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Encouraging Creativity in Capstone Design*

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Capstone design is the "bridge" from school to industry. It is important that this engineering experience is rich in the creative approaches which are valued there. In particular, the capstone class should model the need for exploring divergent solution paths, for listening to alternative opinions, and for stepping back from a problem. Skills in these creative areas typically are not emphasized in the rest of an engineering curriculum. At the 2016 Capstone Design Conference, we participated in a panel on "Encouraging Creativity in Capstone Design." The ideas presented were based on our own experiences in using creativity techniques in design classes. This paper shifts down to the roots of those discussions, describing our individual efforts in applying those creativity techniques. We conclude with a list of situational options, for other practitioners to use in their design classes.

Keywords: creativity; convergent thinking; divergent thinking; concept generation; idea fixation

1. Introduction

Capstone design experiences are a means for undergraduate programs to ensure the readiness of new engineers to enter professional practice. Particular educational goals associated with the capstone experience are as follows:

- Bridge the differences between typical classroom experiences and real engineering projects, so as to more carefully prepare students for the latter.
- Require students to synthesize their learning from multiple courses.
- Give students personal exposure to what it is like to do engineering work in the outside world and to provide self-confidence about that destination.
- Have a clear marker of students' readiness for a career, as a final way of judging students, and also as a way to assess program effectiveness for external audiences such as ABET.

Creative experiences have been a part of the capstone vision since its inception. Capstone courses especially involve open-ended problems, such as those Tina Seelig describes in her book, *inGenius: A crash course on creativity* [1]. Capstone courses are inherently a forced combining of students' prior learning toward solving some new and larger problem. That problem commonly involves outside clients, and may be ill-defined at the beginning. The problem may also be intentionally open-ended. Typically, individuals or student teams work semi-autonomously; they may need to choose which processes to use as well as which technologies and materials; and the style and level of guidance from an outside client, if present, is likely to vary significantly from the classroom instruction or supervision they have received. One could see all of these new ingredients as places where individuals or teams must respond in creative ways.

Thus, we have commonly seen capstone courses include student activities such as brainstorming initial design ideas and pursuing alternative solutions to risks and issues as these come up.

However, the creative activities stirred into typical capstone experiences also have been limited by the following factors:

- The nature of the college experience—students may be unaccustomed to open-ended situations where they have to spend time fumbling with many choices and grappling with the problem definition.
- Students fixate on a single idea during concept generation and keep pursuing this concept even after experiencing initial failures.
- Students expect their class activities to be clearly defined and to lead rapidly and reliably to success. Teams try to continue this easy problem solving when they encounter the more difficult problems in their capstone project.
- Student teams tend to be much more homogenous than industry teams because they all have very similar backgrounds and skills. This points them in more uniform directions.
- The problems may intentionally be less than

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realistic, making it possible to solve them via more routine practices. This could be the policy of the department who picks the projects, or it may be in the nature of the projects offered by outside clients. For example, these clients may be alumni working in engineering organizations, and the projects are not something truly crucial for their own companies to have achieved by students.

There are substantial growth opportunities in providing new ways that capstone programs can stretch students in creative ways. This paper explores techniques for encouraging creativity in the six phases described in the Osborn-Parnes Creative Problem Solving Process shown in Fig. 1 [2–4]. Some of the techniques described such as Design Heuristics and FuseTrail™ are more suited for particular phases of the process. Other techniques such as stressing multiple perspectives and agile techniques may be applied throughout all phases.

2. Background and literature review

Engineering is alive with questions about the role and teaching of creativity in the making of practical and necessary things. Indeed, definitions of engineering vary even as to whether the "value" of an engineering design includes considerations beyond first principles and best practices, historically concluding that convergent thinking is much more valued in this work.

The fact that creativity has not traditionally been considered a fundamental part of the engineering curriculum, and thus not stressed, is noted in papers like R. H. Todd [5]. Yet the need for creativity to meet industrial requirements has been noted, as in R. H. Todd [6], and in W. B. Stouffer [7]. In Todd, et al.'s 1995 survey of capstone engineering programs, 48% of projects included a creativity or concept generation phase, so encouragement of creativity is long-standing.

Within engineering education, there is the age-old conundrum of how much creativity *can* be taught. It is well-known that novice and expert engineers do design and problem solving in different ways [8]. Fixation and experience gaps limit the capacity of students, say, to conceive of as many novel ideas. Although this problem is more apparent in freshman engineering design courses, it also occurs in the undergraduate capstone experience.

We sidestep such large-scale debates and assume creativity in capstone experiences is a desired outcome for engineering programs. Whether divergent thinking is used to achieve beauty or to solve complex systems problems, the exhibition of that, in an undergraduate individual or team's solution, demonstrates their ability to do independent thinking, as well as the application of lessons learned in earlier courses. Typically, a problem given to a capstone individual student or team is sufficiently messy that straight-line reasoning to a solution is likely to be defeated.

Our definition of creativity is the application of creative processes, namely, the alternation of divergent and convergent thinking in problem solving to create something. This is in line with use of the term in brainstorming, in the style of Osborn and Parnes [2, 3]. Defining creativity as an activity operationalizes it, and avoids having to consider the success in deciding if creativity has been done. This may be appropriate for engineering, where we would like to say an individual or a team is being creative by searching widely for answers, then choosing from a rich set of options, rather than fixating or trying to push through a solution on a single thread of thought.

An alternative, which does evaluate the outcome, is that offered by B. A. Hennessey, T. M. Amabile, and J. S. Mueller [9], that creativity is "a product . . . both novel and appropriate, useful, correct, or valuable in response to an open-ended task." This provides a standard which is more "black box" than tracing the processes used. Namely, the authors measured what was creative based just on the results.

These authors also describe a very pragmatic evaluation method to go with this, that something is creative if "appropriate observers independently agree that it is creative." Appropriate observers are those who know the domain for which a product was created [9]. This evaluative activity sounds much like one way typically used to judge capstone project results. C.D. Denson, et al. [10] point out that this assessment definition suggests raters be independent in judging projects on creativity (or on anything else).

In the literature, we see examples of multiple approaches to achieving creativity. L. A. Slivosky, et al. [11], described numerous process ingredients which could be used to stimulate creative design, like exercises in creative problem solving, team building and diversity appreciation events, and a design process including unstructured components.

Several recent studies point to the influence of the environment and social factors on creativity, specifically that being exposed to—or better, immersed in—an environment where you are expected to think differently from the crowd, where you act differently from a partner, or where you have to adapt to a different culture, all improve performance on creativity tasks. C. E. Ashton-James and T. L. Chartrand [12] showed that the capacity for divergent thinking is improved when social mimicry is not present, while the capacity for convergent thinking is improved in an environment where social mimicry is present. Similarly, S. H. Kim et al. [13] found evidence that the feeling of being considered an outsider or having been rejected, while maintaining a strong sense of independence, can facilitate divergent thinking in individuals with an independent mindset. W. W. Maddux and A. D. Galinsky [14] explored the influence of living in a different country on creativity and found that living abroad or even thinking about a past experience living abroad improved performance on creative thinking tasks.

Alternative techniques are noted in Lovell, et al.'s 2016 "Lighting the Fuse for Creative Problem Solving." [15]. The characteristic ways creativity is practiced in engineering are described, while appreciating that creativity is usually no better than equal, as an objective, to resulting functionality and quality attributes. And it may compete with these results. The paper points to the many places in a project where open-ended problems are encountered, not all at the beginning, with opportunities for creative problem solving arising unexpectedly. For example, testing a new kind of system may itself require novel processes. Creativity may be needed for capturing data, or for choosing from among alternative solutions, versus just imagining a design itself.

In reviewing capstone senior projects regarding mentoring and student creativity, W. Mokhtar [16] emphasized the open-ended nature of the projects, with a need for guidance balanced against giving space for creativity. He favored use of team structure which gives visibility to the creative level of a team's experience, and also recommended having a higher-level organization, such as Project Review Board, to help ensure the right level of creative opportunity was provided in each project (across a range of team advisers).

Articles in the current literature may key upon a single approach or variable to improve capstone creativity. That is, they compare using this approach versus a baseline, usually the previous way that capstone design was run at a school.

For example, N. Hotaling, et al. [17], discussed the practical effects of introducing multidisciplinary teams. The measurement was in terms of job placement and/or industry evaluation of student products, versus monodisciplinary teams. Innovation was cited as one measure on which holistic performance was better on the multidisciplinary teams. In their own literature search, these authors found that group diversity can result in more creative solutions, but also that this did not necessarily translate to higher performance overall. Results varied, and they believed the variables have not all been considered systematically.

In A. G. Carrillo's dissertation work at Stanford [18], he studied the diversity of teams as a variable, using six factors including work experience diversity. He was interested in how different dimensions of diversity affected team processes and performance. He found that diversity could increase team creativity, but generalizations about the outcomes were difficult. Significantly, in his observational study he found that low diversity teams produced better results on short (2 week) projects, while high diversity teams produced better results on long (30 week) projects.

The published literature on creativity in business and industry is immense, in contrast to that in engineering. The influential work of proponents like Osborn and Parnes [2, 3] dates back to the 1950's. A common version of their creative problem solving model is shown in Fig. 1. It recommends six

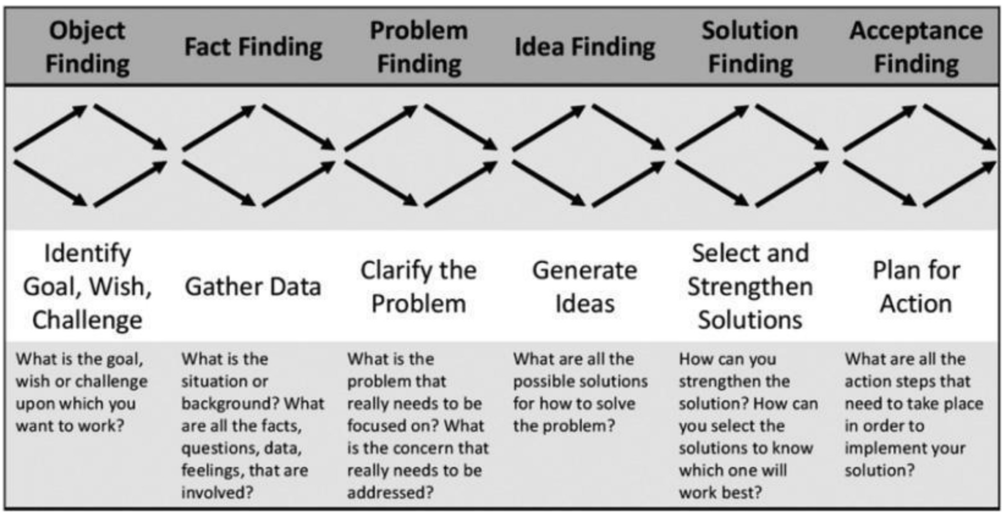

Fig. 1. The Osborn-Parnes Creative Problem Solving (CPS) Process [19].

separate places where brainstorming might be employed, as cycles of divergent and convergent thought occur in solving a complex problem. This visual guide shows how creative exploration can be applied to clarify a problem prior to trying to invent a solution, or to come up with an action plan to use a team's invention. In business, the need for creativity at any of these project stages would relate to the difficulty of proceeding through that stage. These business ideas about using creativity have clear analogies in engineering thus specifically for capstone experiences.

We note that a huge number of more specific creativity practices are used in engineering, with preferences which seem to vary almost at random. Some of these techniques are promoted by specific traditions, by popular books, or by consultants. They are more directive than Osborn-Parnes in different ways. For example, Synectics uses a flow of activities, alternating between divergent and convergent, to approach gradually on intriguing solutions while avoiding throwing them out prematurely [20]. TRIZ uses a selection of synthesis models to apply logically from general to specific design situations [21]. The Creative Education Foundation, founded by Alex Osborn, serves as a central resource and research center in creative processes and their uses [22].

3. Individual efforts at applying creativity techniques

In the subsections that follow, individual authors describe how they used strategic changes and features of their programs to realize creative work by their individual capstone students and student teams. These vary in kind but relate strongly to applying divergent and convergent thinking at various times, as in the Osborn-Parnes model, shown in Fig. 1. For example, recasting a problem from new perspectives is a divergent way of clarifying the problem. Within each section the authors relate their efforts to the specific element of the Osborn-Parnes CPS Process. At the end of the paper we summarize with a table highlighting specific, transferrable aspects of these separate efforts, including Table 3, with "Strategies and Practices That Faculty Can Implement. "

3.1 Diverse teams: bringing together multiple perspectives at RIT

In the Rochester Institute of Technology (RIT) Multidisciplinary Senior Design (MSD) capstone sequence, students follow a typical design process similar to that outlined in Fig. 1, starting with problem identification and ending with build/test, and including the same elements of divergent and convergent thinking along the way. At the time of writing, the course also requires creative thinking when teams develop their initial risk assessment (brainstorm potential risks in categories including technical/social/environmental/resource) and again when problems arise during the course of the project (brainstorm all the possible causes for this problem, then brainstorm solutions for the most likely causes).

The capstone projects span a wide variety of topics: product design, process improvement, continuation (n^{th} generation) projects, clean-sheet designs, incremental improvement projects, wild idea projects, etc. Some of these clearly lend themselves to a greater degree of creativity than others, but all projects are first reviewed by a multidisciplinary faculty team to ensure that each project will provide an opportunity for *some* creative design work. This often addresses the "Object Finding" phase in Fig. 1. For highly constrained projects and 2^{nd} generation projects, there tend to be fewer opportunities for creativity, as the design has already begun to converge on a final solution. It can be challenging for students on these projects to feel like creative efforts are adding value to the outcome. Additionally, clients with a strong preconceived notion of what their final solution should look like can make it difficult for teams to come up with creative ideas. The burden for screening out or coaching these clients lies with the faculty team, and many times the client can be persuaded to keep an open mind about what the team may propose.

3.1.1 Inter-college diversity: the Una-Crutch example

Occasionally, students from outside engineering would participate in MSD projects. The Una-Crutch problem was brought to MSD by an Industrial Design student who had observed a friend face the challenge of switching between using a pair of crutches for long distances and open spaces, and using a single crutch for stairs and moving around in close quarters. The Industrial Designer, three Mechanical Engineers, and one Industrial & Systems Engineer worked together to create a design to address this problem. While the team enjoyed a good working relationship, their work was often completed in a "throw it over the wall" manner rather than in collaboration: the design student developed creative concepts and was the driving force behind gathering end user input on the appearance models, and the engineers conducted stress analysis and performed the detailed design work. Thus, students from the different areas picked the steps from Fig. 1 that they wanted to perform and focused their efforts on those steps.

The Industrial Design students design output consisted of a series of concepts and appearance models for the crutch body as well as the handles and axilla pads, including a variety of concepts that bear some resemblance to traditional crutches, but include some features designed to improve the user experience: they are both novel and useful, but not always practical. The Engineering students' output, consisting of stress analysis and a fully detailed design for a complete pair of crutches, bore a striking similarity to traditional crutches and contained feasibility work that supported convergence to this practical but not novel outcome. The two are compared side by side in Fig. 2.

The resulting design left the engineers disappointed that most of what they did was redesign what was already a perfectly good design for crutches. The resulting design also left the industrial designer frustrated because the design lacked visual appeal and a distinct look compared with a typical pair of crutches.

When the team regrouped and went back to the design drawing board *together*, the Una Crutch was born (Fig. 3). In collaboration, the engineers and designer worked through the problem solving process described in Fig. 1. In each step, all participants advocated for their perspectives. From this multidisciplinary approach, the team created an idea for a retrofit handle that could be attached to a traditional set of crutches. With the designer advocating for ideas that would improve the user experience and bring new functionality to market, and the engineers advocating for ideas that would reduce manufacturing costs and provide structural integrity, the students eventually converged on a new handle that was low-cost to manufacture and easy to install, but gave the added feature of being able to hold two crutches together without adding bulk or weight. This final design met the needs of both design and engineering.

3.1.2 Convergent and divergent thinkers

Beginning in 2015, the collaboration between Industrial Design and Engineering grew to be more formalized. Approximately 20 students from

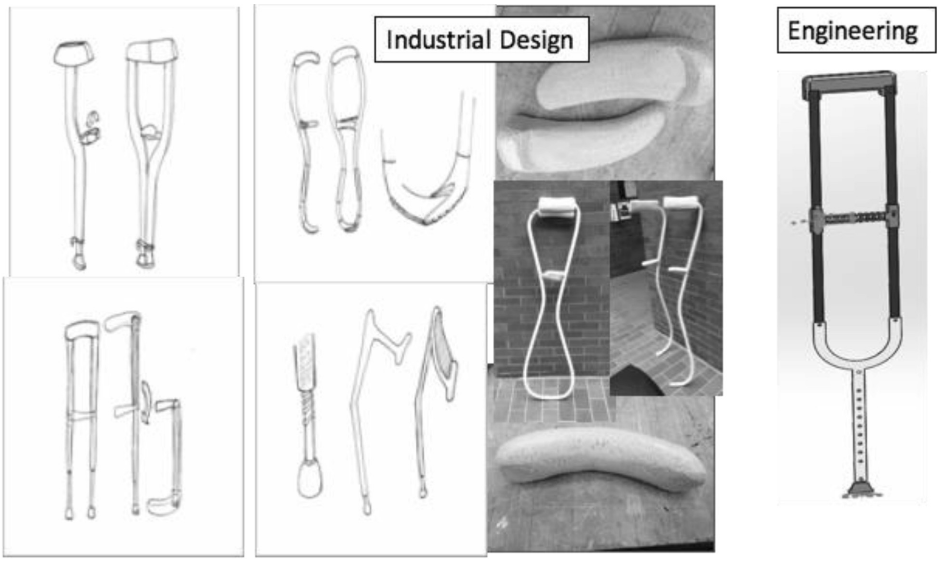

Fig. 2. Design concepts and appearance models from Industrial Design (left) compared with engineering model (right).

Fig. 3. The Una Crutch in its final form.

both disciplines work together during the summer in a design consultancy focused on the development of effective access technology, and some of these projects continue into capstone design. Three 2015–16 MSD teams (two from the summer consultancy) included team members from Industrial Design, and in 2016–17 that number has grown to seven teams (33 students total). In the current collaboration, the Industrial Design students are also using these projects to satisfy their own capstone design requirement, which has led to higher engagement in all parts of the process for all the students involved.

This most recent collaboration structure provides an environment where students with very different backgrounds (engineers and designers) are discussing their design project on a regular basis. In accordance with the literature, bringing together these different viewpoints and forcing students to consider their different points of view should enable them to think more creatively. Teams with a mix of backgrounds (designers and engineers) together are less likely to mirror one another, and more likely to provide an environment where a team member is considered an independent outsider, which may make those teams' members more likely to think divergently.

The 2016–17 cohort is the first group to be included in annual program assessment, and a mid-course debrief with the participating students has provided insight into the student experience. The group of students participating was asked to identify the most positive aspects of their collaboration and the areas that were the most challenging or needed improvement. Two common themes emerged that are relevant here. The first was that the students had to struggle to understand the perspectives and potential contributions of those with vastly different backgrounds, and to understand another discipline's approach to the design process. The second theme was that both engineering and design students noted that the most important positive aspect of the collaboration was the ability to see things from a different perspective, which some students felt helped them to come to a locally optimal solution more quickly than if either discipline had been working alone. The two observations are related: the struggle to come to consensus on everyone's roles and contributions may be what helped the students to have more productive idea generation that resulted in novel yet useful solutions. The other areas for improvement identified by students were primarily logistical hurdles, such as different course scheduling and student work expectations for the designers and engineers. The relatively straightforward changes required to address the challenges are a reasonable tradeoff for the benefit of an environment where students are exposed to different perspectives.

3.2 Agile software development as creativity in capstone experiences at Rose-Hulman

Over the past two decades, software development has seen a movement, from the ''Waterfall'' and ''Iterative'' lifecycle models to ''Agile'' models. The latter involves fast cycles, high client interaction, and delays to as many design decisions as possible until time for implementation. In the fast Agile cycle, all steps of the CPS shown in Fig. 1 are done with every iteration.

Among the features of this newer life-cycle model, a key one is enabling a team of software developers to time decision making so that it is when they and their client are focused directly on implementing some particular requirement, and the team is then able to demonstrate very shortly thereafter the accomplishment of that requirement in their system for the client's evaluation. The attention of both the client and the development team is drawn to a succession of such requirements, normally done in order of importance. This fast flow of ''iterations'' of development provides more meaningful discussions of those very specific requirements, with client feedback and/or sign-off on those following directly. Rework is minimized.

Embedded in the Agile flow is an intentional imprecision in specifying most requirements. They typically are described in sets of ''user stories'' that do not prescribe any more than the most essential needs. For example, from a well-known reference site for Agile development:

> ''As a power user, I can specify files or folders to backup based on file size, date created and date modified'' [23].

This example intentionally leaves off the part of a user story which often is needed—the explicitly stated purpose of the user in doing this action—the ''why''. That is inferred by the ''power user'' role. Power users invent new work, and so have broad, general needs. The point of keeping user stories sketchy is that they can be interpreted close to the time they are implemented, a situation that can vary depending on the development done up to that point.

During a team's interactions with the client, at the beginning of the activity when a requirement will be done, they discuss it in more depth for example, relating this user story to others involving the same user, and detailing the interaction design. That clarification process also is an opportunity for creativity, because the development team is able to inject their own ideas about design into the discussions, and the nature of the interactions allows for new ideas, about both the resulting system and the needs themselves, to be explored. In essence, every short development cycle begins with an opportunity for creative problem solving.

To be complete about how creativity is injected via an Agile process, the process gets its name because it is able to change to meet different circumstances, such as requirements implying variations in the processes a team has used before. In Scrum, the most popular flavor of Agile, at the end of each short iteration there is a Retrospective, an opportunity to re-decide how the current project is being done [24]. This is in addition to the meetings at the start of each cycle, to agree what will be done next, to design, estimate and assign the work; and a meeting at the end of that cycle to demonstrate performance to the client. Thus, the varied aspects of the work—from customer relationship through requirements to how design and development are being conducted—all are able to change. Everything is open for discussion, on a regular basis, and teams take advantage of that via use of creative processes. The organization of a team is essentially flat, promoting contributions by everyone. Anyone can question what is being done or how it is being done. This team design fits the idea of providing the psychological safety for each team member to offer ideas. That is the number one requirement for team success cited in recent, extensive team studies at Google [25].

3.2.1 New style capstone design: Agile

Favoring more interaction meant that more change during a project would need to be acceptable. The notion of "stable requirements" was replaced by the more realistic view that most customers and users "know what they want when they see it." This is a fundamental finding of interaction design, that first principles, best practices, heuristics and well-written specs are insufficient to optimize customer acceptance. Iteration is inevitable based on reactions to the real artifacts [26].

For capstone projects, adopting an agile approach meant encouraging creative solutions to everything, and encouraging teams to step up to creative decisions. All teams were now on different schedules and had different sets of deliverables. The last piece in the creativity puzzle, to make this style work, was creative advising and assessment by the course instructor. This is pretty much where we are now in software capstone best practices. Creativity is an expected part of the process, at all levels: by the client, students, and instructor.

3.2.2 The path to an agile capstone at Rose-Hulman

Since the 2013–14 capstone cycle, the CSSE department has expected an Agile approach from all teams. In the current model, teams do either one or two week long iterations, with products to show their clients at the end of each cycle.

It is possible to make a case that the newer approach is both more creative and also more successful in delivering desirable products to project clients. These are the often contradictory directions engineering teams might choose, but, in these software projects, both dimensions appear to have grown, as Agile became their standard development practice.

For example, a customary capstone project once was to develop a web site for an outside client, using a database for underlying business data. If the team did any iterations, these were large scale, like developing the core pages first, then adding chunks of features to those, in one or a few additional iterations. Now the projects are much more ambitious. Recent successful examples have included:

- Create a universal backup device for machines sharing a LAN, without file duplication.
- Generalize Uber, with middleware supporting any type of delivery service.
- Provide all the logical smartphone services for visitors to a large state park, such as allowing them to add their own images to those taken by others, from any location.
- Create Android and iPhone apps to control remote mobile devices in real time, synchronized with other users of these devices.
- Invent learning tools on tablets for research with children who have disabilities such as dyslexia and autism.
- Provide investors with their current real and on-paper gains and losses, in multiple funds, with an ability to move to additional levels of detail.

At Rose-Hulman, students learn to use the Agile model in software engineering classes during the junior year. By the time they are seniors, students are adept at Agile methods. It is because of this deeper skill base that they are able to take advantage of creative opportunities in their capstone projects. They know how to work, individually and jointly, to come up with new design ideas using divergent thinking, evaluate these themselves, and present them to their client as recommendations. They also have experience problem-solving directly with clients.

Pedagogically, it would tricky to teach the principles of agile software development at the same time students are supposed to be using them proficiently. During each iteration, all the skills are called upon such as requirements gathering, design, current implementation practices, testing, and delivery. That is the first couple weeks or so of a capstone course, to apply all those at once, in a first iteration.

Because of the nature of the Agile process, each design idea developed is regarding a reasonable-sized chunk of the system—usually a part of a feature such as a user interaction which can be written as a single sentence. The atomicity of these requirements enables more freedom for design work responding to them.

In Table 1 we see the derived results of team feedback, in the form of student course evaluations, from 2003–4 through 2015–16, from the author's capstone courses. Numerical course evaluation scores for classes in succeeding years were compared, for three key questions on those instruments. Shown in the table, as correlations, is the trend in the numeric values for the questions over those 13 years.

The major course change associated with the trend was that generations of students used progressively more agile processes over these years, as they pursued their capstone projects. These agile processes enabled greater opportunities for team creativity, particularly in framing the problem being tackled.

The correlations show *increases* in these numbers over those years as the processes morphed. That is, the independent variable is the school term/year, and the dependent variable is the students' summary evaluation, for the three questions shown in Table 1.

The numbers 497, 498, and 499 are the three course numbers for the Capstone sequence, usually taken fall-winter-spring in a student's senior year. The results can be read as, "For the first two of these sections, over the years, student feedback increased significantly (at the 0.05 level)." This was in terms of their quality of learning and their rating of the overall course, though not in terms of overall instruction received. The latter exception can be explained by the fact that the role of an instructor in capstone is more limited than in other classes, and students are encouraged to become ever more self-reliant. The fact only the first two sections of capstone show significant growth in ratings, over the years, could be explained by the phenomenon that, in 499, these ratings appear to be tied closely to the success of the project by a given team. That is, the ratings are lower, the final term, if the project did not come to a fully successful conclusion. In the earlier two terms, the project is still in progress, and team hopes are still high.

Client survey reactions also increased over these same terms/years, with low positive correlations (0.14 for how happy they were with the software delivered, 0.20 for how successful students were at converting their needs, and 0.21 for how well the students communicated with their clients). However, because of the lower number of clients studied, these increases were not significant at the 0.05 level. Students have a choice of projects, with a team usually being able to pick from among two or three times the number of project proposals as there are teams doing this choosing. Encouraged by better preparation prior to capstone, the teams were selecting progressively more complex projects over these years, so client expectations were growing.

It is worth noting additional variables relating to team success. For CSSE majors, 2010–2016, we correlated their grades in prerequisite courses with their grades in these capstone courses. This was done by pairwise comparisons of individual students' grades, from one course to another, over

Table 1. Correlation of average feedback ratings, with successive term numbers that capstone courses were offered, 2003–4 through 2015–16.

Course evaluation Q:	Q1—Quality of learning			Q4—Overall course rating			Q9—Overall instructor rating			Students reporting		
	497	498	499	497	498	499	497	498	499	497	498	499
Correlation with term/year	0.43	0.32	0.18	0.39	0.53	0.00	0.22	–0.19	0.18	82	98	74
Significant at what level?	0.00005	0.001	0.13	0.0003	<0.00001	0.97	0.05	Negative	0.13			

Table 2. Correlation of grades in CSSE capstone courses with grades in their prerequisites

Capstone course	Prerequisite	Correlation	Significant at what level?
497	371 (Software requirements)	0.25	0.00002 (N = 279)
498	374 (Software design)	0.24	0.0003 (N = 224)
498	497	0.43	4E-13 (N = 254)
499	498	0.64	2E-29 (N = 248)

several years. The results were significant at the 0.05 level and indicated that the correlation was low. These are shown in Table 2.

There was low correlation between grades in prerequisite courses and performance in capstone. We also checked the correlation of these capstone courses with other courses in their major, and the correlation was low. The relationship of performance in the capstone, with their overall GPA, or with GPA in their major, was also low. Some authors were surprised that performance in prerequisite courses did not predict success in capstone. There are other factors that influence capstone success. For example, it is possible that teamwork overrides everything else in producing success or that the relationship with a client is most important. The ability to deal with ambiguity may play a role in capstone success. Finally, it is possible that the creative response of a team to the changing requirements of a project plays a significant role in success. The main point demonstrated by Table 2 is that success in prerequisites for the capstone course sequence do not predict success in that sequence. That is, this success is not deterministically set by prior learning, opening the door for situational variables like a team's ability to deal creatively with their problem.

The predictability of grades in 498 and 499, based on the grade in the capstone preceding it, is worth noting. This is not because of a bias by the professor issuing the grades, exactly. In 2015–16, for example, every team had two different professors as their advisors, over the three-term course set of their project.

Each team does have to be judged based somewhat on effort, not by a blanket judgment of success on the projects. Some are surely harder to judge than others. Can a capstone team who failed, and could have been fired by their client, get an "A" for diligence and creativity? For example, our team, charged by their client to create a universal backup device, was successful in achieving this for Windows-based machines, but not for machines with other operating systems. It was a very ambitious project, and it included twists such as, early in the second term, their client discovered he was not going to be able to get the rights to use underlying software from one source, and the team had to make up for that. Does starting over impact their grade?

How does one measure effort? Faculty advisors study contributions of each student on the team repositories (like Github). They run weekly team meetings as a project manager, asking each student whether they accomplished what they had planned to do the week before, etc. And how the current pace leads to eventual success, using tools like burndown charts. They use team peer evaluations and customer feedback in their grade decisions. Perhaps agile grading is the last side of creativity required for this style of capstone experience.

3.2.3 Conclusions regarding agile development

We believe that moving to an Agile project structure, for software capstone teams, makes sense to prepare them for their work environment. However, this also yields the benefit of immersing them in a creative problem-solving environment during their senior year.

At Rose-Hulman, the progressive move from Waterfall and Iterative life-cycle models, to Agile, has generated progressively stronger student feedback about their experiences, particularly during the first two terms of the three-term capstone. The influence of this change to Agile compares strongly with the expected influence of student success in prerequisite courses.

3.3 Fixation in a creative problem solving process at University of Limerick

At University of Limerick the capstone course is traditionally known as the final year project which operates in two modules over one academic year. The student defined final year project is either a research-driven individual project where students focus on a theoretical framework, or a design-driven problem contextualized in Technology Education. The design-driven project takes students through an iterative design process similar to that outlined in Fig. 1. In a creative problem solving process capstone students bring together their cognitive, psychomotor and affective learning from their previous years of undergraduate education toward the culmination of an individual student capstone project. This paper focuses on the idea finding and solution finding process for the design-driven project. During the creative problem solving process the generation of numerous and diverse ideas may be limited by one's imagination and curiosity due to a focus on implementation [1]. This focus on implementation may result in students not realizing their potential, and/or not exploring all possibilities. In addition, the focus on prior or known experiences, existing ideas, or products, is known as fixation, may block new ideas [27].

3.3.1 Fixation in a creative problem solving process

Fixation, or the tendency to become focused on specific options early in the design process, can limit the variety of designs considered [27–30], impede productive problem solving [31], and in some instances, fail to solve the design issue or need [32]. Viswanathan et al., [28] highlighted the manner of presenting external examples, as either sketches or prototypes, influences the amount of creativity and fixation.

Fixation can limit creative problem solving. Everybody has the capacity to be creative [32]. Robinson also argues that as individuals we do not grow into creativity, we grow out of creativity [32]. Creativity researchers generally agree that creativity involves a combination of uniqueness and usefulness [33, 34]. It was proposed that creativity is the interaction among aptitude, process, and environment by which an individual or group produces a perceptible product that is both novel and useful as defined within a social context [34]. The main experiences explored in the context of creativity in this section focus on overcoming fixation on initial ideas (idea finding), by developing initial ideas (solution finding) using Design Heuristics. To overcome fixation and promote the generation of new ideas or development of existing ideas, students should integrate ideation tools into their creative problem solving process. However, many of the ideation tools available are not empirically validated.

3.3.2 Design heuristics in a creative problem solving process, at University of Limerick

The 77 Design Heuristics tool is an empirically validated ideation tool which supports students' idea finding and solution finding thus overcome fixation and promote creative ideation. The Design Heuristic tool is most naturally applied during the idea finding and solution finding steps of the CPS shown in Fig. 1. Design Heuristics (DH) are a collection of prompts to help designers generate alternative solutions that vary in nature [35–37], discouraging fixation and encouraging divergent patterns of thinking (Fig. 4).

Design Heuristics are derived from empirical evidence of industrial and engineering designers' protocol studies [36–39], a comprehensive product analysis of over 400 products [40, 41], and content analysis of an expert designer's over 200 concept sketches to solve a specific design problem over two-year period [42]. They are also empirically-validated in both educational [37, 43–49] and professional settings [50, 51], demonstrating its ease of instruction, use and its impact on the quality of the design outcomes.

At the University of Limerick Technology Education pre-capstone modules, students apply numerous idea finding and solution finding techniques for encouraging divergent and convergent thinking. Some of these techniques include lotus blossom, brainwriting, SCAMPER, morphological analysis, and random inputs. For the 2016 capstone design-based project the Design Heuristic tool was used to support students solution finding thus overcome fixation in idea finding. During the idea finding phase students used individual brainstorming to generate initial ideas. Once students reached idea exhaustion the solution finding phase commenced with the support of the Design Heuristic tool.

In the context of CPS idea finding phase some students initially expressed difficulty generating creative ideas:

> "The first idea generation was very tough; the ideas were very square and existing ideas were very fixed in my mind" (UG student JD).

In the context of the solution finding phase with support of the Design Heuristic tool students noted the generation of creative possibilities:

> "When using the [DH] cards it allowed you to think outside of the box and come up with ideas that I would not have thought of" (UG student JD);
>
> "The cards supported my idea generation for longer and pushed me to develop more ideas than I normally would" (UG student JG);
>
> "I had less brain blocks as the [DH] cards example would open a new window for ideas" (UG student JCH);

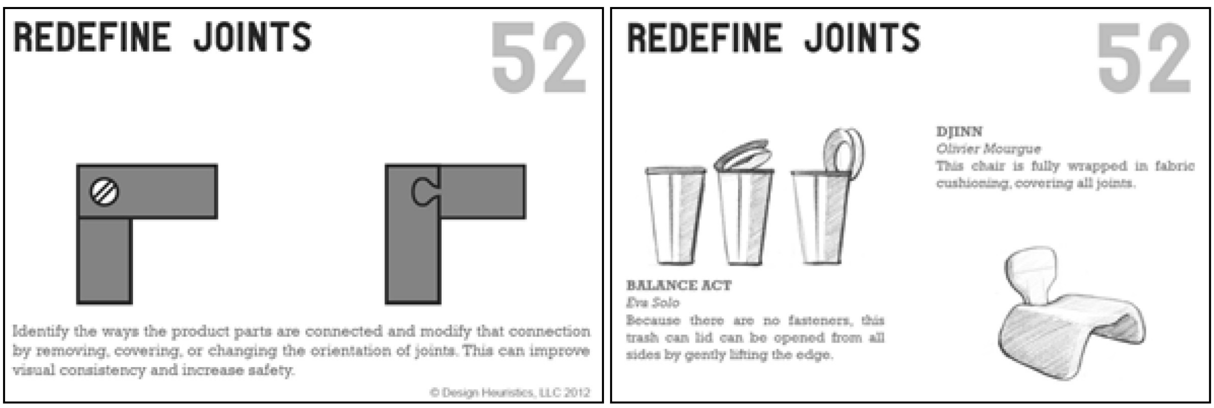

Fig. 4. Heuristic Card Example: Redefine Joints.

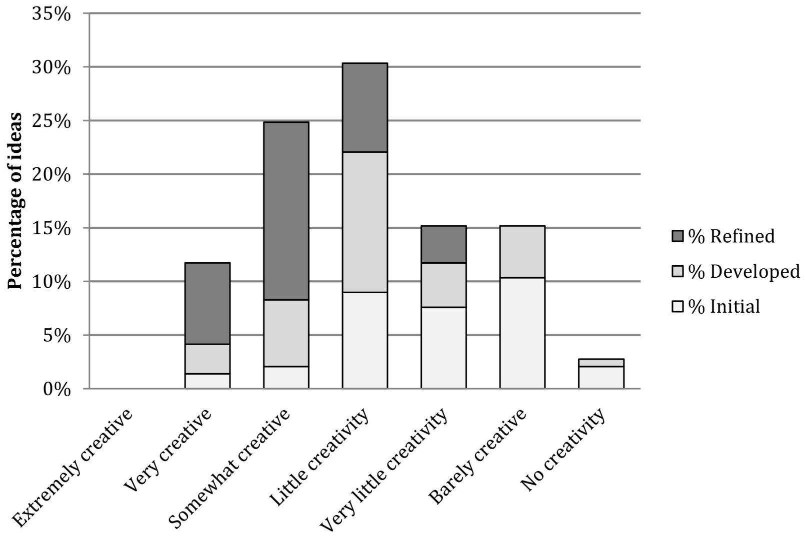

Fig. 5. Capstone student creativity self-assessment in design ideas.

> "They helped me think of ideas that I would not even think about (UG student CB);
>
> "I know myself I struggle with idea generation" so these [DH] cards provide me with starters for my imagination to kick in and come up with more innovative designs" (UG student BE);
>
> "The Design Heuristic cards helped a great deal with coming up with some simple but effective ideas" (UG student DM).

In the context of solution finding the Design Heuristic tool strengthened students solutions by working toward the best solution:

> "They were great to spark your imagination and to stop you from finalizing on one idea" (UG student PC);
>
> "I was able to use various different Design Heuristic cards to come up with better concepts" (UG student CH);

In the context of overcoming fixation with the support of Design Heuristics students noted:

> "The Design Heuristics made me broaden my mind and make an effort to incorporate different aspects" (UG student CK);
>
> "The Design Heuristic cards gave me great ability to explore design. They made me look at everything differently and every card was a new adventure. The cards changed my design completely. I got great value from them as my design now provides a service and has a second function" (UG student DB);
>
> "They definitely helped move passed fixation" (UG student CF);
>
> ". . . compared to the first generation session where it was more me thinking of simple existing solutions and redrawing them or manipulating them slightly. The Design Heuristics led to more thinking and creativity" (UG student NK).

During the creative problem solving process student's creative ideation was supported by the Design Heuristic tool during solution finding. After the idea finding (initial ideas), and solution finding (developed initial ideas and refined ideas) students comparatively self-assessed their ideas in the context of their individual design-based project. It is acknowledged students' self-assessment was not triangulated with assessment by peers or the academic team for the capstone design-based projects. From the student self-assessment it was evident that student's ideas progressed with respect to creativity from initial ideas (idea finding) to developed and refined ideas (solution finding) (Fig. 5).

Overall the individual student ideas were distributed with 32% of ideas in the idea finding (initial ideas) phase, 68% of ideas in the solution finding phase (32% developed ideas, and 36% refined ideas). This overall breakdown represents a greater proportion of solution finding ideas as students progressed from their idea finding (initial ideas) which indicates an expansion of initial ideas, thus overcoming fixation and exhaustion. In terms of ranking individual ideas with respect to creativity; overall the solution finding ideas were ranked more creative. In the context of idea finding (initial ideas) students predominantly ranked their ideas in the least creative categories. This ranking is represented as 9% little creativity, 8% very little creativity, 10% barely creative and 2% no creativity. In the very creative categories students ranked initial ideas as 2% somewhat creative, and 1% very creative, with no initial ideas ranked extremely creative. In the context of solution finding, focusing on developed ideas (32%), ranking of ideas occurred toward the little creativity categories. This ranking is represented as 13% little creativity, 4% very little creativity, 5% barely creative and 1% no creativity. In the very creative categories students ranked developed ideas as 6% as somewhat creative, and 2% very creative, with no developed ideas ranked as extremely creative. In the context of solution finding, focusing on refined ideas (36%), ranking of refined ideas occurred toward the very creative categories. This ranking is represented as 8% very creative and, 17% somewhat creative. As ideas were refined it is evident that the little creativity categories greatly reduced with 3% very little creativity and 8% little creativity. These findings indicate with the integration of the Design Heuristic tool from idea finding to solution finding students increased the number of ideas, overcame fixation, and represented more creative ideas working toward the best solution. It is acknowledged the creative problem solving process is iterative and may require further solution finding tests such as high fidelity prototypes to determine the viability of a creative solution to address their problem.

Statistical analysis was used to determine the independence of idea finding and solution finding ideas which indicated student creativity increased significantly (at the 0.05 level). The correlation between initial and developed ideas indicates a positive relationship (0.636), and between developed and refined ideas indicates a positive relationship (0.5177). Overall the findings indicate students developed creative ideas as idea generation progressed from initial ideas (idea finding) to refined ideas (solution finding) with the support of the ideation tool Design Heuristics. Design Heuristics supported student's ability to overcome fixation and develop creative ideas from the idea finding phase to the solution finding phase in the context of their individual capstone design-driven project.

3.3.3 Conclusions about fixation

Fixation is a practice evident amongst students and professionals. Informing and educating students on fixation and integrating empirically validated ideation tools can promote divergent and convergent thinking. From the student comments and self-assessment it is evident that creative idea development and overcoming fixation were supported by the Design Heuristic tool. Developing students' idea finding and solution finding during creative problem solving requires support tools to extend the pool of creative ideas. Further studies have explored the use of the Design Heuristic tool for idea initiation, transformation and sub-component design [52].

3.4 Art as a tool to improve creativity in design at Rose-Hulman

A course in creativity and creativity techniques was developed as a prototype to test creativity teaching techniques for subsequent incorporation into a capstone design sequence. The primary creativity mechanism was to utilize art both as a prism for new ways of seeing and as a vehicle to explore design in collaboration with the Barnes Foundation of Philadelphia Pennsylvania. Students in this course explored a number of techniques to help them find their creative core, however this discussion will focus on the use art as a prism to see engineering design from multiple perspectives. Seeing engineering design from multiple perspectives can be used in all phases of the CPS in Fig. 1.

Common techniques for brainstorming new ideas involve techniques to get students to view problems from a different perspective (seeing the problem from another person's perspective, changing the laws of physics, triggers, *etc*.). As will be explained, the novel approach used in this course was to use artwork and art techniques developed by the Barnes Foundation in addition to techniques developed for this course to develop different and unique approaches to problem solving. The primary benefit of this approach is that most engineering students and faculty have limited experience with artwork; this allows a similar level of comfort and familiarity, or lack thereof, with a nearly simultaneous exploration of new concepts by the entire class. Students stated in post course surveys that the use of art aided in reducing self-censorship when discussing and exploring the approaches in class, as there is no fear of sounding foolish in front of an expert, including the faculty instructors.

The authors worked with the Barnes Foundation to utilize the techniques the museum had developed as part of their educational programs. The primary techniques explored here were mindful observation of individual art, careful observation of assemblies of art, and techniques to use existing works to help students find and develop their own voice. The careful observation approach, developed by the museum's education group, called "slow-looking", was modified and implemented into the slow-looking and prisms portions of the course. Overall the artwork was used as a mechanism to see engineering design from a unique perspective by exposing students to unique artistic techniques, such as the use of perspective and line by Cezanne, followed by connection to unique engineering designs such as the first graphics user interface from Xerox PARC.

3.4.1 Slow-looking

Slow-looking uses the study of works of art to help design students observe carefully and gather information on what they are observing deliberately. An artwork is briefly introduced followed by several minutes of quiet study of and reflection upon the work. The technique is introduced by a group exercise where the themes of light, line, and color are used to explore a work followed by several short, individual explorations to help students to further understand the technique.

The slow-looking technique was used to explore individual works of art, collections of works by an artist, and wall sized collages of art unique to the Barnes Foundation. Those collages, consisting of fine art, decorative pieces, and antiques, provided the richest application of the slow-looking technique, proving to provide multiple perspectives of the same collage that provoked significant discussion and, based on post-course surveys, gave many students insight into how the same work can be viewed from many different perspectives.

The students applied the same slow-looking technique to the exploration of individual works of art. While the collage analysis provided insight into different perspectives on the same design, the study of individual works resulted in an increased intensity of analysis as students shared their observations that demonstrated a depth of study that encouraged their classmates to elevate their expectations.

The slow-looking approach was initially applied to artwork but was later applied to architecture, engineered products, and finally students were asked to apply it to a design of their choosing. This approach and its techniques are valuable to practicing engineers [53] and also expert designers [54], by giving them tools to analyze the designs of others as well as an approach to the creation of their own designs.

Another art-based approach developed in this prototype course is developing new prisms by initially discussing artwork, the approach of the artists to that work, and from that conceptualizing a "prism" to see it the way the artist might see it. Not only does this approach serve as an alternative to design concept generation methods [39], it also serves to help develop alternative designs and explore the design space more creatively, both of which are valuable techniques for professional designers [53].

Finally, and significantly, a recurring topic of the course addressed dealing with fear. This is a significant barrier to the generation of new ideas and exploration of possible outcomes that are critical to professional designers [53]. In addition to developing their own "Litany Against Fear", several fear-defeating techniques used by artists and their application to engineering design were discussed in class [55–57].

3.4.2 Conclusions about learning from art

The effectiveness of the course was evaluated by reflective prompts throughout the term as well as summative reflective essays at the conclusion of the term. The results of the art-based elements of the course were evaluated to be very successful, with universal approval by the students. A few notable comments from student summative reflections:

> "This class in general opened my eyes to who I am and not what the school was making me into. It brought back my individuality. "
>
> "I really appreciate you both bringing back a part of me that I thought was gone long ago."
>
> "I'm really glad I took this course, as it teaches us lessons that no textbook can convey."

Based on the student evaluation comments, these techniques will be modified and implemented into the capstone design sequences in the coming year.

3.5 Use of commercial system for creativity at Rose-Hulman

At Rose-Hulman, mechanical and civil engineering chose to use a commercial system called FuseTrail™ to enhance the problem finding, idea finding, and solution finding portions of the CPS shown in Fig. 1. The FuseTrail™ involves using a box of objects in a kinesthetic way to generate observations that are used to stimulate unusual ideas. The process can be used with two to twenty participants. The company, Kiln, provides a box of objects that have been carefully chosen to reflect current trends in society [58].

Prior to the session, a facilitator determines the key question that the group should answer. For capstone courses students are asked to state a wish about their project. Sample wishes have been, "I wish there was a better way to hold the meter during testing."; "I wish that the base of the robotic arm didn't wobble."; "I wish this part wasn't so expensive." The wish that is the focus of the session is written and displayed so that all participants can see the wish. Participants are told to read the wish and that the goal is to generate as many ideas as possible about fulfilling the wish. Furthermore, the facilitator tells the group that they will meander away from the wish for a bit and to have faith that the group will address the problem.

A session begins with participants being given a wrapped object and asked, "What do you observe?" Each participant gives a short phrase that describes what they see, feel, or smell when holding the object. Every phrase is recorded so that the group can see what has been said. In the second round, the object is opened and participants are asked, "What does this object mean to you?" Again, each participant is encouraged to give an answer that is recorded for everyone to see. After the second round, a card that describes the social trend that is associated with the object is removed from the box and read to the group. A third round begins as each participant is asked to name a trend that they observe in the object.

After the three rounds are completed, participants are reminded of the wish. They are asked to take two words from any of the three rounds and put the words together in a way that asks a "How might we" question relevant to the wish. So, for the meter question earlier, a potential question could be, "How might we keep the meter still without using mechanical methods? " Participants are encouraged to generate "how might we" questions until 20 or 30 questions have been generated. After 20–30 questions have been generated, participants select the most interesting ideas to pursue. Participants brainstorm as many possible ideas for each of the selected "how might we" questions in the time permitted.

This method was used by both Civil and Mechanical Engineering capstone design teams in the fall of 2015. The data collected was largely anecdotal. Faculty members and students enjoyed the process and felt that the ideas generated were good. Interestingly, at least four external clients commented, without any prompts, that the ideas generated during the fall were the best that they had seen in their time working with Rose.

3.5.1 Conclusions about FuseTrail™

Having a wrapped object was appealing to participants—it appealed to their sense of mystery. Also, touching the object seems to reduce participant anxiety and help them generate more observations. The written material about the object stimulated thinking. Requiring the participants to put together two words as they generated ideas seemed to lead to wider range of ideas. When students are asked to spend significant time generating ideas with a facilitator, they are willing to do so and are often pleasantly surprised by what they achieve.

4. Discussion: strategies and practices that faculty can implement

The opportunities and constraints for creativity in capstone experiences are all related to the situation

Table 3. Creative windows which may exist for senior project practitioners.

Creativity window	Description	Evidence and Rationale
Use participant diversity.	Select team members or outside influencers who think differently.	Teams who do not all think alike are more effective on long-term projects.
Use background diversity.	Pick people with complementary skills	Teams who need to learn from each other invent synergistically.
Level the contributions.	Encourage equality of contribution, generally and in team meetings.	Google's studies [25] show that respect and equality amplify team output. It's a necessary "set" to generate safety for creative thinking.
Inject creativity throughout the curriculum.	Let the capstone hone this skill, not introduce it.	Students tend to reject practices introduced as afterthoughts in their program.
Set up creativity as a goal.	Make a creative and effective solution both be part of a team's grade.	These goals can fight each other, but both are desired.
Invent new meanings for project creativity.	Make any tough problem in a project be a chance for a creative solution.	Creative models are not limited to just the features of the end product.
Put students "outside the box".	Give them an unusual environment to work in.	A regular classroom dictates expectations.
Inject creative stimuli.	A surprise visit from an artist, to show their work to?	The element of surprise is known to open people up.
Make creative assumptions.	Engage creative design people on the project review team.	Expectations drive a lot of student behavior.
Alter the pace of work.	Have students participate in "slow looking" at artistic objects.	More intense review of interesting objects with depth inspire this mode of thinking.
Defer judgment.	Use this rule in brainstorming, and in exploring design alternatives.	This could be a top differentiator between students and seasoned engineers.
Give students maximum responsibility on these projects.	We leave the room while they work, as often as possible. They feel individual responsibility for the work.	We often are a hindrance, because students are filtering their ideas based on our reactions.
Use reflective prompts.	Students do "meta-thinking" about what they are doing.	This is an opportunity for them to change behavior patterns.
Employ agile processes.	Students work in short cycles with customer feedback with everything up for change after each cycle.	A non-fixed process invites creative options continually.
Add indirect creativity.	Have students interact with tools, games and imaginative activities.	Some students feel too challenged by being asked directly to be creative, but respond well to these stimuli.

at hand. For example, if only "canned" projects are pursued, students know that the existing expectations of faculty take precedence over their ingenuity or their awareness of newer solution paths. However, many chances for a team to be creative are unnoticed simply because no one has considered the possibility to solve a part of the capstone problem in novel ways. There are opportunities in each phase of the CPS in Fig. 1 for students to use creativity. We hope that our experiences will spark new dimensions in which engineering programs can make capstone experiences creative.

Table 3 summarizes creativity "windows" that we believe may be available to capstone projects that are often overlooked. These "windows" could work for various types of capstone experiences, such as those of varying lengths. As with every ingredient, adding creativity does reduce time for existing activities; it could be justified as more valuable than rewriting increasingly perfect documentation, or even satisfying every requirement written by a client.

At our Capstone Conference panel discussion, the question was asked, "Can creativity be taught? " We are sure this question is too deep and philosophical to answer from our experiences. At the conference, one of our answers was that you can talk about something else which stimulates students to act creatively, like having them play games or use tools to modify or inject their thought process with a new way of thinking.

As noted in the final item of our "windows", students can become blocked or fixated, when challenged directly to "be creative", while indirect methods do work. Indeed, the divergent side of being creative is close to the simple act of just thinking about something different. Design Heuristics prompt designers to modify their ideas using the 77 concept modifiers. Another standard technique suggested by several creativity writers is to take an "excursion"—go do something unrelated, after focusing long and hard on a problem. [59, 60]

In our discussion at the conference, we suggested as well that creativity involved "trials" of things which may or may not work. And this is true of trying Capstone processes which may or may not stimulate creativity among students in a particular department or school. There are strong cultural factors at play, such as, what tools have students already worked with? At the same time, "being creative" suggests having the initiative to go against standard, known solutions implying a counter-cultural ingredient. Perhaps training students to develop active self-awareness and self-reliance is a foundation for this side of creativity. Our engineering programs increasingly promote that maturation with "Makers Labs" and other prototyping opportunities and a "fail fast" approach to risk-taking.

Our definitions of creativity allow for both elegant and complex variants, developed by students, to qualify. This does not simplify the task of judging what is more creative of their outputs or of their means to achieve them.

5. Conclusions

There are a wide range of implementations to accomplish capstone design course objectives that provide numerous opportunities to encourage and demonstrate creativity. Students, when encouraged to be creative, try and often obtain remarkable results. The techniques presented in this article have been helpful to the authors in the circumstances described. We encourage readers to take advantage of all opportunities for students to exercise creativity. We look forward to hearing your results at the next Capstone Conference.

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