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Quantifying Changes in Creativity: Findings from an Engineering Course on the Design of Complex and Origami Structures

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Quantifying Changes in Creativity: Findings from an Engineering Course On the Design of Complex and Origami Structures

Abstract

Engineering educators have increasingly sought strategies for integrating the arts into their curricula. The primary objective of this integration varies, but one common objective is to improve students' creative thinking skills. In this paper, we sought to quantify changes in student creativity that resulted from participation in a mechanical engineering course targeted at integrating engineering, technology, and the arts. The course was team taught by instructors from mechanical engineering and art. The art instructor introduced origami principles and techniques as a means for students to optimize engineering structures. Through a course project, engineering student teams interacted with art students to perform structural analysis on an origami-based art installation, which was the capstone project of the art instructor's undergraduate origami course. Three engineering student teams extended this course project to collaborate with the art students in the final design and physical installation.

To evaluate changes in student creativity, we used two instruments: a revised version of the Reisman Diagnostic Creativity Assessment (RDCA) and the Innovative Behavior Scales. Initially, the survey contained 12 constructs, but three were removed due to poor internal consistency reliability: Extrinsic Motivation; Intrinsic Motivation; and Tolerance of Ambiguity. The nine remaining constructs used for comparison herein included:

- **Originality**: Confidence in developing original, innovative ideas
- **Ideation**: Confidence in generating many ideas
- **Risk Taking**: Adventurous; Brave
- **Openness of Process**: Engaging various potentialities and resisting closure
- **Iterative Processing**: Willingness to iterate on one's solution
- **Questioning**: Tendency to ask lots of questions
- **Experimenting/exploring**: Tendency to physically or mentally take things apart
- **Idea networking**: Tendency to engage with diverse others in communicative acts
- **Observing**: Tendency to observe the surrounding world

By conducting a series of paired t-tests to ascertain if pre and post-course responses were significantly different on the above constructs, we found five significant changes. In order of significance, these included Idea Networking; Questioning; Observing; Originality; and Ideation. To help explain these findings, and to identify how this course may be improved in subsequent offerings, the discussion includes the triangulation of these findings in light of teaching observations, responses from a mid-semester student focus group session, and informal faculty reflections. We close with questions that we and others ought to address as we strive to integrate engineering, technology, and the arts. We hope that these findings and discussion will guide other scholars and instructors as they explore the impact of art on engineering design learning, and as they seek to evaluate student creativity resulting from courses with similar aims.

Keywords: design; creativity; innovation; arts; STEAM

1. Introduction

Engineering educators have begun pursuing a myriad of strategies for integrating the arts into their curricula [1, 2]. The primary objective of this integration varies, but one common objective is to improve students' creative thinking skills [1, 3]. Creativity itself, however, is a complex phenomenon. Traditionally, creativity is perceived as a unique style of problem-solving that leads to the generation of novel solutions [4]. The practice of engineering design can be characterized as a special case of creativity as it often focuses on the generation of effective and novel solutions [5]. As Bucciarelli [6] described:

> Design, by its very nature, is an uncertain and creative process. In every design task there is an opportunity for creative work, for venturing into the unknown with a variation untried before, and for challenging a constraint or assumption, pushing to see if it really matters. (p. 123)

A separate but related phenomena to creativity is innovation. Specifically, based on extensive interviews with serial innovators, Dyer, Gregersen, and Christensen (the authors of the Innovator's) DNA postulate that innovators tend to be avid questioners, observers, experimenters, and idea networkers. They framed these four phenomena as the "behavioral tendencies" of serial innovators. In alignment with the Innovator's DNA, we identify innovation as much more than a function of the brain but also a function of behaviors [7]. In the context of engineering design, to be an innovative engineer requires the act of doing or creating.

We recognize that behavior is fundamentally contingent upon one's inner drives, motivations, values, self-efficacy, and beliefs. There is not only one mode of being creative or innovative, but rather routes to creativity can widely vary. These various routes generally involve the utilization of multiple and distinct skills that may operate in tandem and, when taken together, have the potential to manifest in novel associations and solutions.

1.1 Study Objectives

Our primary objective in this study was to develop and evaluate the reliability of instrumentation to quantify changes in students' creativity skills and innovative behavioral tendencies. We tested this instrumentation within the context of a mechanical engineering course titled, "The Design of Complex and Origami Structures." This course taught technical engineering skills alongside art skills that emphasized creative thinking or doing. Hence, the primary contribution of this paper involves the development and testing of the instrumentation for evaluation purposes. In contrast, the pedagogical underpinnings of the Engineering Technology and Arts (ETA) curricula, of which this course is a part, are described in Tovar et al. [8]. To help interpret the validity of the quantitative findings [9], potential causes of changes on survey constructs are considered in light of observational data, focus groups, and reflections by the instructors on course implementation.

1.2 Design of Complex and Origami Structures

This course was developed as part of the Engineering, Technology, and Arts (ETA) track in the mechanical engineering department at an urban research institution in the Midwest USA. One of the overarching goals of this track was to enhance creativity and innovativeness in engineering students by integrating art and engineering design methods. The first course in this track, Design of Complex and Origami Structures, was team-taught by instructors from mechanical engineering and art. The engineering instructor presented topics in bio-inspired design and model-based design with an emphasis on topology optimization. The art instructor introduced origami principles and techniques as a means for students to optimize engineering structures. Students completed design projects that integrated origami-based and complex design methods.

The course objectives broadly included (a) developing knowledge and skills for the use of design tools, mathematical modeling, and creative engineering problem-solving and (b) practicing studio learning through peer critique and reflection. The art instructor engaged undergraduate students from an origami class to provide an opportunity for collaborative learning experiences between the engineering and art students. This art course involved a capstone project of installing an origami-inspired structure on the premises of a church. Based on initial design presentations by the art students to their engineering counterparts, six out of 24 engineering students were chosen to collaborate with the art students in the final design and physical installation of the origami-based structure. All other engineering students were required to develop and present a project on self-identified topics, with the minimum expectation that they utilized both origami and engineering design methods, with an added emphasis on creative or innovative solutions. Other project expectations are detailed in the syllabus (see Appendix A).

2. Methods

We hypothesized that student creativity would increase as a result of their participation in the course. Two existing psychometric instruments were utilized to evaluate student changes in creativity: the Reisman Diagnostic Creativity Assessment (RDCA) [10] and the Innovative Behavior Scales [11]. Taken together, the creativity instruments initially contained 12 constructs that, we posited, aligned well with the course objectives of Design of Complex and Origami Structures. In addition to tracking pre and post changes using these constructs, we measured course satisfaction, as well as how students perceived the course to have contributed to their development of an identity as an "engineer" and as an "artist." This data was measured post-course only and is not reported herein.

2.1 Participant Overview

24 students completed either the pre or post survey; 20 students completed the pre-survey; 21 students completed the post-survey; and 17 students completed both the pre and post survey. Hence, there were 17 complete responses, and this is the data analyzed and reported here. The 17 complete responses were all Mechanical Engineering graduate students. 14 reported their sex as male, 2 as female, and 1 did not specify. 16 participants were 25 or younger, and 1 participant was 31 years of age. 14 students reported their race as Asian Pacific, 2 as White, and 1 as Hispanic. 5 students indicated that English was their primary language, 11 indicated that it was not, and 1 respondent did not specify. Table 1 outlines this demographic data.

Table 1. Participant Demographics

Demographic Variable	Total
Complete Responses	17
Gender	
Male	14
Female	2
Not available	1
Race	
Asian Pacific	14
White	2
Hispanic	1
Primary Language	
English	5
Not English	11
Not available	1

2.2 Student Creativity

A survey was designed and implemented before and after the course to measure the impact of course participation on students' self-perception of their creative tendencies. We utilized two existing surveys: the Reisman Diagnostic Creativity Assessment (RDCA) [10] and the Innovative Behavior Scales (IBS) [11]. We chose two instruments, as while the RDCA covered most of the course objectives, an inspection of Reisman et al. [10] indicated that the survey constructs had questionable reliability in prior use. Therefore, our team refined this instrument and its constructs prior to data collection. In contrast, our team had utilized Dyer et al.'s (2008) instrument in the past, with results that had excellent reliability. Notably, the surveys also capture various facets of creativity, as the IBS focuses on *innovative behavioral tendencies* whereas the RDCA emphasizes *creative thinking*.

2.2.1 Revised Reisman Diagnostic Creativity Assessment (RDCA) Survey

Our team utilized Reisman and colleagues' (2016) study as a starting point for quantifying changes in student creativity [10]. The RDCA is a self-assessment instrument used to measure creative thinking. It was developed at Drexel University and has been tested with engineering students. Its theoretical underpinnings trace back to Guilford's (1967) book, *The Nature of Human Intelligence* [12]. As described in Reisman et al. (2016), the RDCA originally contained 40 items that load onto 11 constructs, although many constructs showed less than optimal internal consistency reliability [13]. Constructs and their reliability reported by Reisman and colleagues included Originality ($\alpha = .93$), Fluency ($\alpha = .87$), Flexibility ($\alpha = .65$), Elaboration ($\alpha = .66$), Tolerance of Ambiguity ($\alpha = .77$), Resistance to Premature Closure (α not reported), Divergent Thinking ($\alpha = .67$), Convergent Thinking (α not reported), Risk Taking (α not reported), Intrinsic Motivation (α not reported), and Extrinsic Motivation ($\alpha = .89$) [10].

Due to these less than optimal reliability coefficients, we revised the RDCA by systematically reviewing the original constructs and their underlying items. First, we operationalized each construct by reviewing the items vis-à-vis the authors' definitions. In instances where we perceived misalignment, we chose to either remove or revise the items or re-conceptualize the construct itself. For example, we reframed “Fluency” as “Ideation.” Generally, we retained constructs that showed evidence of excellent internal consistency reliability verbatim (i.e., Originality; Tolerance of Ambiguity). For constructs where revisions were needed to increase reliability but that still appeared salient (i.e., Risk Taking), we reworded or added items. Sometimes, these changes were minor. For example, “I am willing to take a calculated risk dependent on the consequence,” was revised by removing the word “calculate.”

Lastly, we worked from constructs that had poor (i.e., Flexibility, Elaboration) or no (i.e., Convergent Thinking, Resistance to Premature Closure) reliability data reported by Reisman et al. [10]. We removed the constructs Flexibility, Elaboration, Divergent Thinking, and Convergent Thinking. Through this process, we designed two new constructs that merged aspects of these phenomena. The new constructs encapsulated ideas of *openness* and *iteration*. Where possible, we borrowed items directly from the removed RDCA constructs.

In total, the newly designed construct *Openness of Process* included 10 items, many including items adapted or taken directly from the RDCA. For example, we utilized two items from the Resistance to Premature Closure construct: “I stay open to choices before coming to a conclusion,” and, “I restrain from making premature decisions.” We also reframed items from the Divergent Thinking construct. For example, “I prefer situations where there are multiple choices,” was reframed as “I prefer problems where there are many or several possible right answers.” Finally, we incorporated a few newly designed items, such as, “I analyze problems from several different points of view,” and, “I come up with multiple possibilities when analyzing a problem by looking at every angle of the situation.”

The final construct, *Iterative Processing*, included four items, each of which were newly designed by our team. These items emphasized a general comfort with navigating between convergent and divergent thinking regardless of “success” or “failure.” This construct incorporated components underlying the Resistance to Premature Closure construct, although we did not utilize any items from this construct.

The revised RDCA contained 39 items which loaded onto eight constructs. Each item asked respondents to rank their level of agreement on a six-point Likert-type scale wherein one represented strong disagreement, six represented strong agreement, and all items in-between represented a continuum from strong disagreement to strong agreement. Appendix B identifies each individual survey item and the associated construct. The revised RDCA survey constructs utilized for comparative testing in this study included:

- **Originality**: Confidence in developing original, innovative ideas
- **Ideation**: Confidence in generating many ideas (originally described as fluency)
- **Tolerance of Ambiguity**: Comfort with handling the unknown [later removed]
- **Risk Taking**: Adventurous, in general situations
- **Intrinsic Motivation**: Tendency to be motivated based upon an inner drive [later removed]
- **Extrinsic Motivation**: Tendency to be motivated by external rewards [later removed]
- **Openness of Process**: Engaging various potentialities and resisting closure
- **Iterative Processing**: Willingness to iterate on one’s solution

2.2.2 Innovative Behavior Scales

The Innovative Behavior Scales [11] was grounded in the theory of innovation as outlined in the Innovator's DNA [7]. Herein, Dyer and colleagues conceptualized innovation as a function of individual behavioral tendencies. Specifically, based on interviews with numerous entrepreneurs, they found that innovators tend to exhibit four specific behavioral tendencies. The Innovative Behavior Scales was designed to measure these through four survey constructs with 19 total items. The survey constructs included:

- **Questioning**: Tendency to ask lots of questions
- **Experimenting/exploring**: Tendency to physically or mentally take things apart
- **Idea networking**: Tendency to seek opportunities to engage with the thoughts of others
- **Observing**: Tendency to observe the surrounding world

3. Results

3.1 Reliability Testing

As many RDCA items were designed or redesigned by our team (rather than used verbatim from the existing instrument), each construct's reliability and validity was in question. Due to the small sample size, factor analytic methods could not be utilized to ascertain structural validity. Hence, upon collecting all pre and post-responses, we analyzed the internal consistency reliability of these measures using Cronbach's alpha. Throughout this process, our objective was to ascertain which items contributed to or greatly reduced the internal consistency reliability.

Table 2. Reliability testing of survey constructs

Instrument & Constructs	α_{Pre}	α_{Post}
Revised-RDCA		
Originality	.934	.891
Ideation	.942	.854
Tolerance of Ambiguity	.597*	.806
Risk Taking	.863	.703
Intrinsic Motivation	.665	.356*
Extrinsic Motivation	.862	.311*
Openness of Process	.889	.849
Iterative Processing	.933	.818
Innovative Behavior Scales		
Questioning	.845	.728
Experimenting/exploring	.897	.856
Idea networking	.796	.861
Observing	.886	.919

*Note. Data was based on complete responses for pre or post survey. Therefore, the pre sample size = 20; Post sample size = 21; *indicates internal consistency reliability was unacceptable; DeVillis' thresholds for acceptably were utilized (i.e., $\alpha < .60$ is unacceptable; $.60 \leq \alpha < .70$ is minimally acceptable; $.70 \leq \alpha < .80$ is good; $\alpha \geq .80$ is excellent)*

As a result of this analysis, three survey constructs were removed from further usage in this study: Extrinsic Motivation; Intrinsic Motivation; and Tolerance of Ambiguity. Each of these constructs were either unacceptable when the pre or post-course responses were analyzed in isolation (i.e., α less than .60). Importantly, the individual items were explored to see if removing items would improve the scales, but we were unable to ascertain acceptable pre and post scores through this process. Table 2 provides an overview of these results.

3.2 Comparative Testing

Figure 1 provides a visualization of pre-course responses, or responses collected before students participated in the course (January 2017), versus post-course responses, or responses collected following students' completion of all course activities (May 2017). All responses were collected on a six-point Likert-type Scale where 1 = Strongly Disagree and 6 = Strongly Disagree. As Figure 1 shows, student responses increased on nearly every construct. The construct with the highest increase from pre to post was Idea Networking (Δ = .96, *SD* = .77), followed by Questioning (Δ = .78, *SD* = .70). Figure 1 is sorted from smallest to highest post-course responses on the survey constructs.

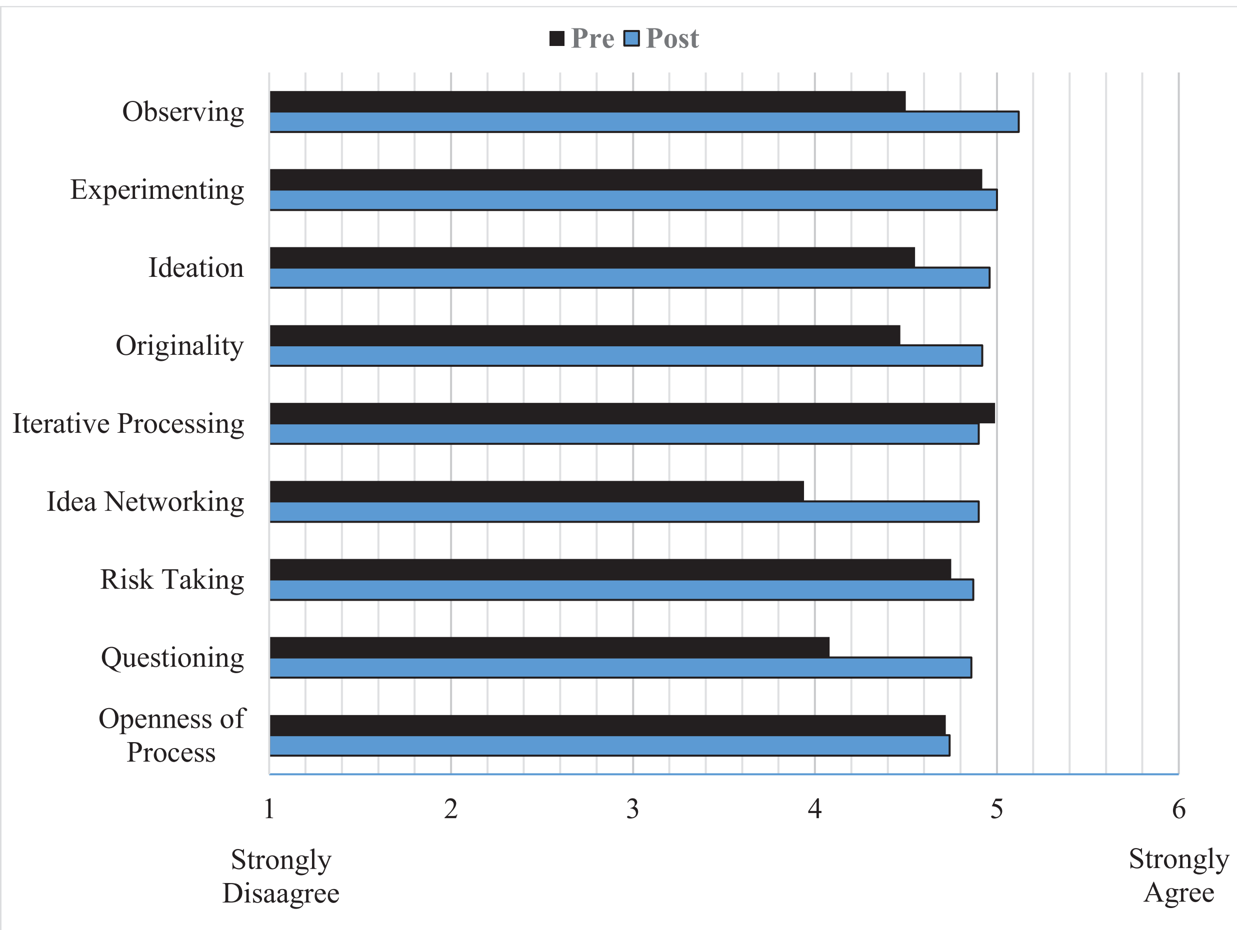

Figure 1. Overview of Pre and Post Descriptive Statistics (n = 17 complete pre/post responses)

Next, we compared pre and post responses through a series of paired t-tests. As a precursor to this analysis, we investigated the normality of the difference scores for each construct (e.g., the distribution of the post minus the pre scores) by computing Shapiro-Wilks coefficients [14]. The difference scores were approximately normal for each construct with the exception of Risk-Taking (W = .813, p < .05). Nonetheless, we report the findings for this construct in Table 3, although we caution making inferences from its results. Table 3 summarizes these findings.

Table 3. Paired t-test results for creativity constructs

	Pre		**Post**		**Std. Error**		**Sig.**	
	M	***SD***	***M***	***SD***	**Mean**	**t-stat**	**(2-tailed)**	***d***
Idea Networking**	3.94	1.09	4.90	0.93	0.19	5.11	0.000	0.94
Questioning**	4.08	0.95	4.86	0.73	0.17	4.63	0.000	0.92
Observing**	4.50	0.91	5.12	0.67	0.16	3.75	0.002	0.77
Originality*	4.47	0.95	4.92	0.68	0.15	2.95	0.009	0.55
Ideation*	4.55	0.91	4.96	0.65	0.14	2.97	0.009	0.52
Risk-Taking	4.75	0.76	4.87	0.72	0.15	0.80	0.436	0.16
Experimenting	4.92	0.77	5.00	0.52	0.17	0.48	0.638	0.13
Openness in Process	4.72	0.67	4.74	0.65	0.12	0.15	0.886	0.03
Iterative Processing	4.99	0.97	4.90	0.75	0.21	-0.43	0.675	-0.10

Note: Responses were on a 6-point Likert-type scale where 1 = Strongly Disagree and 6 = Strongly Agree
**p < .005 (threshold if utilizing a Bonferronni correction); *p < .01

A series of paired-samples t-tests were conducted to evaluate the impact of the intervention on students' self-reported creative abilities. By order of magnitude, we found statistically significant increases in the following constructs:

- **Idea Networking**, t (16) = 5.11, p < .001 (two-tailed), large effect size (d = .94)
- **Questioning**, t = 4.63, p < .001, large effect size (d = .92);
- **Observing**, t (16) = 3.82, p < .01 (two-tailed), medium effect size (d = .77);
- **Originality**, t (16) = 2.95, p < .01 (two-tailed), medium effect size (d = .55);
- **Ideation**, t (16) = 2.97, p < .01 (two-tailed), medium effect size (d = .52).

We used Cohen's thresholds for ascertaining the magnitude of effect size [15]. Further, we note that Bonferroni correction would adopt a stricter significance threshold of p < .005 rather than p < .05 (as nine hypotheses were tested, we would divide the traditional significance level of .05 by nine [16]). If we utilize this more conservative threshold, then significant changes would only include Idea Networking, Questioning, and Observing.

4. Discussion

4.1 Measurement Considerations

We used two instruments to measure changes in student creativity: (a) a revised version of the Reisman Diagnostic Creativity Assessment (RDCA), which was designed to measure creative thinking; and (b) the Innovative Behavior Scales, which was designed to measure innovative behavioral tendencies. We modified the RDCA based on our review of the constructs, their conceptualization, their underlying items, and previously reported reliability evidence [10]. As we reviewed these constructs and their underlying items, we sought to retain those that had good internal consistency reliability and we adapted of items of those with poor or no reliability statistics reported [10]. Finally, we removed four constructs and added two new constructs.

Through reliability testing, we ascertained that the Innovative Behavior Scales constructs all showed good to excellent reliability, including the two newly designed constructs, Openness of Process and Iterative Processing. In contrast, three constructs from the revised RDCA had unacceptable reliability evidence: Tolerance of Ambiguity; Risk Taking; and Intrinsic Motivation. While we recognize that Cronbach's alpha is not the ideal mechanism for ascertaining psychometric validity [17], in the instances where Cronbach's alpha values fell well below a threshold of .60 (i.e., those described above), we suggest that moderate revisions be made before using these constructs in future studies. Appendices B and C contain survey items.

We also caution readers and note that this study is limited as we did not utilize factor analytic procedures to ascertain structural validity [9]. In the future, as the sample size grows, we intend to do so, and we would encourage others to follow similar procedures before broadly adopting this instrumentation. Such validation studies might do so in collaboration or consultation with the original survey designers.

4.2 Triangulating Assessment Data

We found significant changes for five constructs when comparing pre and post responses. In order of significance, these included *Idea Networking*; *Questioning*; *Observing*; *Originality*; and *Ideation*. To help explain these findings, to bolster our confidence that these constructs are measuring reality, and to identify how this course may be improved in subsequent offerings, here we triangulate the quantitative findings with teaching observations, responses from a mid-semester student focus group session, and informal faculty reflections. Specifically, an instructional designer (Author 2) from the university teaching center observed two class sessions taught by each of the two instructors. In Table 4, we sought to attribute specific instructional and assessment practices of the engineering and arts instructor that were observed and that may have led to significant increases in these constructs.

Despite differences in the two instructors' approaches to instruction and assessment, which are implicitly grounded in their personal teaching style and disciplinary conventions, each instructor actively encouraged peer interaction and collaboration between the art and engineering students. For example, the art students presented their capstone project proposals to the engineering students, who asked questions and provided suggestions for improved structural stability. Engineering students were asked to present their final project in multiple stages of design and development to receive peer and instructor feedback. Significant increases in the Idea Networking, Questioning, and Observing constructs could be attributed to the design of the final project assignment and the learning activities in these class sessions.

In addition to classroom observations, student perceptions of the course structure, course content, instructors' teaching methods, and assessments were gathered through a mid-semester student focus group. 21 students participated in the focus group. They provided feedback on what aspects of the course helped them in their learning and what aspects they felt could be modified to improve their learning. Results indicated that all the engineering students enjoyed interacting with their peers and course instructors. Over 50% of the students indicated that they better understood the perspectives of the art students and appreciated the opportunity for collaboration. Despite this engagement and interest with the art aspects of the courses, about 30% of the engineering students felt that their role was limited to that of a contractor or consultant on the art project. All students believed that collaborating sooner with the art students could have minimized this perception and created a truly integrated and collaborative project.

Table 4. Practices that Potentially Contributed to Changes in Creativity and Innovation

Construct	**Engineering instructor's practices**	**Art instructor's practices**
Idea Networking	-Prompted students to present project development at various stages and, thereby, to receive incremental peer and instructor feedback.	-Created multiple opportunities for collaboration between art and engineering students. -Collaboration involved discussing design goals and processes across disciplines and receiving peer feedback.
Questioning	-Used in-class activities that modeled concepts required for projects. -Note: reflection prompts or questions were not explicitly embedded in these activities.	-Created a reflection prompt that encouraged self-questioning. -Challenged engineering students to seek clarifications from art students on an art installation.
Observing	-Both instructors presented several examples of complex structures and origami-based designs to emphasize disciplinary design challenges and potential for interdisciplinary solutions	
Originality	-Promoted student involvement in state of the art methods in design of complex structures, particularly in bio-inspired design and topology optimization. -Rewarded unique applications and modifications to approaches reported in literature.	-Encouraged the students to research for inspirations on different origami-based designs. -Prompted students to make unusual connection, see analogies between origami designs through imaginative thinking. -Asked students to materialize their imagination through making and prototyping (e.g. by folding their original origami models), as new ideas and possibilities often come into view through the processing of making.
Ideation	-Both instructors emphasized the iterative process of developing project designs, evaluating them, and seeking peer and instructor feedback	

4.3 Integrating Engineering and the Arts

Gess (2017) suggested, “In order to facilitate an effective STEAM [Science, Technology, Engineering, Arts, and Math] educational experience for your students, you should be participating in the same iterative cycles of design and reflection that you are planning for your students” [18, p. 41]. This study serves as a catalyst for reflection on the initial implementation of a course designed to integrate engineering and the arts. We hope this reflective exercise will manifest in iterative improvements for future implementation. To further facilitate our own reflection, we note that Gess offered four “hallmarks” for effective integration of the arts into science, technology, engineering, and mathematics, including the following:

1. Approaches should be **intentional**, meaning anticipated learning outcomes are pre-defined and that strategies for attaining those outcomes should be strategic
2. Approaches should be **integrative**, meaning they are responsive to the students
3. Learning should be **anchored in design**, wherein engaging in design, both as an “engineer” and as an “artist,” is the primary vehicle for achieving the sought outcomes
4. Art should be **equal** to other STEM components and not only “an afterthought”

In this final discussion section, we list thought-provoking questions that we and others might consider addressing as we seek to foster student creativity through the integration of engineering and the arts in the graduate or undergraduate engineering curriculum. This is not to say that no work has been conducted to address these respective questions. Nonetheless, with the understanding that such interdisciplinary border-crossing can be fraught with challenges [see 1], we hope that these suggestions provide a structured set of items for other scholars and instructors to consider addressing when seeking to integrate art and engineering.

Intentional:

- How does one conceptualize creativity in a way that includes and does service and justice to both the engineering and arts perspectives?
- In the given context of a program or course, what does it mean to integrate engineering and the arts in terms of student learning outcomes?
- What are disciplinary and interdisciplinary pedagogical considerations (i.e., theoretical, evidence-based, prior knowledge) that need to be adhered to when developing and offering a course that integrates engineering and the arts?
- What additional learning outcomes could be added, including but not limited to the creativity and innovation constructs from this study?
- How can instructors account for, and potentially capitalize on, various situational variables (i.e., university context; resource availability)?

Integrative:

- What role can and should art and engineering instructors play when situating the arts within an engineering design context?
- How can arts and engineering instructors utilize and leverage learners’ prior knowledge and values to create learner-centered classrooms?
- How can instructors ensure that teaching strategies do not create counterproductive learning moments for students (i.e., assuming arts are inferior to engineering)?

- What kinds of integrative formative assessments can instructors use, and what is the ideal method for doing so?
- How can and should arts and engineering instructors critically reflect on and collaboratively respond to student concerns about a STEAM course over time?

Anchored in Design:
- In the context of a program or course, what does an integrated "engineering and art" design process look like?
- In what ways can art and engineering design goals, processes, and theories converge and diverge in a collaborative design project that involves artists and engineers?
- What types of communication and feedback mechanisms can be set in place by instructors to ensure meaningful and persistent collaborations between the two groups?
- What design-based theory or paradigms are most applicable to STEAM curricula?
- What assessment strategies are most appropriate for providing evidence for the applicability or fidelity of STEAM towards creative thinking/skill development?

Equal:
- How can artistic concepts and principles be embedded into the core of engineering design, rather than "bolted-on"?
- What are strategies for working through disciplinary or specialization biases?
- How can external entities facilitate this cross-disciplinary dialogue or collaboration?
- How does one ensure that instructor intentions are implemented into classroom practices in a way that respects all parties?
- How can assessments be created to equally harness the learning and practice of art and engineering design principles?

5. Conclusion

This paper described a strategy for quantizing changes in student creativity. This evaluation strategy was tested within the context of a single Mechanical Engineering course. Respondents answered survey questions pre and post course, and changes in responses were compared. Classroom observational data was utilized to contextualize findings and also to inform our own interpretation of the trustworthiness of the instrumentation utilized. The primary contribution of this paper involves the potential for other instructors to utilize this instrumentation for their own evaluation purposes. Naturally, given the small sample size and implementation within a single course, future data collection, reliability testing, and validation procedures should be applied.

This evaluation was of one course that was part of a three-course sequence that seeks to integrate engineering and the arts. This curriculum and its rationale is described in Tovar et al. [8]. While our team has mapped out this curriculum, we also recognize that we need to continue identifying the ideal mechanisms for truly and effectively integrating the domains of engineering and the arts. Like others who have pursued STEAM-like approaches, members of our team have faced numerous challenges through this journey, and it is from these challenges that we have listed the thought-provoking questions that conclude the preceding section. In the future, we plan to continue addressing these questions. In addition, we hope to develop a taxonomy for integrating the arts and engineering by reflecting on Gess's proposed hallmarks in light of our experiences.

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Appendix A: Shortened Course Syllabus

Course: Design of Complex and Origami Structures

Description: This graduate-level course introduces principles in art and engineering analysis and optimization with focus on design of complex, irregular (organic), free-form, and origami structures. This course provides a sound grasp of structural analysis and design optimization methods, the origami arts, and fundamental creative strategies used in the design thinking process.

Prerequisite:
- ME 26200 – Mechanical Design I
- ME 27200 – Mechanics of Materials
- ME 27400 – Basic Mechanics II
- Recommended: A course in Finite Element Analysis, CAD, and Programming or Numerical Methods

Recommended books:
- Adriaenssesn, Block, Veenendaal, Williams (Eds). Shell Structures for Architecture: Form Finding and Optimization. Routledge, Taylor & Francis Group, 2014.
- Mastinu, Gobbi, and Miano. Optimal Design of Complex Mechanical Systems, with applications to vehicle engineering. Springer, 2010.

Course Objectives:
1. Utilize computer-aided design tools to create complex and origami structures
2. Model loading conditions in complex and origami structures and predict stresses and strains
3. Create complex and origami structures utilizing optimization, form-finding, and experiential approaches
4. Critique and defend designs in public and private settings
5. Appreciate the value of studio-based learning in technical design

Learning Outcomes:
1. Predict strains and stresses in structures subjected to mechanical loads.
2. Apply form-finding approaches to the design of structural layouts.
3. Explain the mathematical and physical principles for the design of origami structures.
4. State and solve structural optimization problems using mathematical programming.
5. Explain the effect of manufacturing, material, and design in the structure's lifecycle and sustainability.

Course Topics:
1. Numerical modeling and analysis of trusses, beams, and shells
2. Physical modeling and form finding methods
3. Origami structures
4. Model-based design
5. Design and analysis of computer experiments
6. Structural optimization methods

Course Content and Methodology:
The first part of the course will be conducted in "hands-on" interdisciplinary art and design studios in which studio-based pedagogy will be emphasized in order to cultivate students' identities as designers, develop their conceptual understanding of design and the design process, and foster their design thinking.

Student participation, collaboration and peer learning will be stressed as an important part of a studio culture ethos. The students will meet (physically or virtually) in large design studios on both the IUPUI and Bloomington campuses.

The design studios in Bloomington have flexible and modular furniture layouts allowing for fluid movement between one-on-one discussion and critique, small group collaboration, and large group critique. In addition, the students will have access to technological resources, such as laptops, digital cameras and printers. Since the design studios are located in close proximity to the fabrication labs, students will have access to digital fabrication tools including a laser cutter, digital cutter, and CNC machine tools, allowing them to experiment with material and making techniques in various stages of design processes.

The students will apply such studio-based experiences in generating creative solutions for the problems posed in the course project. Specifically, students will be asked to come up with irregular, free-form, and origami designs in the context of material, construction, artistic form finding, and form making. They will do so in response to an open-ended problem related to sustainability and product lifecycle. Students will first be introduced to origami art and techniques of using paper folding as a means for form finding and form making. Students will then conduct research on aspects of product lifecycles including production, distribution, use, and disposal.

The students will develop schematic designs with multiple visual ideas and experiment with tangible materials, inspired by the art of origami, in order to identify the environmental issues in the current product lifecycle. They will further develop their ideas via iterative designs in a series with each version suggesting subsequent problems to explore in order to address the issues they identified earlier in the schematic design phase. At the end, students will professionally present their work and communicate their ideas to the general public, as well as professionals.

Grading Distribution:
In-class work 20%
Project 1: Complex structure 20%
Project 2: Origami structure 20%
Project 3: Final project 40%

Project briefs with detailed description and a course outline with dates and scheduled course activities will of each project will be delivered the first week of classes.

Completion of Projects
The primary requirement in this course will be the competent completion of assigned projects. Each of these projects will have interim outcomes intended to teach you specific skills and methods, as well as helping you create the final portfolio. Completion of each interim activity will be considered in determining your grade for each project. These interim activities will compose part of your final project grade. Preparedness and participation in all activities, and in critiques is essential.

- absences are not "excused"
- you are expected to attend all classes, arriving promptly and staying until dismissed
- consistently late arrival, early departure, and/or frequent absence will adversely affect the "work habits and participation" portion (10%) of your semester grade
- you are responsible for acquiring and mastering all information, handouts, materials, etc., missed because of lateness or absence; no other person is responsible for seeing that you obtain or master this material
- assignments are to be handed in on the dates and times scheduled
- incomplete work is not accepted
- work submitted by others is not accepted
- extensions are not granted
- make-ups are not granted

Project Expectations
These metrics overlap with performance criteria that are outlined in professional design educational organizations, such as the National Architectural Accrediting Board.

- **Pre-Design**: Ability to conduct comprehensive research (lifecycle analysis), assess design problems, opportunities and needs; examine and comprehend fundamental principles.
- **Schematic Design**: Ability to refine design parameters by limiting variables and ID-ing problems, employing multiple visual ideas, and engaging in material and making to test initial designs.
- **Design Development**: Ability to develop the design through a reiterative open-end process and test alternative outcomes against relevant criteria.
- **Professional Communication**: Ability to write and speak effectively and use representational media to illustrate design solutions.
- **Collaboration**: Ability to work in an interdisciplinary team environment.
- **Participation in Group Critiques**: Ability to raise clear and precise questions, use abstract ideas to interpret information, consider diverse points of view, and reach well-reasoned conclusions.

Grading Scale:
97 = A+ 77 = C+
93 = A 73 = C
90 = A- 70 = C-
87 = B+ 67 = D+
83 = B 63 = D
80 = B- 60 = D-

APPENDIX B: REVISED REISMAN DIAGNOSTIC CREATIVITY ASSESSMENT CONSTRUCTS

Note that many of these items were revised from the initial survey publication [10]. Reliability testing was conducted utilizing on Cronbach's alpha, which leading to the removal of three constructs Extrinsic Motivation; Intrinsic Motivation; and Tolerance of Ambiguity.

Item	Construct	Item Description
RC01	Risk-Taking	I am willing to take a risk independent of the consequence.
RC02	Process	I follow many paths to come up with possible solutions.
RC03	Risk-Taking	I take calculated risks in certain situations.
RC04	Process	I prefer problems where there are many or several possible right answers.
RC05	Originality	I can come up with novel uses for things.
RC06	Originality	I come up with unique suggestions.
RC07	Process	I generate multiple possibilities when analyzing a problem.
RC08	Tolerance	I can tolerate ambiguity.
RC09	Process	I prefer situations that have only one possible response. (-)
RC10	Originality	I come up with new and unusual ideas.
RC11	Intrinsic Mot.	I engage in activities that are personally satisfying.
RC12	Iterative	After I have a solution, I continue testing it while remaining open to other possibilities.
RC13	Ideation	I can produce a lot of ideas.
RC14	Process	I persist in gathering as much information as possible before making a decision.
RC15	Originality	I think in unusual ways.
RC16	Originality	I am innovative.
RC17	Ideation	I can generate many solutions.
RC18	Process	I restrain from making premature decisions.
RC19	Extrinsic Mot.	Knowing that I am going to be rewarded enhances my motivation.
RC20	Risk-Taking	I am willing to tackle challenging tasks.
RC21	Intrinsic Mot.	I do well on activities or tasks that interest me.
RC22	Extrinsic Mot.	I perform tasks better knowing there will be a reward or recognition.
RC23	Ideation	I generate many ideas.
RC24	Tolerance	I cope with uncertainty.
RC25	Process	Before I make a decision, I consider multiple possibilities.
RC26	Process	I consider the perspectives of others before making a decision.
RC27	Extrinsic Mot.	I will put more effort towards an activity or task if there is some kind of incentive.
RC28	Process	I stay open to choices before coming to a conclusion.
RC29	Iterative	Even if a solution is successful, I tend to imagine other potentialities.
RC30	Iterative	Even while testing a potential solution, I remain open to other possibilities.
RC31	Intrinsic Mot.	Curiosity, enjoyment and interest energize me to complete a task.
RC32	Iterative	If I select a solution that turns out wrong, I am comfortable identifying and testing a new solution.
RC33	Intrinsic Mot.	My performance on a task is enhanced by my interest in the task.
RC34	Intrinsic Mot.	My motivation to perform well does not depend on external recognition.
RC35	Risk-Taking	I take action where risk may be involved.
RC36	Originality	I think out of the box.
RC37	Tolerance	I can tolerate the unknown.
RC38	Intrinsic Mot.	I do not do well on activities or tasks that do not interest me. (-)
RC39	Process	I analyze problems from several different points of view.

APPENDIX C: INNOVATIVE BEHAVIOR SCALES[11] SURVEY ITEMS AND CONSTRUCTS

Item	Construct	Item Description
IBS01	Questioning	I often ask questions that challenge the status quo.
IBS02	Experimenting	I am adventurous, always looking for new experiences.
IBS03	Experimenting	I have a history of taking things apart.
IBS04	Experimenting	I frequently experiment to create new ways of doing things.
IBS05	Observation	I have a continuous flow of new ideas that comes through observing the world.
IBS06	Idea Networking	I have a large network of contacts with whom I frequently interact to get ideas.
IBS07	Questioning	I am constantly asking questions to get at the root of the problem.
IBS08	Idea Networking	I initiate meetings with people outside of my discipline to spark new ideas.
IBS09	Idea Networking	I have a network of individuals whom I work with to refine my ideas.
IBS10	Questioning	I am constantly asking questions to understand why products and projects underperform.
IBS11	Observation	By paying attention to everyday experiences, I often get new ideas.
IBS12	Observation	New ideas often come to me when directly observing how people interact with products.
IBS13	Questioning	I am always asking questions.
IBS14	Questioning	Others are frustrated by the frequency of my questions.
IBS15	Idea Networking	I attend professional and/or academic conferences outside of my discipline.
IBS16	Observation	I regularly observe others' use of products to get new ideas.
IBS17	Experimenting	I love to experiment to understand how things work and to create new ways of doing things.
IBS18	Experimenting	I actively search for new ideas through experimenting.
IBS19	Questioning	I regularly ask questions that challenge others' fundamental assumptions.