having a clear method as to how to do so [29-30]. Open-ended conditions have less clear objectives and are thus more exploratory in nature (See [31]). For instance, food engineers in response to customer demands may aim to develop a healthier alternative to processed sugar, thus having the objective of creating something sweet but not necessarily having the confines of using a specific base ingredient to achieve said sweetness like sucrose. Innovation can occur whether engineers are exploring opportunities in both close-ended settings, where they seek to meet clearly defined outcomes, and open-ended settings, where the goals are ambiguous and the solutions open to interpretation and exploration.

Table 1. Commonly-known cases of improvising in engineering in situations of crises, troubleshooting, and innovation.

Improvising Situations	**Description**	**Characteristics**	**Examples**
Crisis	Engineers tackle crises which are natural, accidental, or purposeful events that severely affect people, environment or material resources.	Urgent cases Require immediate attention	Crisis Innovation: Engineers work to increase the quality and speed of production of protective equipment to reduce the risk of infection during the COVID-19 pandemic.

Troubleshooting	Engineers engage in troubleshooting when a system deviates from its expected operation, producing an unfavorable outcome without necessarily causing damage to individuals, systems or material resources.	Moderately urgent Driven by expectations	Updating and fixing the bugs in a software for a 3D printer machine for additive manufacturing of vehicle parts.
Innovation	Engineers aim to create new products, solutions or new approaches (or applications to approaches in new contexts).	Least urgency Moves fast	Research & Development of products and technologies.

Improvising in Chemical Engineering: Leveraging Chemical Knowledge to Manage Chemical Processes

As a discipline, chemical engineering is founded on a history of uncertainty and constraints regarding chemicals, the processes that created desired chemical products, and the conditions that are optimal to store them across the globe [32-33]. In the broadest sense of the discipline, chemical engineering considers the lifecycle of a pure chemical component or mixed chemical product, from its raw material extraction and synthesis to its storing, transporting, and eventual chemical degradation leading to the loss of chemical properties and consumer and industrial waste [34]. Although chemical engineering is historically seen as a highly structured discipline, improvising is strongly tied to crisis, troubleshooting and innovation in storing and synthesizing chemicals as well as developing and controlling processes (e.g., [35-36]). In a study on crisis management in chemical firms, Samra and colleagues [37] found an association between new product development outcomes (speed and success), improvisation and crisis. For instance, Whitfield et al. [38] provide an example in their examination of bricolage among crew members in a simulated crisis, a medical emergency on Mars. Given gypsum, an abundant mineral on Mars, crew members were tasked with extracting water from the rock upon it being heated. Crew members improvised three methods to collect water for drinking and industrial purposes via the simulated environmental resource constraints [38].

Scholars have also described situations where chemical engineers together with operators and scientists needed to improvise solutions via open-ended conditions in chemical processing and synthesis when troubleshooting. For instance, the increased complexity in the petrochemical industry requires an “adaptation to novelty” where plant operators must change and accommodate their practices to new situations and contexts where they respond by improvising solutions themselves [39]. Meadowcroft addressed this aspect of improvising in the petrochemical industry in a process control course to prepare chemical engineering undergraduates for the workforce, suggesting that disciplinary-based improvising has pedagogical value for students interested in working as professional engineers [40]. Furthermore, Malhotra describes moments of improvising when an increased demand of the esters produced by her company required the plant capacity to be doubled [41]. While engineers in this situation would typically resize the plant, creating a larger plant to store and produce more material, time constraints made it difficult to expand the plant in a timely manner. In response, Malhotra and her team “had to improvise using the existing plant”, meeting the production objectives with an installed metal deflector and empirically-determined optimal temperature to ensure that esters of the same quality as before were being produced onsite [41].

Improvising in Software Engineering: Leveraging Computer Science & Design Knowledge to Manage Digital Interfaces

Software is about developing tools that help people with their work. Although software engineering is often seen as a linear and algorithmic process, Suscheck and Ford [42] describe software engineering as a discipline where multiple issues that need to be tackled go beyond technical aspects, into sociotechnical matters, where a top-down approach in which there is a fixed objective and constraints rarely works. Additionally, the software industry has recently increased their attention to practice people-centered approaches like agile or scrum which focuses on the social interactions in the organization rather than solely the technical interventions in the organization [42].

Gallardo-Valencia and Sim studied how much software engineers use the software process to improvise in their work [43]. The authors describe two types of software development methods: *Methodical software development*, a controllable event with a goal that can be followed sequentially in a linear path, and *amethodical software development*, asocial, imploded, event that appears as an effect of prevalent and unanticipated circumstances and usually does not follow a linear path, in other words, a crisis. According to the authors, software engineers improvise using both methods when they need to address unexpected situations such as change in the size of the project because the client requested faster implementation. While software engineers design user interfaces, they often have limited strict guidelines for the design process. Thus, during the design process, software engineers draw on their creativity to improvise in less-constrained circumstances, mirroring situations where innovation takes place, where solutions can be displayed over relatively longer time periods in comparison to crisis situations that must be resolved as soon as possible. The authors further discuss that even when engineers improvise in amethodical process, they require some level of planning that leads often to situations where people improvise [43].

Beyond methods for software development, software engineers improvise when they engage in the practices of entrepreneurs to design and create “off-the-shelf” softwares using a type of software development method that researchers call “lead-driven development” [44]. In this method, improvisation is practiced to improve the product features and fix the bugs which are reported by the marketing team (i.e., troubleshooting), mostly during the product demo phase of software development. For example, while developing complexity management softwares, there arise various convoluted situations that should be addressed quickly to meet expectations. Once the complexity management software is deployed, detected issues must be addressed immediately to prevent customer dissatisfaction. Such problems that are rooted on the customer, including the need to integrate the product to meet the customer’s workflow and connecting the product to the customer’s internal system requires a great deal of flexibility and a disposition to engage in improvising. These examples illustrate the people-oriented nature of the software development industry where the process of designing and creating new solutions and products focuses on improvising while drawing on disciplinary knowledge and experience.

Improvising in Civil and Environmental Engineering: Leveraging Material and Physics Knowledge to Manage Infrastructure

Civil and environmental engineering is about developing durable infrastructures that will serve people, and protect the ecosystem in the long term. When there are uncertain events like failures in a project due to time constraints or failures due to lack of proper planning, Alhussein et al. [45] recommend civil engineers to develop an improvised, temporary, solution to keep the construction process under control and play down losses in the project, particularly human. The authors also highlight the role an engineer's background (their prior experiences on the job, capability to respond to time constraints and risks, ease of communication with other members of the team and organizational experiences) plays in successfully solving uncertain, ill-defined, problems in the construction industry [45]. Sakr and Nassar state that due to the nature of the construction industry, an "one-size-fits-all" method cannot be applied, suggesting the use of the six-sigma method for troubleshooting any managerial issues. Six-sigma, a data driven method to improve process efficiency and customer satisfaction, which was initially developed for manufacturing and industrial projects, has been undertaken in the construction industry as an improvised problem-solving approach [46].

Another example of improvising is a civil engineer's constant work in improving building materials such as concrete. Concrete is widely used in the construction of civil infrastructures, but it has a high carbon emission footprint. To address the environmental challenges of using this technology in construction, the concrete industry is trying to bring innovation by developing an environmentally friendly concrete called "green concrete," which is a new form of the material that requires less energy to be produced, has at least one waste material as an integral component for their production, and emits less CO_2 than regular concrete [47]. For example, Yu et al. presents an innovative technology that replaces up to 80% of cement by fly ash, a waste product from coal burning to create green concrete [48].

Improvising in the construction industry goes beyond strategies or materials. For example, Hamzeh and colleagues present a model of improvisation for the construction industry with six different stages [1]:

1. *Looking for the need to improvise*: Studying the prerequisites of the planned actions,
2. *Preparation for improvisation*: Analyzing the current situation(s) and brainstorming different solutions,
3. *Making the decision*: In this stage, the engineers have an idea of how the solution will work out in their head and the potential risks of possible failures, so the engineers take into account multiple perspectives and decide the best course of actions in terms of the kinds of solutions that they want to implement, ranging from a "satisfying solution" to an "optimum" solution,
4. *Asking for a second opinion:* Engineers engage with others from different teams in the same construction firm to explore ways to optimize the solutions,

5. *Documentation of the method and the results of improvisation*: Engineers keep multimodal records of the approaches used and the outcomes of such approaches,
6. Continuing the regular tasks .

In this process of improvisation, engineers are frequently recalling past experiences and their knowledge of the construction industry or the discipline [1]. In this case, improvisation and when to improvise are vital for engineering decision-making [1] as civil engineers rely on their previous experiences, disciplinary knowledge, time constraints and other factors to make decisions about if and when they need to improvise.

Implementing Improvising in Engineering Education

As described in the introduction, much of the literature on improvising in the educational context is situated in performing arts disciplines. We can thus learn how to teach improvising in the engineering classroom from the performing arts. One approach to teaching improvising views improvising as a variety of behaviors that develop over time [49]. Kratus categorized these behaviors into seven levels of improvising. The first level is "Exploration" where the kids are given time to explore the musical instruments by listening to what different notes sound like with little to no constraints. Here the instructor's role is to provide students with the opportunity that will enable students to play the instruments independently and hear while playing. The second level is "Process-oriented improvisation" which is about being able to manipulate the musical instrument to create a sound of their choice. For example, students playing more cohesive patterns or playing repeated patterns to create music when they grow their understanding of connections among different patterns. Here, teachers can let the students figure out the patterns and they can highlight students' improvisation and talk about the connections of the patterns they used. The third level of improvisation is called "Product-oriented improvising" so that when you know what kind of music you want to make and then you look for ways to make patterns to achieve that music. Here, the teacher might present some examples of the music patterns as an inspiration for students and have students work in groups. This gives students the opportunity to produce their own music collaboratively and asks for students' conscious effort to tune musical sounds or the vocal to achieve their desired music. The fourth level is called "Fluid improvisation" where students have ideas on the patterns of music, they automatically know what needs to be done to achieve a certain pattern of music and they improvise to make more polished sounds in their compositions. Here, the teacher emphasizes relevant performance skills needed in improvisation and practices done in genuine music making. Levels five to seven—structural improvisation, stylistic improvisation, and personal improvisation—refers to more advanced levels akin to the early, mid-level, and senior-level career engineer, in which their ways of improvising are directly shaped by greater understanding of concepts and extended years of expertise [49]. Thus, the first four levels are most relevant to undergraduate engineering education for preparing students to transition into early career engineering professions.

In investigating how improvising can inform engineering design particularly with design thinking, Yazdanpanah et al. interviewed musicians, asking them about how they view improvisation, how they navigate the unknown, negotiate with stakeholders, etc. [50]. Similar to Kratus [49], one major recommendation from a harpist was to think of improvising in terms of levels rather than extreme benchmarks of being the novice or the highly-innovative composer. As she explains, we cannot all be the "Mozart or Beethoven" but we can all work on developing a strong technical skillset complemented with an open-mindedness that may naturally give way to improvising. Another musician highlighted how improvising is most possible in situations when there is the space to explore. When the individual is overloaded with work, they have less time to engage in more open-ended exploration which would allow them to find things they may not have found otherwise [50].

Applying these ideas to engineering education, the first level of exploration in Kratus' model [49] mirrors the tinkering-based projects encouraged in broadening engineering participation programs, where students are given few parameters and told to create a solution, and first-year engineering programs which tend to be more design-focused [51-52]. The second level, process-oriented improvisation, reflects what is predominantly done in middle-year undergraduate engineering education. In this period, students are often enrolled in core engineering science coursework (e.g., Thermodynamics) where they learn foundational concepts relevant to the engineering discipline. However, in these more engineering-science-oriented courses, students usually do not engage in design-based work. They are typically exposed to concepts, equations, and apply these in specific contexts on problem sets [53-55]. Following theoretical bases and implementing assumptions, students learn engineering solutions in a more algorithmic form where there is clear objective, adequate constraints such that there is no degree of freedom, and a single "correct" solution. Level 3, product-oriented improvisation, can describe ill-structured problems. For instance, the student may apply a mass balance to the situation but not have clear input and output values of the process. Such questions require application of foundational concepts in contexts with a general idea of what the product *should* look like but few constraints, allowing for degrees of freedom in the variables and general exploration of which values may be best for a parameter and how those parameters may influence the final product. Finally, fluid improvisation can describe ill-structured problems with even less constraints. The student may similarly encounter a problem that requires concepts to be applied in a different context, but there are fewer instructions as to what process should be taken to achieve the objective. For instance, with final-year capstone projects, students may reflexively conduct a mass balance to gain a better understanding of the process but there are less clear parameters and many of the theories taught in the classroom may no longer apply, causing students to determine how to best model the situation with approximations and/or empirical-based equations. Therefore, it may be beneficial to implement more project-based assignments and/or ill-structured problems related to student interests in middle-year undergraduate engineering education. For example, Melsky et al. [56] included specific fluid mechanics problems in an undergraduate mechanical engineering course based on students' expressed interests in cooking, amusement park rides, skiing, and space. Although they did not find major differences in students' positive or negative engagement, the balance of student participation in a group, or knowledge construction when comparing student discourse surrounding the personalized and non-personalized problems, the authors maintain that personalized problems provide an opportunity for students to better engage with the material and understand how the theories connect to real-world events [56].

Conclusion

In the select engineering cases above (chemical engineering, software engineering and civil and environmental engineering), we find improvising to be the throughline between widely-referenced engineering practices in the literature including working with ambiguity and working under uncertainty, and/or under constraints. Situations where engineers engage in improvising often involve needing to interpret outcomes, components or results in a way that has not been previously done before, fostering an environment for exploration and experimentation that is not scripted. In other words, it requires that the engineer *improvise* to create, maintain, and distribute the desired products, processes, solutions and systems. Despite the crucial role that improvising plays as a connector and central engineering practice, the scholarship on improvising in engineering remains limited at best. Even when looking in the related categories of crisis, innovation, and troubleshooting, our team found that improvising was sporadically used and loosely operationalized in manuscripts as a thing an engineer did but never defined or expanded upon as an important engineering practice.

Moreover, improvising has yet to be understood and well-defined in engineering education scholarship. For example, in engineering learning environments, academic pressures (e.g., false perceptions of improvising as a less rigorous approach to engaging in engineering, improvising seen as a purely artistic endeavor or distorted conceptions of academic rigor that deem sociotechnical aspects of engineering as less important to engineering work) often interfere with students' openness to engage with improvising in engineering problem-solving and tasks. Explicitly introducing improvising in engineering classrooms as a component of everyday life that manifests itself in specific forms in engineering practice can prepare undergraduate students for industry, demonstrating that there are often better or worse solutions, rather than right or wrong solutions, especially in contexts of industrial uncertainty. Encouraging problem-based improvising in the classroom may require some reconsideration of grading practices and pedagogical approaches so that students are more likely to engage in ill-defined situations where uncertainty and ambiguity prevail. Furthermore, more scholarship is needed on how people learn engineering in innovative contexts where the ingenuity of people is at play in the wilderness of the real-world. Such is the case of engineering in the communities where applications of technical and scientific expertise bring to life engineering epistemologies and ontologies.

Therefore, future research should investigate improvising in the context of engineering practice and how the practice of improvising can serve as a bridge between everyday life, engineering schooling, and engineering practice. We find that improvising is a common problem-solving approach used in engineering practice, but the context and scale of the improvising differs between situations and disciplines, and the education of those who are learning to be engineers rarely make this valuable practice visible to them.

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