ASEE'S VIRTUAL CONFERENCE
At Home with Engineering Education
JUNE 22 - 26, 2020 #ASEEVC
Paper ID #28734

Are Creative Capstone Design Projects Successful? Relating project creativity to course outcomes.

Dr. Bridget M. Smyser, Northeastern University

Dr. Smyser is a Teaching Professor and the Lab Director of the Mechanical and Industrial Engineering at Northeastern University. Her research focuses on lab and design pedagogy.

Prof. Andrew Gouldstone, Northeastern University

Are Creative Capstone Design Projects Successful? Relating project creativity to course outcomes.

In the past ten years, numerous papers have presented techniques for fostering creativity in design courses and in individual engineering students. Creativity is desirable because the ability to combine and synthesize ideas, take risks, and innovate is necessary to address open-ended problems with novel and innovative solutions. However, capstone design students typically earn grades by developing complete, justified solutions, communicating their design process clearly, and satisfying the needs of sponsors and external or internal evaluators. Because of this, creativity is often not explicitly measured in capstone design courses and is only indirectly part of the final measured course outcomes. This study examines the relationship between measures of creativity and course outcomes for a mechanical engineering capstone design course. This work focused on projects that were intended as or could be potentially developed as commercial products. Multiple reviewers using the validated VALUE rubric for creative thinking evaluated eighteen projects. The VALUE rubric assesses works on *acquiring competencies, taking risks, solving problems, embracing contradictions, innovative thinking,* and *connecting, synthesizing and transforming ideas.* Scores on individual rubric items as well as the total rubric score were compared to course outcomes including prototype grade and communication grade, as well as project group characteristics. Analysis was performed using Pearson's Product Moment correlation. In addition, alumni jury evaluations of the projects were also examined to see if projects with high creative thinking scores were also perceived as successful by outside observers. Of the VALUE items, the ability to connect, synthesize, and transform ideas was most highly correlated with the total creative thinking score ($P<.001$, $\alpha = .05$). Total creative thinking was positively correlated with high prototype scores ($P = .048$) and in particular the ability to embrace contradictions was highly correlated with high prototype scores ($P = 0.007$). Having a high creative thinking score was facilitated by having a high number of students on the team with a common native language. As the creativity skills were also strongly correlated with the communication grade, this seems to indicate that improving creativity requires improving communication between group members. As part of their evaluation, jurors are asked to name 'successful' and 'unsuccessful' teams. The average creative thinking score for successful groups (17.7/24) was significantly higher than the average for unsuccessful groups (9/24) at $P = 0.001$ and $\alpha = 0.05$. These results demonstrate that creative thinking skills are highly valuable for developing successful projects that are also recognized as such by external evaluators. This validates the need to actively teach creative thinking skills. It also demonstrates that time spent on teaching communication skills within student teams is vital to enhancing creative thinking skills.

Introduction

Creativity has been studied in many contexts, traditionally focused on built objects or artistic works. Creativity is important to engineering design as it leads to new products and new industries, as well as allowing people and societies to adapt to changes in environment and circumstance, and identify new problems to address. The most relevant working definition of creativity is the ability to generate a novel or innovative solution that solves a problem with certain constraints. This can include either producing a new functional object or creating a new process or direction for existing objects. Creativity cannot be fully evaluated without considering the interaction between the creator and the creative environment. Previously creativity was treated as something that could not be studied or taught – one was either creative or not. The current literature agrees that creativity is a psychological construct, and there are certain individual traits and environmental factors that can encourage or inhibit creativity [1].

For individuals, high creativity is associated with traits such as self-confidence, openness to new experiences and risk taking, an orientation towards complex concepts, an appreciation of aesthetics, and the ability to independently judge their own work. Intelligence can play a role; although some creative people have high IQ, this can also interfere with creativity if thinking is highly algorithmic and rigid [1]. Environments that encourage creativity, particularly in academic settings, rely heavily on good leadership from the faculty in charge. Providing open-ended problems that are not over constrained, and not overly controlling the process or outcomes leads to environments that promote creativity. Creative environments are stimulated by freedom to pursue a variety of paths, good project management, sufficient resources and time to finish the project, a collaborative atmosphere in which creativity is recognized, and enough of a challenge to require innovative thinking to accomplish goals. Creative climate is particularly dependent on communication. Creativity can happen in an environment where communication is competitive and punishing, but is more likely in supportive, cooperative environments [2].

Capstone design and other engineering courses would seem to require creative thinking. Clear goals, freedom to follow a number of possible paths, resources, guidance, and encouragements can all be built into the fabric of a typical capstone design course. Dym, et al. described skills needed by successful designers, including the ability to tolerate ambiguity, consider the big picture, and communicate design concepts to others. Engineering design requires an organized approach to generate ideas and evaluate them with regards to the project requirements [3]. Dym et al. did not seem sure that creativity could be taught, however numerous subsequent studies have put forth techniques for teaching and evaluating creativity in engineering design courses. Since concept generation is a necessary part of engineering design, this is a natural place to insert techniques designed to enhance creativity. One study compared two well established methods – morphological analysis directed brainstorming and Theory of Inventive Problem Solving (TIPS) – to newer methods found in the literature – transformational design using mind mapping and word net-based design by analogy. In addition, the authors developed their own techniques: far-field analogies and principles from historical innovators. The work studied the number of concepts generated by each team, and also surveyed students to determine which technique they found most helpful. Although the study was somewhat limited, it demonstrated that creativity can be taught and that specifically teaching creativity strategies made a measureable difference in creativity outcomes [4].

Assessing creativity in design courses has been the subject of many studies in the past decade. Several studies focused on encouraging and measuring creativity in design at the pre-college level. Denson et al. [5] used the Consensual Assessment Technique (CAT) developed by

Amabile [6] to assess creativity in high school students during an engineering summer camp. CAT requires evaluations by experts in a given domain and a clear definition of creativity. Denson showed that a particular web-based adaptation of CAT worked in informal situations, but also noted that standards-based programs could sometimes inhibit creativity. Another study that focused on pre-college students described five "creative habits of mind" used as the basis for a metric to measure creativity. These habits include being imaginative, inquisitive, persistent, collaborative, and disciplined [7]. Capstone students who brainstorm effectively, ask relevant questions, persist in the face of difficulties, work effectively with others, and demonstrate good organization and time management tend to produce results that are both novel and useful. Further studies focused on the interaction between creative thinking and critical thinking, both of which contribute to design quality [8].

At the college level, one study [9] compared the CAT with the VALUE rubric used in the present study [10]. The adapted rubric based on CAT measured intellectual skills, knowledge in a field, thinking style, motivation, personality and environmental influences on creativity. Problem solving heuristics were specifically taught in [9], as they are in the course in the current study. The authors of [9] were teaching an Introduction to Design course and found that students tended to achieve an intermediate level of creativity at that point in their education. A study by Oman, et al. [11] looked at junior level design students and focused on methods to compare the creativity of similar designs. They looked at design from a customer (individual consumer) point of view, as these clients often want something that is not only functional, but also interesting and novel. Creativity requires divergent thinking and a solution that goes beyond a routine solution to a problem. If a solution is both novel and has pleasing aesthetics, it can be considered an elegant creative solution. If a solution combines elegance with being applicable to other situations beyond what was originally intended, it can be considered innovative according to [11]. Specifically teaching ideation methods and heuristics can foster innovation, but can also be seen by students as cumbersome busywork. To combat this, other authors have suggested that creativity should be one of many metrics assessed, and the assessment should focus on client satisfaction [12]. The focus on an outcome that satisfies specific customer needs and wants seen in various existing works led to the decision to focus on potential consumer products in the current study. Assessing creativity in capstone design courses generally builds on existing creativity assessment models, and can show positive correlations between novelty/usefulness and communication scores [13], which has also been noticed in the current work.

Research Questions and Methods

This study seeks to answer the following questions:

- Is there a relationship between creativity and project/course outcomes?
- Are certain aspects of creativity more important for project success than others?
- Are there team, project, or other factors that seem to inhibit creativity?

The projects evaluated in this study are listed in Appendix A. Thirty projects from 7 previous terms were evaluated using the VALUE creativity rubric [10] (see Appendix B). Multiple raters were used to establish reliability. The VALUE rubric was chosen as it is a validated and well-studied rubric. Additionally, since creativity can be highly subjective, this provided a framework for a more objective and clearly defined assessment of project creativity. The projects selected for study were charged with developing consumer-oriented products, either for general consumers or for particular audiences (i.e., amputees or individuals with particular health problems). This was done to ensure that the projects were reasonably comparable, with similar desired outcomes.

In addition to the VALUE rubric items, other aspects of the projects were also evaluated:

- **Number of team members:** Simple count of students on team.
- **Sponsor:** Given a value of 1 for faculty proposed projects, 2 for industry proposed projects, and 3 for student proposed projects. An increasing value indicates increasing student involvement in project development. It must be noted that many industry sponsored projects are brought in by students who have worked at a certain company during their co-op experience.
- **Phase 1:** Given a value of 1 for projects that are original problems being worked on for the first time, and a progressively lower (fractional) value for projects that are continuations of previous projects. Thus a Phase 3 project is ranked lower than a Phase 2 problem.
- **Team formation:** Given a value of 0 for instructor faculty formed teams and a value of 1 for fully student formed teams. Teams which are formed partially by the students with a minority of students added by the instructor would be given a fractional value.
- **Number of female students:** Simple count of female team members.
- **Number of international students:** Simple count of students who are not US natives.
- **Number of countries represented:** Simple count of the number of different countries of origin among the team members.
- **Number of students with common language:** Simple count of the number of students on a team who speak the same native language, regardless of which language.
- **English proficiency:** Evaluation of the overall English language ability of the team. This is given a value of 1 for low proficiency, 2 for medium proficiency, and 3 for high proficiency. This is determined by the instructor responsible for the communication grade.
- **Communication grade:** A single instructor who is not advising any particular group evaluates all projects for communication ability. The communication grade includes performance on oral presentations, written reports, the executive summary document, and the final poster presentation.
- **Prototype grade:** This grade is assigned at a point two weeks before the end of term, when the executive summary is turned in. This is a previously validated scoring metric [15] that awards from 1-5 points for completeness of project and 1-5 points for completeness of validation testing. A score of 10 indicates a project that is complete and validated at a point 2 weeks before the end of term. High scores indicate successful project management and high functioning teams.

- **Delivered/Initial:** This score is on a 1-10 scale and is assigned by the course coordinator at the end of term. This metric compares the finished prototype with the goals developed by the team and their advisor at the beginning of the project. A score of 10 indicates a team that fully met all the goals laid out at the beginning.
- **Delta:** The difference between the Delivered/Initial score and the Prototype score. This provides a measure of progression during the last 2 weeks of the course.
- **Successful/Unsuccessful:** On the final day of the course the students present their final prototype to a jury of alumni who are currently active in industry. As part of their evaluation, jury members are asked to list groups that were particularly successful or unsuccessful. This is not a numerical score.

The numerical results were analyzed using Pearson's Product Moment Correlation analysis. This analysis was chosen due to the random nature of the variables and for its utility in determining values that are associated with maximizing or minimizing an outcome [14]. Outcomes from successful and unsuccessful groups as determined by jury feedback were compared using paired t-tests assuming unequal variances.

Course Details

The Capstone Design course at Northeastern University is a two semester required sequence taken during senior year. The first semester occurs during one of the two 7 week summer terms. The second semester occurs in either the following fall or spring. Students work on teams of 4-5 members. Projects can be proposed by the faculty, by industry, or by students. All projects must be vetted by the course coordinators prior to the start of Capstone 1. During the first week students rank the proposed projects based on their level of interests. Students can submit their preferences as individuals or student formed teams. Students who cannot form teams are grouped with other students who share similar preferences. Each group is assigned a project based on rankings (unless the project was student proposed) and advised by a faculty member who is responsible for a majority of the final grade. One of the course coordinators is responsible for evaluating communication skills for the groups. The other coordinator evaluates team performance and other measures. The advisor and coordinators confer on the final grade at the end of the course.

A number of content lectures are provided during the two capstone terms. In addition to typical lectures in project management, technical writing, and intellectual property, there is an entire 100-minute lecture devoted to problem definition and creative brainstorming techniques. Students are introduced to several methods of creative brainstorming including 'brainwriting', lateral thinking, vertical thinking, free association, and the use of design heuristics. This lecture includes hands-on group work where groups are challenged to come up with the longest list of ideas in 15 minutes. As this lecture occurs soon after they receive their problem assignment, this serves as a kickstart to further team brainstorming. Advisors typically reinforce these skills by asking to see lists of brainstormed ideas and guiding the team into further brainstorming during advisor meetings. The newly renovated capstone design studio provides a large number of whiteboards for ideating, as well as access to leftover materials from previous projects to use in exploring early low fidelity prototypes.

Results

Correlations between items on the VALUE rubric were expected, but some items in the rubric were more strongly correlated with the total creativity score than others, as shown in Table 1. For this group of projects, high total creativity scores seemed to be most strongly correlated with being able to connect ideas and transform them into new forms. The ability to both solve problems and discuss the reasons for and consequences of the solution is also very important. Taking risks had the lowest correlation with total creativity score, however all correlations were strong and significant.

Table 1: Pearson's R values for correlations between total creativity score and items on VALUE rubric

Item	Pearson's R value for correlation with total creativity score	P value ($\alpha = 0.05$)
Connecting, Synthesizing, Transforming	0.96	0
Solving Problems	0.88	0
Acquiring Competencies	0.87	0
Innovative Thinking	0.87	0
Embracing Contradictions	0.83	0
Taking Risks	0.78	0

Other factors are also associated with high total creativity scores, presented in Table 2. The only strong correlation was between total creativity score and communication grade. Several correlations point to the need for communication to produce high creativity scores. The communication grade measures the ability to present the design to a range of audiences outside of the team. The number of students with the same common language and overall English proficiency are linked to the ability to communicate and develop ideas within the team. Projects with high creativity scores also tend to generate higher prototype scores and are more likely to have student formed teams working on them. It should be noted that the Pearson's R values for team formation and English proficiency show that the correlations are nearly statistically significant.

Table 2: Pearson's R values for correlations between total creativity score and factors not on the VALUE rubric

Item	Pearson's R value for correlation with total creativity score	P value ($\alpha = 0.05$)
Communication Grade	0.75	0
# of Students with Common Language	0.49	0.006
Prototype Grade	0.48	0.008
Team Formation	0.37	0.05
English Proficiency	0.36	0.05

The prototype score is a measure of project quality, verification testing, and indirectly, the team's project management skills. Table 3 presents factors which are positively correlated with high prototype scores. The correlation between communication grade and prototype score has been observed previously [16]. Although all the items on the VALUE rubric are positively correlated with prototype score, the ability to embrace contradictions is most highly associated with a high prototype score. Overall, the various items on the rubric are similarly correlated with prototype score.

Table 3: Pearson's R values for correlations between prototype score and other factors

Item	Pearson's R value for correlation with prototype score	P value (α = 0.05)
Embracing Contradictions	0.59	0.006
Delivered/Initial score	0.55	0.001
Communication Grade	0.53	0.002
Total Creative Thinking	0.48	0.008
Innovative Thinking	0.45	0.01
Taking Risks	0.40	0.03
Acquiring Competencies	0.39	0.03
Connecting, Synthesizing, Transforming	0.36	0.05

A number of positive correlations support the idea that communication both within the team and with external parties is key to creativity as expressed through capstone projects. Table 4 shows the correlations for factors that are related to communication with external parties. This skill is primarily measured through the communication grade. Total creative thinking skills, in particular the ability to connect and synthesize ideas, take risks, embrace contradictions and solve problems, seem to be the most pertinent for communicating the prototype's features to others. External communication can be a sub-project of its own, as students who have been immersed in a project for months may find it difficult to explain to someone who is seeing it for the first time. Being able to synthesize ideas and transform them into an easily digestible form is clearly helpful for explaining ideas to others. The highest correlations for communication related skills fall into the category of external communications.

Table 4: Pearson's R values for correlated factors related to external communication

Paired correlated factors related to external communication	Pearson's R value for correlation	P value (α = 0.05)
Total Creative Thinking/Communication Grade	0.75	0
Connecting, Synthesizing, Transforming/Communication Grade	0.73	0
Acquiring Competencies/Communication Grade	0.66	0
Embracing Contradictions/Communication Grade	0.65	0
Solving Problems/Communication Grade	0.65	0
Innovative Thinking/Communication Grade	0.63	0.0002
Taking Risks/Communication Grade	0.56	0.001
English Proficiency/Communication Grade	0.53	0.003
Communication Grade/Prototype Grade	0.53	0.003

Table 5 shows the correlated factors related to communication within the team. These correlations were moderately significant. All of the correlations related to the number of students on the team that spoke the same native language. Commonly this language was English, but in some cases groups consisted of multiple international students from the same country of origin. Innovative and creative thinking seems to require the ability to trade ideas back and forth within the team to develop divergent solution paths. Taking risks is also easier when communication is not a problem. Acquiring competencies, while correlated positively with speaking the same language, seems to be possible regardless of native language. However, the relationship between acquiring competencies and the number of students with a common language is weak and barely significant.

Table 5: Pearson's R values for correlations related to internal communication within teams

Correlated factors related to internal communication.	Pearson's R value for correlation	P value (α = 0.05)
Innovative Thinking/# of Students with Common Language	0.52	0.003
Total Creative Thinking/# of Students with Common Language	0.49	0.006
Taking Risks/# Students with Common Language	0.46	0.01
Solving Problems/# Students with Common Language	0.46	0.01
Embracing Contradictions/# Students with Common Language	0.38	0.04
Connecting, Synthesizing, Transforming/# Students with Common Language	0.38	0.04
Acquiring Competencies/# Students with Common Language	0.36	0.05

The lowest correlations were for factors related to the group's overall English language proficiency, as shown in Table 6. English proficiency is useful for both internal and external communication, and English proficiency is overall higher in groups with larger numbers of members with a common language. Unlike factors specific to internal or external communication, English proficiency was not significantly associated with any VALUE rubric items except taking risks. Taking risks is apparently easier when English proficiency is high. This may point to either cultural factors that tend to discourage risk taking, poor team communication in general, or marginalization by more dominant team members. The relationship between total creative thinking and English proficiently is weak and barely significant.

Table 6: Pearson's R values for correlations between factors useful for both internal and external communication

Correlated factors related to internal and external communication	Pearson's R value for correlation	P value (α = 0.05)
English Proficiency/Taking Risks	0.46	0.01
# Students with Common Language/English Proficiency	0.41	0.02
Total Creative Thinking/English Proficiency	0.36	0.05

A series of moderate positive correlations were found between certain group or project related factors and skills evaluated using the VALUE rubric, shown in Table 7. In particular, the method of team formation (instructor formed, student formed, or partially student formed) and whether or not the project was a phase 1 project seemed related to aspects of creative thinking. Student formed teams tend to be large teams that are likely to have group members with a common native language. Having a student-formed team is also moderately correlated with innovative thinking, taking risks, acquiring competencies, and total creative thinking. Phase 1 projects, which are original projects as opposed to those that are a continuation of a previous effort, seem to encourage or require creative thinking. Multiphase projects may be more constrained than the original projects and therefore may not encourage as much creative thinking. Correlations between team formation, taking risks, and total creative thinking are weak and barely significant. Similarly acquiring competencies is only weakly correlated with Phase 1 projects.

Table 7:Pearson's R values for correlations between VALUE rubric items and team/project characteristics

Correlated factors related to team and project characteristics	Pearson's R value for correlation	P value (α = 0.05)
# of Team Members/# of Students with Common Language	0.52	0.003
Team formation/# of Students with Common Language	0.50	0.005
Innovative Thinking/Team Formation	0.44	0.02
Phase 1/Team Formation	0.43	0.02
Taking Risks/Team Formation	0.37	0.05
Total Creative Thinking/Team Formation	0.37	0.05
Acquiring Competencies/Phase 1	0.36	0.05

Although there were many positive correlations between various factors, there were also several negative correlations that point to the strong interactions between creativity and communication (Table 8). Teams that do not manage their project well, and thus do most of their work in the last two weeks of term, tend to produce lower quality projects and communicate their results poorly.

Teams with poor management skills (thus a larger Delta between the prototype and delivered/initial scores) seem to be less able to embrace contradictions and engage in innovative thinking.

Overall, the more diversity on the team in terms of the number of different countries represented and the number of international students, the lower the creative thinking scores. The strongest correlations speak to the difficulties of communication within groups due to language barriers and cultural factors. The correlations between team diversity, innovative thinking, and total creative thinking are weak and barely significant.

Table 8: Pearson's R values for negatively correlated factors

Negatively correlated factors	Pearson's R value for correlation	P value (α = 0.05)
Delta (Delivered-Prototype)/Prototype Grade	-0.74	0
# of Countries Represented/English Proficiency	-0.60	0.0005
Delta (Delivered-Prototype)/Embracing Contradictions	-0.45	0.02
Innovative Thinking/# of International Students	-0.43	0.02
# of Countries Represented/Communication Grade	-0.42	0.02
Taking Risks/# of International Students	-0.41	0.02
Delta (Delivered-Prototype)/Communication Grade	-0.41	0.02
Delta (Delivered-Prototype)/Innovative Thinking	-0.40	0.03
# of International Students/English Proficiency	-0.38	0.04
Total Creative Thinking/# of International Students	-0.38	0.04
Innovative Thinking/ # of Countries Represented	-0.37	0.05
Total Creative Thinking/# of Countries Represented	-0.36	0.05

As mentioned previously, the projects are judged by a jury of alumni at the end of the course. Projects that were identified as 'successful' or 'unsuccessful' by the jury were compared using paired t-tests to determine if there were any statistically significant differences between the groups. Table 9 shows the P values (α=0.5) for the factors with significant differences.

Table 9: Results of t-tests comparing projects identified as successful/unsuccessful by alumni jury

Factor	Average of Successful Groups	Average of Unsuccessful Groups	P value
Solving Problems	3.86	2.00	0.0006
Connecting, Synthesizing, Transforming	2.71	1.43	0.009
Total Creative Thinking	18.00	10.57	0.007
Embracing Contradictions	2.43	1.29	0.03
Taking Risks	2.86	1.86	0.04
Innovative Thinking	2.86	1.71	0.04
Delivered/Initial Score	10.00	7.86	0.04
Acquiring Competencies	3.29	2.29	0.05

To further illustrate the validity of the analysis method, two examples of student project work are presented below in Figures 1 and 2. Figure 1 represents a project with a high creativity score. This group was tasked with developing a reusable watertight cover to allow patients with central venous catheters to shower while keeping the bandages around the catheter site dry and intact. This group had a total creativity score of 20/24, a communication grade of 97/100, a prototype grade of 10/10, and a delivered/initial grade of 10/10. In addition, they were noted as successful by a majority of the jury members. Their design process was highly organized but encouraged individual and group creativity in the process. Figure 1 shows 4 initial design sketches plus their initial alpha prototype. They brainstormed a large number of initial ideas, and developed sketches to illustrate the most promising. This group had a high overall English proficiency and were also seen to be very collegial in their interactions. In the lecture on brainstorming, they were not afraid to voice ‘silly’ ideas, such as using superglue or lots and lots of duct tape. In the end they had a functional prototype that was thoroughly validated.

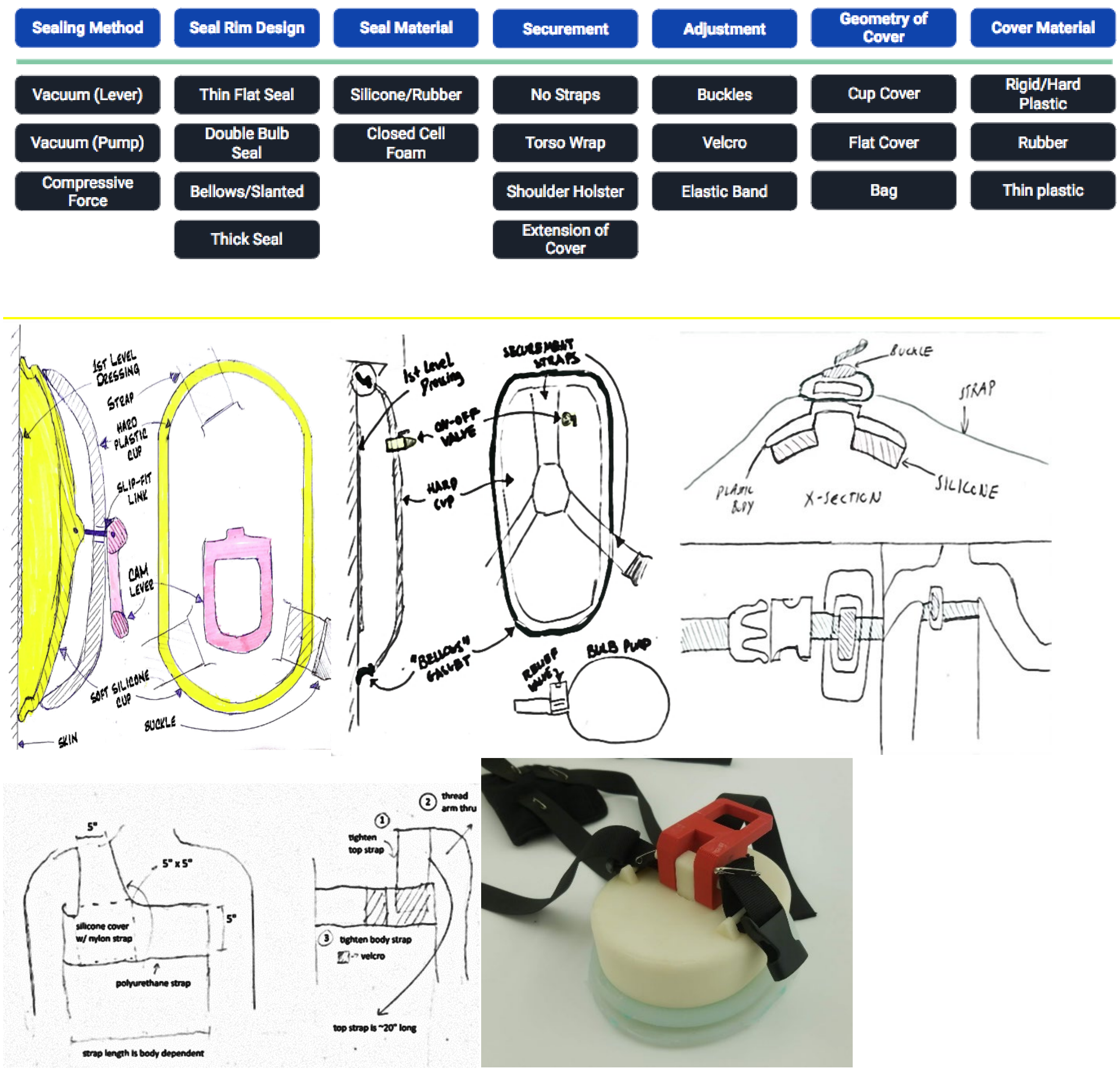

Figure 1: Design process of group with high creativity score

Figure 2 depicts the design process for a project that was judged to have a low degree of creativity. This team was tasked with developing a low-cost automatic opening window shade to aid patients with circadian rhythm disorder. This group had a total creativity score of 7/20, a communication score of 76/100, a prototype score of 5/10, and a delivered/initial score of 10/10. The group overall had a medium English proficiency level and were not mentioned as either successful or unsuccessful by the jury. They had no rough design sketches and never looked outside the concept of a roller shade. In the end they came up with a motorized version of an existing design which was not particularly innovative or unusual. They struggled to come up with even obvious divergent ideas, such as using blinds rather than a roller shade to block light. Although the team treated each other respectfully, one of the four team members tended to do noticeably less work than the others. Additionally, the team did not feel empowered to challenge the basic premise of the project, which was proposed by the team's advisor. During the creativity lecture, they struggled to come up with more than 10 ideas, where other teams came up with 20 or more. Dysfunctional team dynamics, an overly prescribed problem, and poor communication among the team members appear to have combined to prevent this group from realizing their full creative potential.

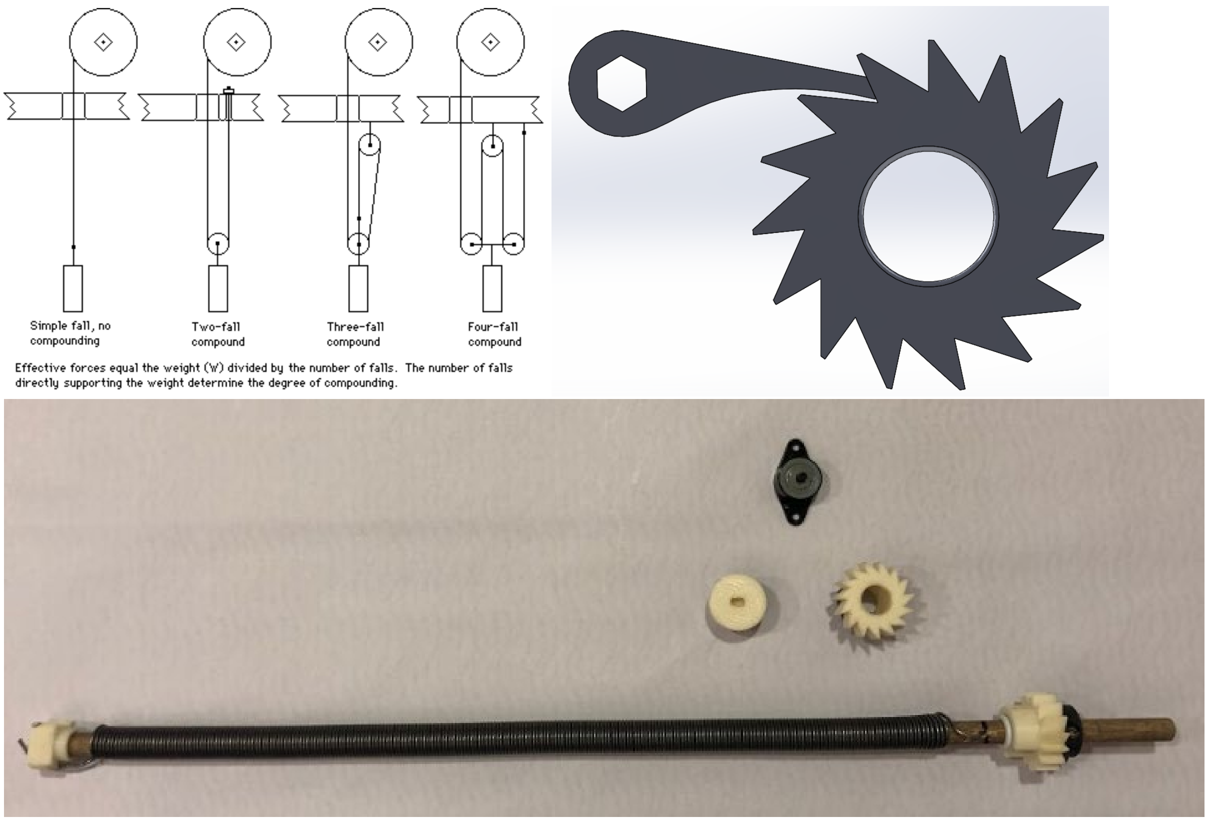

Figure 2: Design process of group with low creativity score

Discussion

The results indicate interactions between different creativity aspects and total creativity scores, which is to be expected. However, there are also interactions between creativity skills and prototype skills, communication skills, and various group and project factors. Not all correlations are positive, and negative correlations seem largely related to communication skills. There are also significant differences between the creativity skills of successful and unsuccessful groups.

Creativity Skills

As expected, all individual items on the creativity rubric were strongly correlated with the total creativity score. The largest correlation (R = 0.96) was between the total creativity score and the ability to connect, synthesize, and transform ideas. The ability to take ideas and connect them in new ways, or to merge ideas into novel ideas clearly takes strong creative skills. Interestingly, the ability to take risks was the weakest correlation (R = 0.78), as creativity is often associated with being ‘out there’ or having completely novel ideas. However, this is still a very strong correlation, and is thus a strong contributor to total creativity.

Total creativity score was also shown to be positively and significantly correlated with several course metrics. The correlation between communication grade and total creativity score is strongly positive (R = 0.75). This corroborates other data, discussed below, showing the strong relationship between the ability to communicate ideas and creativity. The communication grade evaluates the team’s ability to use a variety of media (memos, reports, oral presentations, academic posters) to interact with individuals outside the team. External parties range from team advisors to peers to industry experts, all of whom require a different set of information presented in a different manner. Creative groups can figure out how to do this, and in communicating their ideas they are also able to clarify and build on them. Successful communication within the team also correlates with high creativity scores, but less strongly. In particular, having a large percentage of team members with the same native language seems to provide an avenue to bounce ideas off each other without excessive barriers. Creativity also leads to higher prototype grades. High prototype grades indicate that students have substantially completed their project at a point 2-3 weeks before the end of the term. This seems to require those creative skills of taking risks, solving problems, thinking innovatively, and becoming competent in new areas in order to get their work done. Two barely significant factors were the method of team formation (student vs. instructor formed) and English language proficiency. This would seem to indicate that the way teams are formed and the exact common language isn’t as important as being able to speak to and understand the other team members.

Prototype scores

Prototype scores are positively correlated with communication grade, which has been seen in earlier studies by one of the authors[]. This makes sense, as effective communication allows students to get feedback to improve the technical aspects of their prototype in addition to aiding creativity. Teams who have substantially completed their work early also tend to fully fulfill their design requirements. Although total creative score is positively correlated with high prototype score, not all individual aspects of creativity are similarly correlated. Embracing contradictions, which encompasses the ability to consider and incorporate alternative or divergent ideas, is most strongly correlated with prototype score. The ability to generate a large number of possible ideas seems to mean that the group is more likely to hit upon a workable idea early and refine it. Interestingly, solving problems was not one of the creativity skills associated with prototype score, and the association with connecting, synthesizing, and transforming skills was barely significant. This is a surprising result, with no immediate explanation.

Communication aspects

All the individual creativity skills as well as the total creative thinking score are strongly and positively correlated with the communication score (R = 0.53 or higher). English proficiency is also strongly associated with communication score, which is to be expected in an English-speaking country, and the correlation with prototype grade was previously discussed. Students who can communicate their ideas to others both within and outside the team can more easily solve problems together, learn new skills, and connect ideas in new ways. Students who can communicate well can brainstorm with others, build on others' ideas, and collaborate to find innovative solutions much more easily. This seems to imply that course activities designed to improve communication skills will also benefit creativity skills.

Having team members who speak the same native language, regardless of language, correlates moderately with creativity skills and outcomes. Particularly, innovative thinking and total creative thinking seem to flourish when students can communicate in the language they are most comfortable with. This is not to say that creativity requires a common language. Engineering students in particular are often skilled in visual presentation of information (sketches, CAD drawings, graphs, etc.) and thus may be more equipped than other majors to deal with language barriers. In addition, it could be argued that quantitative performance of engineering projects is often sufficiently objective to be taken at face value. This is supported by the fact that English proficiency has a very slight positive correlation with taking risks and total creative thinking, but otherwise does not strongly affect outcomes.

Group and Project Factors

Team and project factors in some cases were strongly correlated with each other, but not necessarily with creativity factors. For example, larger teams seemed to have more students with a common language, as did student formed teams. Students who choose their own team members seem to choose partners they feel comfortable with. This may contribute to a feeling of safety and belonging that encourages out of the box thinking. Student formed groups tend to acquire new knowledge, take risks, think innovatively, connect ideas in non-obvious ways, and overall exhibit creative behavior.

In addition, groups working on Phase 1 projects seem to have more positive outcomes. Developing a list of projects can be a daunting task every term, particularly for large classes. It can be tempting therefore to continue a previous project that was only partially completed or seemed to have an opportunity for expansion. However, Phase 1 projects seem to inspire or require more creativity than continuation projects. Phase 1 project teams tend to acquire new knowledge, take risks, connect and synthesize ideas, and think innovatively. Student formed groups tend to be attracted to Phase 1 projects. Continuation projects often have an existing prototype left over from the previous team. Even if the new team does not actually use the prototype, it tends to consciously or unconsciously constrain the team's thinking. This could also be due to a Phase 2 project being more of a stopgap or 'emergency' project than a true step along the path to full product development.

Negative Correlations

Negatively correlated factors also provide useful information. A higher 'delta' score – indicating a large difference between the prototype score and the final delivered product score – indicates that students did the bulk of their work in the last two weeks of term. Thus a lower delta score indicates a project that was completed early. Low delta scores are correlated with an ability to embrace contradictions, communicate effectively, and think innovatively. These beneficial negative correlations point to the importance of project management skills in conjunction with creative behaviors. Students who can engage in innovative thinking and overall creative thinking seem to be able to achieve early success with their project, as evidenced by prototype scores and delta scores.

Some negative correlations support the need for communication, particularly within the group. A highly diverse group in terms of countries of origin, native languages, and level of English proficiency may spend more time struggling with basic communication and less time on creative idea generation. International students who are isolated on a team of native English speaking students may contribute fewer creative ideas due to language or cultural reasons. This means that the team as a whole could generate fewer ideas overall, limiting creative outcomes.

Conclusions and Takeaways

Both literature sources and the current study speak to the value of teaching creativity in capstone design. The course taught by the author actively teaches creative ideation and brainstorming skills, as well as providing supplies and physical space to sketch, collaborate, and quickly try out different ideas. As in most capstone courses, communication is also a strong focus of the class, both in terms of teaching and assessment. The results of this study indicate a need to continue to build upon these skills and encourage them (including, perhaps, efforts to convey to students the data and conclusions reached in the present study). In addition, strategies for improving communication between students with different languages and cultures will benefit the development of creativity skills, which will in turn generate more complete, innovative, and novel solutions to these open-ended problems.

The addition of targeted lectures and activities on brainstorming skills should become a standard skill that is taught and guided in capstone design. It is easy to focus on project management, teamwork skills, and discipline specific skills. However, adding in modules on creativity, either as standalone lectures or in class activities during other content lectures can keep students from fixating on their first idea. Training advisors in these techniques, if they are unfamiliar with them, and encouraging advisors to use these techniques during team meetings would be another point of contact for students to practice creative techniques. Requiring students to reflect on and document their creative process and write concrete plans for solving problems would both directly reinforce creativity skills and enhance the physical design process. Capstone instructors can also help by setting up assessment tools that do not penalize taking risks.

Future work by the authors will investigate additional brainstorming methods that are less verbally based. Although the students in this study were taught creative problem solving techniques, these techniques are still by and large verbally based which, while allowing for near-unlimited creativity and instant feedback between team members, is a disadvantage for students who struggle to communicate in English. Visual brainstorming techniques, the use of Lego^{tm} bricks or clay to create physical representations of ideas, and encouraging low-fidelity prototypes made out of cardboard may provide an additional avenue for students to present ideas and build on them.

References

[1] K. J. Holyoak, and R. G. Morrison, eds. The Cambridge handbook of thinking and reasoning. Vol. 137, Chapter 15, pg. 351, Cambridge: Cambridge University Press, 2005.

[2] G. Thompson, and M. Lordan. "A review of creativity principles applied to engineering design." Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering 213.1 (1999): 17-31.

[3] C. L. Dym et al. "Engineering design thinking, teaching, and learning." Journal of Engineering Education 94.1 (2005): 103-120.

[4] D. Jensen et al. "AC 2009-2369: Techniques to enhance concept generation and develop creativity." Proceedings of Annual Conference of American Society for Engineering Education. 2009.

[5] C. D. Denson et al. "Developing Instrumentation for Assessing Creativity in Engineering Design." Journal of Technology Education 27.1 (2015): 23-40.

[6] T. M. Amabile "Social psychology of creativity: A consensual assessment technique." Journal of Personality and Social Psychology 43.5 (1982): 997.

[7] B. Lucas "A five-dimensional model of creativity and its assessment in schools." Applied Measurement in Education 29.4 (2016): 278-290.

[8] K. Shively, K. M. Stith, and L. DaVia Rubenstein. "Measuring what matters: Assessing creativity, critical thinking, and the design process." Gifted Child Today 41.3 (2018): 149-158.

[9] S. Husted et al. "Multidimensional assessment of creativity in an introduction to engineering design course." Proceedings of Annual Conference of American Society for Engineering Education. 2014.

[10] Association of American Colleges and Universities (AAC&U). (2009). Creative Thinking VALUE rubric. Retrieved from https://www.aacu.org/value/rubrics/creative-thinking. Last access 1/26/2020

[11] S. K. Oman et al. "A comparison of creativity and innovation metrics and sample validation through in-class design projects." Research in Engineering Design 24.1 (2013): 65-92.

[12] D. K. Sobek and V. K. Jain. "Two instruments for assessing design outcomes of capstone projects." Proceedings of the American Society for Engineering Education Annual Conference and Exposition, 2004.

[13] I. Chiu and F. A. Salustri. "Evaluating design project creativity in engineering design courses." Proceedings of the Canadian Engineering Education Association (CEEA) (2010).

[14] Mason, Robert L. Gunst, Richard F. Hess, James L. Statistical Design and Analysis of Experiments - With Applications to Engineering and Science (2nd Edition) - 14.3. Scatterplot Smoothing. John Wiley & Sons. (2003) Retrieved from

https://app.knovel.com/hotlink/pdf/id:kt003Y20Z7/statistical-design-analysis/scatterplot-smoothing

[15] B. M. Smyser and G. J. Kowalski. "Assessing the effect of co-op sequence on capstone design performance." Proceedings of the American Society for Engineering Education Annual Conference and Exposition, 2011.

[16] G. J. Kowalski and B. M. Smyser. "Success factors for international students in capstone design teams." The International Journal of Engineering Education 33.5 (2017): 1432-1441.

Appendix A: List of Projects in Current Study

Table 10: Projects included in current study

Project Title	Project Source	Project Description
Amplified Jumping Device	Student proposed	Develop a wearable device to allow a person to jump safely to above average heights
Photodynamic Therapy	Faculty proposed	Develop a device to deliver specific wavelengths of light for skin therapy
Ergonomic Portable Standing Desk	Faculty proposed	Develop an adjustable standing desk geared for taller users
Instant Ice Maker Phase II	Faculty proposed	Improve upon an initial prototype for a countertop sized rapid ice maker
Liquid Purification with an Active Tea Bag	Faculty proposed	Develop a small water purification system using faculty's proprietary treatment method
Van Wheelchair Lift	Faculty/End user proposed	Develop a user powered wheelchair lift for a van
Measuring Toe Walking in Autistic Children	Faculty Proposed	Develop instrumented shoes to measure abnormal gaits in autistic children.
Snow Removal for Roofs	Faculty Proposed	Develop a roof mounted device to eliminate the need to shovel snow off roofs by hand.
Light Therapy Blinds	Faculty Proposed	Develop window blinds with embedded lights to combat seasonal affective disorder
Assisted Kneeling for Gardening	Faculty Proposed	Develop device to assist elderly gardeners in kneeling to garden and returning to standing.
Liquid Purification with an Active Tea Bag Phase II	Faculty Proposed	Continuation/modification of previous project to develop consumer water purification device.
Rotating Braille Display	Faculty Proposed	Develop a portable device that can take computer input and generate braille text in response.
Project Mercy	Faculty Proposed	Develop a water delivery system for shelter felines to encourage hydration.
Rapidly Deployed Wheelchair Assist	Faculty Proposed	Develop a motorized device that attaches to a non-

		motorized wheelchair to assist caregivers.
User Controlled Hoyer Lift Phase II	Faculty Proposed	Continuation/modification of previous project to develop a patient controlled lift for disabled patients.
Jack Wagon Log Splitter	Industry Proposed	Develop a motorized log splitting device adapted from a jackhammer.
Wind Powered Owl Decoy	Faculty Proposed	Develop a moving, wind powered, realistic owl to deter garden pests.
Quick Connect Console Adapter	Industry Proposed	Develop a means to rapidly connect and disconnect components on the floor of a vehicle.
Steamspout	Faculty Proposed	Develop a floating device to alert someone to water boiling in an open pot.
Kayak Transportation Device	Faculty Proposed	Develop a device to assist with carrying a sea kayak from the car to the water.
Compression Stocking Donner Phase II	Faculty Proposed	Continuation/Modification of previous project to develop a device to assist in donning a compression stocking.
Cardboard Cutter	Faculty Proposed	Develop a safe, low force device to aid in cutting cardboard for recycling.
Device to Recycle Crayons	Faculty Proposed	Develop a device to allow schools to recycle old crayons into new crayons.
Multi Chamber Beverage Container	Faculty Proposed	Develop device to contain multiple ingredients for a shelf stable, user mixed cocktail.
Catheter Cover for Dialysis Patients	Faculty Proposed	Develop device to allow patients with central venous catheters to shower.
Trash Skimmer Pedal Boat	Faculty Proposed	Modify a pedal powered boat to collect trash from the surface of a body of water.
Solar Raptor	Faculty Proposed	Develop a solar powered drone that can be used to deter waterfowl from landing on solar panels.

Agricultural Adapter for Power Take Off	Faculty Proposed	Develop a device to allow amputee farmers to easily connect farm machinery to a tractor power take off.
Music Experience for Deaf and Hard of Hearing	Student Proposed	Develop a wearable device to transmit vibrations from music to a deaf user.
Farm Gate	Faculty Proposed	Develop a non-powered gate that allows users to drive through at a reasonable speed without exiting the vehicle.
Circadian Shades	Faculty Proposed	Develop automatically opening shades to combat circadian rhythm disorder.

Appendix B: Creative Thinking VALUE Rubric

CREATIVE THINKING VALUE RUBRIC

for more information, please contact value@aacu.org

Association of American Colleges and Universities

The VALUE rubrics were developed by teams of faculty experts representing colleges and universities across the United States through a process that examined many existing campus rubrics and related documents for each learning outcome and incorporated additional feedback from faculty. The rubrics articulate fundamental criteria for each learning outcome, with performance descriptors demonstrating progressively more sophisticated levels of attainment. The rubrics are intended for institutional-level use in evaluating and discussing student learning, not for grading. The core expectations articulated in all 15 of the VALUE rubrics can and should be translated into the language of individual campuses, disciplines, and even courses. The utility of the VALUE rubrics is to position learning at all undergraduate levels within a basic framework of expectations such that evidence of learning can by shared nationally through a common dialog and understanding of student success.

Definition

Creative thinking is both the capacity to combine or synthesize existing ideas, images, or expertise in original ways and the experience of thinking, reacting, and working in an imaginative way characterized by a high degree of innovation, divergent thinking, and risk taking.

Framing Language

Creative thinking, as it is fostered within higher education, must be distinguished from less focused types of creativity such as, for example, the creativity exhibited by a small child's drawing, which stems not from an understanding of connections, but from an ignorance of boundaries. Creative thinking in higher education can only be expressed productively within a particular domain. The student must have a strong foundation in the strategies and skills of the domain in order to make connections and synthesize. While demonstrating solid knowledge of the domain's parameters, the creative thinker, at the highest levels of performance, pushes beyond those boundaries in new, unique, or atypical recombinations, uncovering or critically perceiving new syntheses and using or recognizing creative risk-taking to achieve a solution.

The Creative Thinking VALUE Rubric is intended to help faculty assess creative thinking in a broad range of transdisciplinary or interdisciplinary work samples or collections of work. The rubric is made up of a set of attributes that are common to creative thinking across disciplines. Examples of work samples or collections of work that could be assessed for creative thinking may include research papers, lab reports, musical compositions, a mathematical equation that solves a problem, a prototype design, a reflective piece about the final product of an assignment, or other academic works. The work samples or collections of work may be completed by an individual student or a group of students.

Glossary

The definitions that follow were developed to clarify terms and concepts used in this rubric only.

- Exemplar: A model or pattern to be copied or imitated (quoted from www.dictionary.reference.com/browse/exemplar).
- Domain: Field of study or activity and a sphere of knowledge and influence.

Creative Thinking VALUE Rubric

for more information, please contact value@aacu.org

Association of American Colleges and Universities

Definition

Creative thinking is both the capacity to combine or synthesize existing ideas, images, or expertise in original ways and the experience of thinking, reacting, and working in an imaginative way characterized by a high degree of innovation, divergent thinking, and risk taking.

Evaluators are encouraged to assign a zero to any work sample or collection of work that does not meet benchmark (cell one) level performance.

	Capstone	Milestones		Benchmark
	4	3	2	1
Acquiring Competencies *This step refers to acquiring strategies and skills within a particular domain.*	Reflect: Evaluates creative process and product using domain-appropriate criteria.	Create: Creates an entirely new object, solution or idea that is appropriate to the domain.	Adapt: Successfully adapts an appropriate exemplar to his/her own specifications.	Model: Successfully reproduces an appropriate exemplar.
Taking Risks *May include personal risk (fear of embarrassment or rejection) or risk of failure in successfully completing assignment, i.e. going beyond original parameters of assignment, introducing new materials and forms, tackling controversial topics, advocating unpopular ideas or solutions.*	Actively seeks out and follows through on untested and potentially risky directions or approaches to the assignment in the final product.	Incorporates new directions or approaches to the assignment in the final product.	Considers new directions or approaches without going beyond the guidelines of the assignment.	Stays strictly within the guidelines of the assignment.
Solving Problems	Not only develops a logical, consistent plan to solve problem, but recognizes consequences of solution and can articulate reason for choosing solution.	Having selected from among alternatives, develops a logical, consistent plan to solve the problem.	Considers and rejects less acceptable approaches to solving problem.	Only a single approach is considered and is used to solve the problem.
Embracing Contradictions	Integrates alternate, divergent, or contradictory perspectives or ideas fully.	Incorporates alternate, divergent, or contradictory perspectives or ideas in a exploratory way.	Includes (recognizes the value of) alternate, divergent, or contradictory perspectives or ideas in a small way.	Acknowledges (mentions in passing) alternate, divergent, or contradictory perspectives or ideas.
Innovative Thinking *Novelty or uniqueness (of idea, claim, question, form, etc.)*	Extends a novel or unique idea, question, format, or product to create new knowledge or knowledge that crosses boundaries.	Creates a novel or unique idea, question, format, or product.	Experiments with creating a novel or unique idea, question, format, or product.	Reformulates a collection of available ideas.
Connecting, Synthesizing, Transforming	Transforms ideas or solutions into entirely new forms.	Synthesizes ideas or solutions into a coherent whole.	Connects ideas or solutions in novel ways.	Recognizes existing connections among ideas or solutions.