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Engineering/Design Frictions: Exploring Competing Knowledge Systems via Efforts to Integrate Design Principles into Engineering Education

Dr. Dean Nieusma, Rensselaer Polytechnic Institute

Dean Nieusma is Associate Dean for Curricular Transitions, Associate Professor in Science and Technology Studies, and Director of the Programs in Design and Innovation at Rensselaer.

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Introduction

Human-centered design methods and design thinking are being promoted and increasingly adopted beyond the traditional creative design disciplines. These approaches are touted as tools for enhanced creativity that help align narrow problem solving in any domain with actual human capabilities and experiences—and hence the broader human condition [1]. Engineering education, in particular, has been impacted by the rise in use of human-centered design problem-solving and educational approaches, largely for the better. Design-centric pedagogies can enable heightened student engagement [2], better contextualized problem solving [3], a broader range of inquiry methods employed to understand the problem and posit solution concepts [4], and increased emphasis on experimentation, prototyping, and user testing [5].

These developments in engineering education have led to a sort of design evangelism within the field: Human-centered design (hereafter, just "design") is cast as a generalized fix to a range of shortcomings faced by mainstream approaches to engineering education [6]. My own work in the areas of engineering education research and engineering studies, both individually and with collaborators representing a range of disciplines, has often contributed to this educational reform effort [7, 8, 9, 10, 11, 12]. Despite being a consistent proponent of design methods and design thinking in engineering, I nevertheless see many challenges associated with folding design approaches into engineering problem solving, engineering education, and engineering worldviews more broadly. In that vein, this paper shows how design approaches frequently exist in tension with mainstream approaches to conveying engineering knowledge to students, and argues that engineering educators should not assume design approaches can be simply overlain on top of those of engineering. In key respects, design and engineering educational approaches exist in contrast to one another. To make this argument, the paper will identify some of the conceptual frameworks underlying mainstream approaches to design and engineering education and then identify key tensions between the approaches. Drawing loosely on the work of philosopher of science, Thomas Kuhn, in particular his thesis of incommersurability among competing scientific paradigms [13], I suggest epistemological conflicts exist between the disciplinary experience base of engineering and that of design, but that there remain opportunities for learning from the process of borrowing across disciplines, even if the lessons are of a different sort than anticipated.

To explore these conflicts, the analysis opens with a background section elaborating the tendency I see to gloss the nuances of design thinking in many efforts that promote their application within engineering. I then identify and summarize a set of design principles common within design thinking. Next, I describe mainstay conceptual frameworks and assumptions underlying engineering education and describe how these defy or contradict each of the design principles previously identified. Finally, my experience directing an interdisciplinary design program, I conclude the analysis by reflecting on the extent to which the tensions identified are truly incommensurable and, where they are not, describe opportunities for meeting in the middle.

Background:
5 Easy Steps to Design Creativity and Other Myths of Engineering Education Reform

As Director of Rensselaer's Programs in Design and Innovation (PDI), I frequently receive invitations by course instructors and program administrators to present one or another form of a "Design Creativity" session to engineering students, faculty, and researchers. I elaborate briefly on the structure and culture of PDI toward the end of the paper, but at this point it is important to share two points. First, PDI is structured as a coherent set of dual-major curricula, with a liberal-arts design curriculum representing one side and, for 85% of our students, one of Rensselaer's engineering disciplines representing the other side of the dual major. Second, PDI students, who number about 30 per cohort (compared to Engineering's approximate 1000 per cohort), are known on campus as being creative yet practically focused as well as technically competent, entrepreneurial, strong communicators, and leaders in the broadest sense. In other words, they are what many faculty members and administrators consider to be ideal engineering students.

While I am usually inclined to accept invitations to speak about teaching creativity to engineers, it increasingly became clear to me that those making the request had in mind something very different than my understanding of what made PDI successful. As a social scientist and design scholar, what made PDI most successful had more to do with the educational structures we have put in place rather than any discrete knowledge that was taught in the classroom. These structures included the configuration of our curricula, particular pedagogical strategies, how we cultivate students' interdisciplinary identity, the nature of our program's educational culture, student-teacher relationships, the deliberateness with which we recruit, how we advise on careers, etc. While my presentations about PDI's successes (and challenges) were typically warmly received, they nevertheless seemed to miss the mark in terms of what participants expected from me. They seemed to have an implicit model for what creativity was (namely, an internal cognitive act) and how it should be taught (using a traditional didactic approach), but they felt they lacked the *content* of what should be conveyed within that model of creativity education. In other words, creativity was like statics or circuits, with a handful of orienting principles and problem-solving protocols that could be identified, conveyed discretely, practiced, mastered, cumulated, and ultimately integrated with other engineering analytic skills. What I presented about what made PDI students creative and successful problem solvers both misaligned with what my engineering peers understood creativity to be and contradicted how they imagined it being taught.

This alignment problem has been made more accute by the ascent of design thinking in engineering [14], management literature [15], and education more broadly [16, 17] as well as the notable success of Stanford's Hasso Plattner Institute of Design (better known simply as "the d.school")—success both in terms of bold visioning/implementing that vision and in terms of branding/disseminating its design-centric approach to creativity and innovation. Design thinking is increasingly recognized as a legitimate domain of inquiry and education, having outlived its academic fad years of the early 2000s. Admittedly, I share this positive assessment and think of design thinking and the d.school as transformative forces for education, especially engineering education. I have attended d.school workshops; I have used their publications and resources in my teaching; and I am an enthusiastic supporter of their educational philosophy and overall institutional mission. But, in some respects, the glossy approach to design education promoted by the d.school, Design for America, and other institutional advocates of design-thinking in education throws into sharp relief the disjunction I have experienced as a social scientist trying to explain innovation education to the engineering faculty I work with. While the breadth of design thinking educational initiatives do not represent any singular vision of design, as a whole it does tend to promote an approach to creativity education that is distilled into easy-to-disseminate key principles [18, 19]. Furthermore, design thinking is often targeted to and institutionally supported by engineering programs specifically: the d.school historically has been effective in reaching engineering students at Stanford and DFA National is housed within Northwestern's McCormick School of Engineering.

As a social scientist interested in educational reform and as an educational program director, I am typically quick to point out that the d.school is not, in fact, a "school." That is, the d.school is not a degree-granting entity, does not have its own students, and does not have dedicated, tenure-faculty members. It exists largely apart from academic administrative apparatus at Stanford. In fact, the d.school proudly proclaims as a strength—and it *is* a strength, but also a telling one—that the d.school's programming is "100% opt-in": "The people who are here want to be here. No student or faculty member at Stanford is required to participate" [14]. As a course instructor, I cannot say enough about how fortunate I feel to have 30 students in a class who all genuinely want to be there. But this opt-in framework compares poorly with a typical course within an engineering curriculum, or almost any disciplinary curriculum for that matter, where there are likely to be a nontrivial minority of students who, left to their own devices, might otherwise not have chosen to elect the course. After all, academic disciplines are called "disciplines" for a reason: I assume most educators, and even most students, consider disciplining to be a sort of bitter medicine, unpleasant at the time but necessary for developing required domain expertise over the long term.

I do not mean to suggest that creativity does not require a type of disciplining in its own right, or to suggest that d.school-styled educational interventions are devoid of discipline or intellectual growth. The point is more that the intellectual and institutional latitude available to the d.school is not only unavailable to most academic programs but also that, administratively, the d.school's programming and output is optimized around a kind of consumer-choice model, whereby students and faculty members opt in when desired and where possible, subject to the opportunities and constraints of their primary academic affiliations and the associated, institutionally-sanctioned requirements (and the limited availability of seats). Unlike academic degree programs, the d.school is free of the need to grapple with the entirety of any given student's academic competencies. And while there are significant educational benefits to accommodating student choice, I suspect most educators would agree there are and should be important distinctions between how students choose electives courses and how coherent educational programs are structured and implemented.

Again, I must emphasize that this analysis of the d.school's approach is not to criticize it, and certainly not to dismiss its role or effectiveness. To the contrary, I believe the d.school is remarkably effective and rightly serves as an educational exemplar, just not in direct comparison with traditional academic programs. In fact, that is largely what makes it so successful: that it serves as a complement to high-quality, traditional disciplinary education. Throughout my analysis, then, the d.school serves more as a foil for the considerable and enduring challenges associated with integrating creativity consistently into engineering education. This is the contention built into this section's title, and ultimately the paper's argument: that teaching creativity effectively, consistently, reliably to engineering students is, in fact, quite difficult—for a variety of reasons.

5 Principles of Design Thinking and Human-Centered Design Practice

Before I move on to the challenges of integrating design approaches into engineering education, I will provide a brief introduction to a typical set of design principles represented in design thinking materials. These principles are selected largely based on my own experience in directing an interdisciplinary design program, but are informed also by my work at the intersection of design and engineering education reform initiatives over the past 20 years. The list I provide belwo overlaps substantially with similar such lists, including the above-referenced "8 Core Abilities" of the d.school and the "Design for America Process Guide" by DFA, both of which will be used to elaborate my points.

1. Context is Key

Designing thinking presumes that addressing the particularities of the use context of a given to-be-designed object is central to successful design process and output. Attending to context is important for enabling designers to understand the relationships among people, objects, and their environments, including how users interact with objects and how such interactions are shaped by the environments within which they take place. Observing people going about their lives in their "native environments" also allows designers to identify new opportunities for innovation.

The d.school includes attention to context among its 8 Core Abilities: "Learn from Others (People and Contexts)." This principle specifically addresses the importance of "observing and learning from unfamiliar contexts" [18]. The DFA Design Process Guide does not have a dedicated principle dedicated context, but instead attends to context across its 6-step design process. Context is treated most directly in the "immerse" step, which, following the d.school approach, considers the designer's immersion with both people (targeted users and other related stakeholders) and contexts (the settings within which users use designed objects) [20]. Despite that I illustrate the placement of context as a component *within* each of these two design approach, both the d.school and DFA are clear to state that context should be attended to *throughout* the design process.

Context is important, certainly, but can be a tricky concept. Context can be anything and everything. Identifying with precision which contexts are most relevant to a design process and creating manageable boundaries around any given context are both exceedingly difficult to do, at least reliably. Furthermore, a large number of designed objects do not have a common, specific, or singular "context of use," and so contextualized observations are always themselves particular or "context specific." Embracing such ambiguities and complexities, design thinking and design methods direct designers to take context seriously and to become active participants in the mutual shaping among people, objects, and environments [21].

2. Problem Framing (and Reframing)

Most design approaches attend to the centrality of problem framing in the design process. For designers, problem framing is understood to be iterative—returned to repeatedly over the course of the design process, including allowing for the possibility of totally redefining the problem as promising solution concepts provide insight into where innovation is most promising. The derivative concept of "pivoting" has become commonplace in design and entrepreneurship settings to describe the practice of reframing a given problem in response to the dead ends arrived at after pursuing a problem originally framed in a different way. Pivoting encourages the designer, who may be well along a solution path, to rethink their original goal, not merely the path taken to arrive at it.

DFA's Guide dedicates fully half of its design process to its version of problem framing. Under the higher-order category, "Understand," the Guide lists three steps: Identify, research, and reframe [20]. Arguably, these steps work together as a set to direct designers regarding the problem to be addressed. A problem is first identified (tentative problem framing), research is carried out to understand the nuances of the problem space, and then the problem is reframed in response to insights gained from research before the problem statement is formalized. The step of "reframing" is informed primarily by research into people and contexts in this formulation, but there is also recognition that these steps are not followed in strict linear sequence. The d.school's 8 Core Abilities addresses the issue of problem framing and reframing most directly under the principle, "navigate ambiguity," where problem reframing is recognized as a strategy of managing the inevitable uncertainties that arise throughout the design process [18].

Many design commentators invoke a version of the Pareto Principle to justify special attention to problem framing in the design process. In this formulation, the principle indicates that the majority of the success of a given design solution is determined by a minority of the overall design decisions, with problem framing being the single most influential stage in the process. Design thinking applies that insight by privileging an informed trial-and-error approach to problem framing, so that problem framing occurs not in the abstract and only prior to the solution generation process, but is repeatedly brought into dialogue with designers' various explorations of context, users, and early solution proposals.

3. Prototypes: Making to Learn

Designers privilege making activities, such as sketching, modeling, and the creation of mockups and prototypes. These activities are pursued by designers not just to represent and functionally test solution concepts, but as a way to explore the problem space, to direct their inquiry, and to better understand users' needs. Designers can be said to think via their making activities; they *make to learn*, not simply to "apply" learning or to materialize a concept at a late-stage in the design process [22].

The DFA "Guide" includes making as one of its six steps, "build," which focuses specifically on the late-stage goals of concept testing and verification. However, "prototyping" is also considered as a key step within the preceding step of "ideate," which entails a range of activities that contribute to the generation of solution concepts [20]. While learning necessarily occurs in both stages of the process, they are different types of learning—the first explores which path should be taken and the latter explores how best to pursue that path. It is this first type of making that aligns most closely with my conception of "making to learn." The d.school also splits making activities into two of its 8 Core Abilities. "Experiment rapidly" includes low-resolution building activities as way of exploring concepts quickly and without significant investment of energy or resources, and "build and craft intentionally" entails the creation of a series of prototypes (or test objects), at increasingly higher but always "appropriate" levels of resolution.

In my experiences with teaching design to non-designers, this is perhaps the most difficult of the design principles to internalize and, hence, to practice routinely. Partly, this is the logical result of not wanting to "waste time" making a prototype before having figured out what the most promising solution concept is: We should first think through our options, then identify the most promising one, and only then act to physically instantiate something. This reasoning is sensible, but it presumes that "thinking" happens abstractly and not materially—that it is possible to effectively explore the solution space exclusively cognitively, or perhaps using rough sketches. In contrast, designers think via making activities; they "get material" early in their process as a way of finding opportunities for insight and innovation that would have been difficult or impossible to arrive at through abstract reasoning.

4. Analysis Plus *Synthesis*

Better than other disciplines with which I am familiar, experienced designers move continuously and fluidly between analytic and synthetic modes throughout the entirety of their solution-generation process. In my formulation here, analytic work entails systematically confronting a complex problem by identifying its components and their relationships, whereas synthetic work entails creative assembly of solution components to produce novel outcomes. In prior work, I have demonstrated how this practice plays out in complex technological systems design, where I label the phenomenon as "directed oscillation" between solution posing and solution critique/deconstruction [23].

Neither d.school nor DFA tackle this principle in quite the same way as I do, but there are parallels. One of the d.school's Core Abilities relates loosely to my framing of this principle: "move between concrete and abstract," where the designer is to "nest the concept within the larger ecosystem that relates to it." [18]. The ecosystem in this framing is not the same as the *context* of the design process/product, but instead refers to the *conceptual* ecosystem. The point is that designers should regularly reflect on (or analyze) their design work in a way that questions its fit within a larger system of ideas.[1] DFA's Process Guide also references among its "design attitudes" the command: "Reflect regularly!" Unfortunately, this treatment of reflection—recommending to "pause and take a step back"—fails to provide insight into the relationship between analytic and synthetic modalities, or even between the abstract and concrete dimensions of design practice.

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[1] The d.school's 8 Core Abilities also includes "synthesize information," but this principle entails drawing together information from a wide range of sources rather than the interplay of competing approaches to knowledge generation as I describe it.

Designers are sometimes criticized by social scientists for borrowing social scientific methods but then employing them unsystematically, hence failing to properly analyze the contexts those methods are intended to work within. Similarly, designers are sometimes criticized by technologists for "designing" new concepts without firm comprehension of how such a concept can be operationalized: "It may be a neat idea, but it can't be built!" Here, the shortcoming is one of synthesis—not all of the necessary components have been assembled, specified, or proven. Arguably, however, the power of design comes not through systematic, robust analysis or synthesis, but by knowing how to analyze just enough to gain insights about a problem space and knowing how to synthesize at just the right level of specificity to be maximally generative without becoming swamped by all the challenges of "making it work" [24]. Rather than seeking insight through a systematic, precise analytic or synthetic framework, designers find insight through productive and continuous interplay between analytic and synthetic modes of practice.

5. Fail Early, Fail Often

This mantra is widely expressed across design thinking communities [25]. The premise is that there is much to be learned from low-risk failure, and that rather than striving to avoid failure by careful planning and robust analysis, failing early in the design process will provide quicker, higher density learning so that success can be achieved sooner. The underlying principle is to carryout low-risk experimentation throughout the design process and, thereby, to identify opportunities for innovation in both process and outcome.

DFA's Guide emphasizes the importance of embracing failure within its design attitudes. The category, "Iterate Fervently!," entails "learning by doing [which] requires teams to embrace failure and avoid perfectionism" [20]. The d.school does not include attention to failure explicitly among its 8 Core Abilities, but does include attention to the tenet of experimentation throughout its approaches, including by offering a short course dedicated specifically to the topic, entitled "Fail Faster" [26].

Of course, the sensibility, not to mention effectiveness, of employing this principle depends on how one defines "failing" and the corresponding risk associated with failure at any given stage of the design process. To a large extent, this principle could be interpreted as an inoculation against the tendency to overvalue abstracted analysis relative to informed trial-and-error in responding to complex problems [27].

5 Foundational Assumptions of Engineering, and How They Invert the Design Principles

This section identifies mainstay conceptual frameworks and assumptions underlying engineering education in a way that parallels the prior section on design education. In addition to briefly characterizing these five "key principles" of engineering, I will describe how each defies or contradicts its parallel design principle. My purpose here is not to offer a detailed analysis of how each of these principles plays out in engineering, but instead merely to contrast engineering ways of problem solving with the guiding principles of design reviewed above.

1. Analytic Power through Abstraction and Universalization

Following key tenets of the scientific method, engineering enables analytic purchase via abstraction and universalization. Engineering studies scholar, Louis Bucciarelli, has insightfully illustrated how this process is achieved for real-world (i.e., contextual, material) engineering problem solving in his work on engineering design and the history of engineering force diagrams [28]. Bucciarelli shows that among the most important skills engineering students learn from the beginning of their education is how to "simplify" real-world problems into solvable "engineering problems." This entails learning which abstractions to make in order to align a problem with the capabilities of universalized engineering tools, such as the free body diagram.

Of course, a significant amount of work has been dedicated to regaining or reintroducing an appreciation of the importance of context within engineering practice and engineering education, with entire volumes in the tradition of engineering studies dedicated to the theme [29, 30]. But the fact that such effort is needed, and that despite such efforts it remains exceedingly difficult to succeed at in a reliable way across engineering programs, indicates the extent to which context is challenging to account for in engineering problem solving.

Surely, as engineering students and practitioners gain increasing levels of expertise, they learn to rely less and less on simplifications of real-world problems and learn more and more about the significance of many of the assumptions they make. In this way, engineering practice increasingly accommodates the complexities of context. But even here, those contextual factors that are accounted for tend to revolve around the technical dimensions of engineering problem solving, with modest attention to financial and legal dimensions of a problem as well. Questions surrounding users' experiences, broader social impacts, and ethical implications can all be overlain onto engineering problem solving—and are often argued to be relevant to engineering problem solving, but they also exist conceptually outside of or beyond the "core engineering" (technical analytic) part of any given problem.

Hence, whereas design thinking starts with context and centers it throughout the problem-solving process as a way to find opportunities for innovation and to allow dynamic problem reframing, engineering problem solving strips contextual nuance away in order to identify the essential technical problem that is susceptible to engineering analytic tools. To deny that process of abstraction—to reject the associated simplification and universalization—is to sacrifice the analytic purchase of engineering problem-solving approaches. Neither contextualization nor abstraction by itself is adequate means to systematically work through complex problems, of course, so engineering and design may be understood to be complementary in this regard. However, in the context of my broader argument, engineering and design assume an inverse posture with regard to this dimension of problem solving, such that gaining strength in one area comes at the cost of strengths in the other.

2. Problem Framing as Problem Definition

As described in the prior section, the first step in translating a real-world problem into an engineering problem is abstraction from context and isolation of the relevant dimensions of the problem that are susceptible to engineering analytic methods. The output of this process is formalized in how engineering typically begins the problem-solving process, with a formal problem definition, ideally including quantified metrics of success. In a powerful acknowledgement of the significance of context, many treatments of problem definition also include the requirement that students list their assumptions, but even these assumptions are subject to the same basic limitations of the abstraction process, treating known simplifications of the technical solution path rather than the larger context, its uncertainties, and the potential confounding variables that are at play within that context. Nevertheless, problem definition formalizes the problem to be solved and strictly specifies and usually quantifies the design objectives to be achieved. In this way, problem definition carefully bounds the solution space that engineering problem solving will occur within.

Engineering problem definition contrasts with design problem framing (and reframing) not only by imposing simplification and formalization of the process. Certainly, design also demands its own sort of simplification (for example, not needing to know "how it will be built" from an engineering perspective, with the "it" referring to the outcome of the process). Engineering and design approaches to problem framing also contrast regarding how the very earliest stages of the process direct future problem solving, with engineers seeking to specify the solution space and determine in advance what a successful outcome will achieve, and designers seeking to open up the solution space by allowing themselves the flexibility to reframe the problem as the opportunity arises—as potential new solution paths are identified during the problem-solving process. Consistent with this difference, engineering problem framing is typically limited to the very beginning of the process, is completed as quickly as possible in order to get into the solution phase, and is rarely revisited unless a contradiction is found during the solution process indicating a factual error translated into the problem definition. Design, on the other hand, treats the problem statement not as definition, but as provocation, and that provocation can be revisited continually as the solution process unfolds.

Here again, we see a direct inversion of the underlying principle guiding problem solving between engineering and design. And while pursuing the strengths of one approach here is not necessarily strictly contradictory to the other—for example, engineering problem definition does not completely determine *how* the problem will be solved—the competing approaches clearly cannot be reconciled in an additive way, such that the two approaches can be resolved into a single, overarching problem framing method. Engineering and design employ competing frameworks for how to get traction on the problem confronting each discipline's approach.

3. Prototypes: Making as Proof of Concept

Engineering treats making activities in a way that is arguably close to dominant cultural understandings of when and how making ought to occur, that is, *after* the concept is finalized and in order to "prove" the concept's validity: We first imagine; we then sketch or otherwise visualize in two dimensions; and finally we build a physical model to see how the idea comes together in the material world and to test its functional performance. Proving the concept's functionality by materializing it has several dimensions: geometric and formal, material and component interfaces, quality of interaction, etc. And there is learning to be done along each of these dimensions regardless of the level of resolution of the built artifact.

For many engineering students, this is important, if complementary, learning given the predominance of analytic problem solving throughout the majority of their educational experience. But I argue that it is not the same sort of learning designers experience when materializing their concepts, particularly at very early stages of the process. Whereas designers experiment with the solution *concept* via making activities, assessing whether a particular approach is promising before committing to any particular material configuration, engineers for the most part are taught to prototype only after the concept—and usually most of its design specifications—has been finalized. Hence, engineers make to create material proof-of-concept, to test or to provide evidence that the design objectives that were established during the problem definition have been satisfactorily achieved.

Unlike with abstraction-versus-contextualization or problem definition-versus-problem (re)framing, the tensions surrounding this core educational principle are not necessarily conceptually contradictory but do provide a contrast in emphasis. "Learning" through making occurs in both approaches, as does "proving" of a concept. But the difference in emphasis is significant in principle and in practice. In principle, designers tend to have a different relationship to materials and materialization in their work, particularly by emphasizing experimentation with novel materials and using materials as much for their emotional or experiential associations as their functional capabilities. Engineers treat materials often exclusively functionally, even when experimenting with a novel material's suitability (that is, functional performance). In practice, designers make sooner, more often, and more consistently over their process, whereas engineers tend to make toward the end of their design process, particularly in design educational contexts, where there is less emphasis on testing and manufacturability. These differences of principle and practice are readily apparent by observing designers' and engineers' design studio courses consistently over various stages over the semester.

4. The Engineering Design Process Flowchart

Engineering education on *the design process* as a whole tends to revolve around process flowcharts, neatly separating conceptually and methodologically distinct stages of a linear process. Most treatments of this process provide appropriate, if equally "linear," attention to feedback loops, which enable iteration of specific stages of the process until a particular "stage gate" goal is met. Unlike designers' treatment of process as loosely structured and fully recursive, meaning the whole cycle can be repeated within any given step of the process, engineering design is structured with clear conditions required to be met for moving on to the next stage in the process. Hence, engineering design education and process overviews tend to emphasize the analytic dimensions of design problem solving.

Surely, engineers acknowledge that engineering design, like all types of design, requires creativity in synthesizing the components of a given process/output model. However, those dimensions of design—and the derivative latitude they enable within the design process—are infrequently addressed systematically in the educational setting, largely because they fall outside of the guiding analytic frame for the process (and engineering knowledge generation more broadly). As the linear-flowchart-with-iteration approach suggests, then, engineers are guided throughout their process by an analytic framing, which may admit but not otherwise address the important role to be played by creative engagement with the process and its components. Here is precisely where most engineering educators want design creativity to fit: Inserting creativity content or process into the design flowchart at precisely the right moment (perhaps to take maximal advantage of the Pareto Principle). This disjuncture, I suspect, is at the root of the misalignment between my approach to sharing the creativity achieved within PDI and what my colleagues expect when they invite me to present to them and their students how to be more creative.

Again, we do not necessarily see a conceptual contradiction between engineers' flowchart-approach to the design process and designers' on-going oscillation between analytic and synthetic modes, but the differential framing of how design ought to proceed is both telling and significant in understanding the challenges associated with overlaying design creativity with engineers' training around design practice.

5. Technical Rigor: "Bridges Must Stand"

The final point of comparison I will raise between the guiding principles of engineering and design revolves around their differential treatment of "failure." To a significant extent, much of engineering education's socialization goal entails guiding students to value "rigor" [31], specifically technical analytic rigor. In important respects, including especially their role in exclusion [32], engineering constructs of rigor can actually impede robust problem solving [33]. While I share these same concerns and believe them to deserve greater attention within engineering studies and engineering education research, my interest with rigor in this paper is limited to how engineering's privileging of rigor contrasts with design's privileging of failure.

Admittedly, the disciplinary difference here has legitimate historical origins and contemporary significance. After all, as engineers point out to the degree that it has become cliché: "bridges must stand." Certainly, they must. And when they fail to stand, lives are at risk, among other unacceptable social and financial costs. In positive ways, then, and despite necessary criticisms for over-extending its application, valuing technical rigor can be interpreted as a corollary to valuing safety in engineering solutions as translated into the engineering educational context [see 34]. Nevertheless, rigor as an explicit value can overshadow safety as an implicit value by emphasizing the importance of technical analysis for its own sake, rather than as a required component of safe and just engineering outcomes. These qualifications notwithstanding, rigor is consistently and forcefully centered within engineering education discourses and values.

Designers, for their part, also need to create output that is attentive to potential risks and harms, even if to a different degree and in a different way than engineers do. However, the design tenet of "fail early; fail often" is never cast as an alternative to inappropriate risk-taking—just as engineering's emphasis on rigor does not contradict emphasizing safety. To the contrary, the goal of promoting (early, low-risk) failure in design is to learn from experience where the stakes are lowest and the opportunities for gaining fundamental insight are highest. As another version of the "fail early" tenet puts it like this: "fail early to succeed sooner." So, whereas engineering problem solving centers around systematic, comprehensive (i.e., rigorous) technical analysis as the primary defense against unacceptable (social) risks, design emphases experimentation and trial-and-error learning where risks are low—in fact, typically negligible. Once again, we see here a rhetorical contradiction in how risk-mitigation is cast within the design process, but not necessarily a conceptual contradiction in how risk mitigation is actually achieved. Still, the differential approach is both notable and significant in how design is to be carried out, with engineering biased toward relatively rigid formalization and formulization in order to avoid unacceptable risk taking, and design toward loose structure and experimentation in order to promote acceptable, productive risk taking early in the process.

Conclusions: Incommensurability or a Possible Meeting in the Middle?

I conclude this investigation of the incongruities between design and engineering approaches by reflecting briefly on the extent to which the tensions identified are truly incommensurable and, where they are not, describing the opportunity I see for meeting in the middle. Table 1 below summarizes the key principles/approaches reviewed in the sections above, each laid out adjacent to its corresponding "inversion."

	Design	Engineering
1.	Contextualization	Abstraction / Universalization
2.	Problem Framing (and Reframing)	Problem Definition
3.	Making to Learn	Making as Proof of Concept
4.	Continual Oscillation	Process Flowchart with Feedback
5.	Privileging Failure / Risk Taking	Privileging Rigor / Risk Avoidance

Table 1: Comparative Emphasis of Core Approaches to Design and Engineering

I have arranged the list of principles/approaches loosely ordered according to a logic of decreasing conceptual "contradiction." I assess the competing approaches of 1, contextualization and abstraction, to be a near-perfect inversion, both conceptually and in execution. On the other hand, 5, failing fast and technical rigor, merely suggests differential emphasis; while they remain inversions in terms of how risk if framed, in practice they are more complementary than oppositional. As one moves down the list, I see increasing opportunity for folding the competing approaches together.

Meeting in the middle, however practicable, I argue, is not without its own conceptual tradeoffs, and here we get to the crux of the argument about whether and how design creativity might be beneficially overlain onto engineering design practice and education. Academic disciplines hang together not only by a shared, largely agreed upon system of knowledge and analytic toolsets (in other words, epistemologies), but also because of value systems and cultural forces that interpenetrate with those epistemologies. The components of these discipline-making "systems," we could call them disciplinary logics, are contingent but not arbitrary, and their components cannot be randomly swapped out without trickle-through effects and tradeoffs.

This paper has shown five specific ways that the disciplinary logics of design and engineering are distinct (and often contradictory), but in these very distinctions, they also hold together as consistent and mutually supporting "wholes." It is simplistic to assume a knowledge-making tool can be stripped from one system of meaning making and be inserted, wholecloth, into a different knowledge system without changing meanings and disciplinary logics—both of the tool and of the system it is inserted into. In this way, I think my illustrations above have shown how design approaches create conflict or friction when imported from design into engineering. The slippage impacts both the tool, which is difficult (or can be impossible) to employ efficaciously in the new context, and the coherence of the knowledge system, which must adjust to potentially incommensurable inputs. To a non-trivial extent, the experimentation and play that is characteristic of design contracts the seriousness of purpose and analytic, cognitive, and emotional disciplining that is characteristic of engineering.

That said, disciplinary knowledge systems are not static, and are never "pure," but instead are always evolving, hybridizing, and resolving some newly internalized contradictions, while proliferating others. What makes design education powerful as a system of knowledge making is distinct from what makes engineering education powerful, and yet engineering could benefit from strategic engagement with design and vice versa if adequate attention is paid to the broader system. Ultimately, the epistemological "problem" of integration arises when a discipline presumes it can simply incorporate the most-promising tools of another discipline without tradeoffs or without adapting itself in the process. As in my opening narrative, the incorporation of social science methodologies into design was not intended to achieve the same goal in the design context as the social sciences context. Similarly, incorporation of design tools into the engineering design process could create productive frictions or hybridizations, but cannot arrive at the same results in terms of design creativity as designers understand and achieve it.

It is for these reasons I fear efforts to integrate "design creativity" into engineering by overlaying discrete, creative content, without attention to how engineering education knowledge making works as a system, is bound to fail. My effort in presenting the educational successes of PDI to engineering audiences is intended to help them see PDI as itself a coherent knowledge-making system—drawing on but distinct from both engineering and design traditions. For engineering educators to systematically enhance student creativity, they do not need an introduction to the key principles of design, which can be distributed in a glossy, two-page handout. Instead what they need is, paraphrasing myself from above, is to attend to the configuration of the curricula, its particular pedagogical strategies, how they cultivate students' identity, the nature of their programs' educational cultures, student-teacher relationships, deliberate recruit, career advising, etc. By attending to the entire educational system, and not focusing on discrete "creativity" knowledge chunks, engineering educators are more likely to reliably arrive at robust educational outcomes of enhanced student creativity, but then those changes will come at a cost to educational outcomes currently achieved. Engineering educators may wish to assume there is no friction between engineering and design educational logics, and hence to define their education design problem accordingly, but the resulting solution will not withstand contact with the real-world context of educational practice. Better is to treat that friction as a significant variable, to understand its impact on the components of the system, and to move forward accordingly.

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