Integrated 2D Design in the Curriculum: Effectiveness of Cross-Subject Engineering Challenges

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Abstract

Multidisciplinary engineering design is difficult in the undergraduate years, particularly in the early Freshman and Sophomore years, since the students have not enrolled in a breadth of subjects. Multidisciplinary problems are often left to latter years, thereby leaving the students with an incomplete picture of how course subject matters relate and fit in a larger view of engineering and design. At the Singapore University of Technology and Design, a novel approach to multi-disciplinary engineering education was instituted in the Freshman and Sophomore years, where during a particular term we had all courses simultaneously attack a common design problem. For one dedicated week, the courses stopped coursework and instead simultaneously worked on the design challenge problem engaging the subject matter of those courses. We call this the *2D design challenge*, were the design problem is multidisciplinary, but exclusively restricted to the domains of the courses being taught. We found the approach generated highly effective learning on the multidisciplinary nature of design problems, including statistically significant impact on student perceptions of their ability to solve multidisciplinary design problems. As an example, courses in biology, thermodynamics, differential equations, and software with controls were merged in a design challenge problem of developing a perishable food delivery system composed of unrefrigerated unmanned ground vehicles. We recommend that successful 2D challenges require instructors to establish a-priori a chain of requirements linking the design activity in each course. Effective execution of a 2D design challenge ensures that the design problem has co-dependent requirements from each discipline that cannot be independently determined in isolation. This then allows for creative interdisciplinary solutions to be developed.

Introduction: Multidisciplinary Engineering Education

An observed difficulty in engineering curriculum is finding means to educate students in multidisciplinary engineering design problems. Modern-world engineering problems are often described as no longer solely within a single discipline; for example traditional mechanical engineering designs often now involve software, controls, electronics and perhaps biology, etc.

One primary difficulty in posing multidisciplinary design problems in the undergraduate curriculum is that within the student body of a course there is variety in the past courses and experiences. An instructor can only expect students to have taken the pre-requisite courses, which thereby limits the range of multiple disciplines that a project can cover. Further, instructors from these other disciplines are typically not available during the course project for learning and consulting on issues from these other disciplines. Therefore, most engineering curricula wait until the later undergraduate years to begin exposing the larger multidisciplinary problem space to students, through project courses with instructors from multiple disciplines. Unfortunately, this approach delays big-picture understanding of design and how the subject area materials learned by the students integrate.

We present here a different approach taken very early in the freshman and sophomore years at the Singapore University of Technology and Design (SUTD). Our approach is to present short, one-week design exercises that exclusively engage the set of disciplinary subjects the students are enrolled at that moment, and no other course materials. No attempt is made to engage courses from previous terms in these design exercises. Yet, all instructors from the subject matters taught at that moment are available and engaged on the design project during that one week. This lateral approach allows early experiences in multidisciplinary engineering design, and also enables student success with the multidisciplinary design project, based solely on what they already have learned very early in their education.

In this paper, we present the approach and data on the positive efficacy that results when providing short, one-week design challenge problems that exercise disciplinary content from all courses a student is enrolled during a term, what we call *2D design challenge problems*. We find the approach allows for very early introduction to multi-disciplinary design, allowing students to successfully exercise and combine materials immediately learned in parallel courses.

The next section introduces the 2D design challenge concept, and discusses relevant experimental work. Then we present statistical data on efficacy of the 2D approach from the perception of the student and what they felt they learned. Lastly, we discuss difficulties encountered in correlating the success at 2D with differences in grades within the core subject courses.

Background and Context: Big-D Design Thinking

The SUTD has been established in collaboration with the Massachusetts Institute of Technology (MIT) and Zhejiang University. Since its foundation in 2009, it is striving to establish a 21st century innovation paradigm that recognizes the synergy between innovation and design with a unique emphasis on design-centric education university-wise. Specifically, some of the objectives are: (i) to take an integrated and interdisciplinary approach, as well as, (ii) to include exposure to real-world experiences[22] SUTD utilizes a technology and design-centric pedagogy in its educational approach, rather than an engineering science centric pedagogy. The SUTD curriculum is built upon a solid foundation of engineering sciences, humanities and design fundamentals in the so-called *Freshmore year* (the freshman year plus the first semester of the sophomore year), a multidisciplinary approach with core subjects and electives cutting across disciplines and a focus on a broad view of engineering and architectural design.

Design, as an academic discipline, cuts across and integrates all curricula at SUTD (Figure 1 showing details about the SUTD curriculum). The view of design at SUTD is referred to as the *Big D* view of design[23]. Big-D laterally includes architectural design, product design, software design, systems design and basically all technically grounded design. It also includes longitudinal consideration of design through conception, development, prototyping, manufacturing, operation, and maintenance – the full value chain. It also includes an understanding of the liberal arts, humanities, and social sciences' influence on engineering design. In short, Big-D encompasses the art and science of design[30]. SUTD seeks to instill the students with an understanding of how design is a core component of the human endeavor.

Given this Big-D background, SUTD has implemented a new *4-D educational framework* and initiatives to integrate design throughout the curriculum. As discussed next, the design activities are considered and classified into 1D through 4D experiences, representing an expanding set of disciplines considered in the problem. This provides the context for the 2D design challenge presented in this paper.

At the engineering course level, short design projects or activities are conducted in direct relation with the course's learning objectives: this constitutes the *1D Design Activity*. This approach is not new in engineering education; as will be discussed in the related works section, many have successfully engaged design into the engineering disciplinary courses.

Novel to SUTD, however, is what we term the *2D Design Activity* using *2D design challenge* problems. During each term of the 3-term Freshmore year (SUTD's first 3 contiguous terms) all students in a class are required to attend the same four courses as detailed in Figure 1. During each of these 3 terms, a one-week long design activity directly related to the content of the 4 parallel courses is conducted: this constitutes the 2D Design Activity. This article focuses on the 2D Design Activity as a platform for multidisciplinary design education, and provides analysis and data corresponding to the third 2D Design Activity conducted during the last term of the Freshmore year (Term 3 in Figure 1). As will be detailed, this example discussed is therefore in connection with the following courses: Engineering in the Physical World, Modeling the Systems World, The Digital World, and Introduction to Biology.

For context, beyond the 1D and 2D Design Activities and in the Junior and Senior years the SUTD pedagogy also contains higher dimensional design activities, namely *3D Design Activities* that incorporate learning from earlier courses, and finally a *4D Design Activity* which asks the student to incorporate design into their experiences outside of their coursework. Being a new University in its second year of teaching, these 3D and 4D Design Activities are still in the process of being fully incorporated. More details about the 3D and 4D Design Activities and the SUTD curriculum can be found in[22].

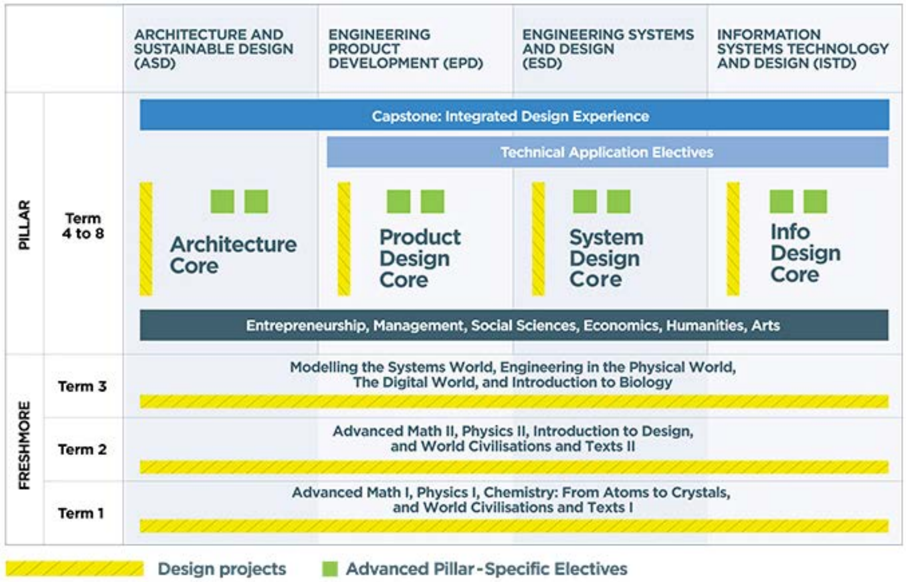


Figure 1: The Design Centered Curriculum at the Singapore University of Technology and Design (SUTD). The four SUTD Degree Program Pillars are shown as columns. In the first 3 terms, all students take the same set of multi-disciplinary courses, each with a 2D Design Challenge.

Given this framework for design education pedagogy, the question arises as to its effectiveness. What is the relative efficacy of 1D, 2D, 3D and 4D educational activities, and what can be done to enhance them? SUTD is vigorously assessing this and making improvements. This paper here discusses results on the 2D Design Activities.

Pedagogical Outcomes

While the potential excitement and joy of participation in this activity for students and instructors seems visible at face value, the worth in terms of learning objectives for the 2D design activity must be investigated. Taking a week of material out of each course to make room for the week of 2D Design Activity must be justified. Why bother?

The pedagogical foundation for the 2D Design Activity rests in the Kolb learning model[18], which describes the complete progressive cycle of learning experiences. As shown in Figure 2, this model is based on four fundamental progressive experiences needed for learning: *concrete experience*, *reflective observation*, *abstract conceptualization* and *active experimentation*. In the Kolb model of learning, the goal for any course or teaching activity is to follow this progression of student led learning, and to act as a facilitator in the natural inquisitive exploration that will occur in this progression.

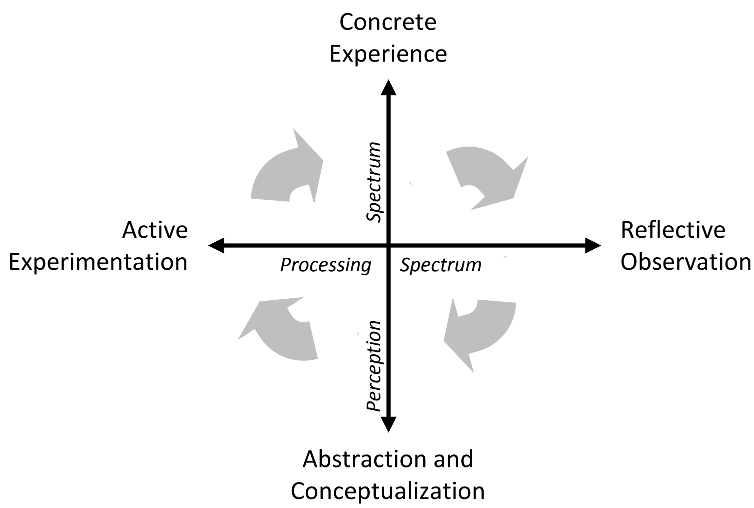


Figure 2: Kolb's learning model. For engineering analysis courses, the 2D Design Activity is ideal to provide either the concrete experience or the active experimentation phase in the Kolb learning model of the engineering material.

For such active learning progression, the Kolb model generally starts with a *concrete experience* in the subject matter. For example, a design activity can be assigned in the engineering disciplinary material. Without benefit of the understanding of the disciplinary course material, the student attempts to solve the design problem anyway, usually in a trial and error experimental approach, typically with less than ideal results. For example, in the thermodynamics course, students might be asked to design a cooler to keep perishables cold. They can do this by generating concepts using structural and insulating materials, but are unclear how thick to make such elements before being trained in heat transfer modeling. Trial and error is used.

After such an experience, the Kolb model follows immediately with a *reflective observation* of that experience. In the thermodynamics example, instructors can reflect with the students on the numerous set of prototypes, which had to be built to achieve the design goal, each of various thickness of insulation, and the excessive labor needed and so the limited performance achieved when excluding random luck. This motivates the students to want to learn material on heat transfer to do better on this project, and further simply generates natural inquisitive interest in subject matter explanations of what they experienced.

With this motivation, the next progressive phase of *abstract conceptualization* is the heart of most engineering analysis courses, to provide the theory and principles needed to understand and work within the domain. Students are lead through the derivation of the physical balance relationships and application of advanced mathematics to provide new understanding of the problem they previously experienced. In the thermodynamics example, students learn the differential equations of heat transfer modes, and compute solutions to design requirements such as time for a mass of perishables to rise to a maximum allowable temperature for a given insulation thickness.

Finally, the Kolb model asserts the education is not done until the students are given another concrete experience to apply this newly understood knowledge in a new application. After and only after this second *active experimentation* phase have students begun to understand the learned material. In the thermodynamics example, students are given another related 1D heat transfer design problem, such as determining required insulation to keep a perishable mass warm instead of cold, or a different mass, etc. A key feature in the engineering context, however, is to keep the experiences *concrete* as real physical projects rather than simply textbook problems. Seeing the design prototype work properly or not and being able to do something about it through engineering analysis is the key motivational observation of the Kolb learning model.

The pedagogical objectives for the 2D Design Activity, therefore, becomes clear in light of the Kolb learning model. The design challenge is a one week activity to exercise the combined materials of all four courses taught simultaneously. As such, it is an ideal platform for the two experiential phases of Kolb learning model, the first concrete experience phase or the last active experimentation phase.

As a platform for the first Kolb phase of concrete experience, the 2D design activity provides a multi-disciplinary problem for an early experiential demonstration of the need for the course subject matter. This ought to occur early in the term, in weeks two or three. As an example, a combined biology and thermodynamic design problem might be to design a container to keep a perishable item unspoiled for a period of time by keeping it cold. A trial and error approach is very tedious, requiring the means to measure when the product is spoiled, how that changes with temperature rise rates, and how temperature rise rates change with different thicknesses of insulation. Without understanding of exponential microbial growth rates, temperature dependency, thermal mass, and heat transfer processes through insulative materials, the design process is largely guesswork. Further, the students realize they do not know how to accomplish their design task, and are thereby then naturally inclined to be very interested to learn the biology and thermodynamics materials.

As a platform for the fourth Kolb phase of active experimentation, the 2D design activity provides a multi-disciplinary problem for using the course subject matter in a much more real world context than a subject textbook problem. This ought to occur late in the term, in the fourth or third final week. Following the same example of the combined biology and thermodynamic design problem, understanding of the biological principles of exponential growth rates and temperature dependency allows the students to create a exponential curve of time and temperature combinations that define the perished limit. This provides a time-temperature design constraint for the thermodynamic insulation design problem that can also be readily solved. Students develop a working prototype in one or at most two design prototypes, avoiding the tedious trial and error work.

This leaves the second and third phase of the Kolb learning model dedicated to the subject disciplinary courses. Specifically, the 2D Design Activity is designed itself to last 1 week; there is very limited time available for any theoretical derivation. 2D should not be yet another mini-course that requires its own subject matter derivations; rather, 2D should make use of the material of the subject matter courses. All derivations needed for 2D must occur in subject matter course lectures or otherwise. 2D is about integrating these subject matter materials into a multidisciplinary design project.

As clarification, this does not relieve the subject matter course from creating their own internal 1D active learning modules. Active learning should occur throughout the curriculum, and the 2D Design Activity does not provide the exclusive hands-on-experiences for the subject matter courses. Subject matter courses should still include lecture or recitation based demonstrations, hands on activities, designettes, or subject matter laboratories; all of the 1D Design Activities. As intended, the 2D design challenge is a short dedicated active learning activity on multi-disciplinary engineering that can be deployed very early in the curriculum.

In summary, the 2D Design Activity is meant to provide a real world active learning context of the subject materials on a problem more complex than a 1D disciplinary subject matter design problem. While useful, the subject matter disciplinary courses unfortunately can isolate the course subject matter into a contrived design problem. The 2D design challenge is a natural approach to expanding the problem beyond a single course' subject matter yet contains the design problem to materials that the students are versed and complete with instructor support – those courses currently being enrolled.

Wood et al[30] proposed a set of learning objectives for short design experiences of arbitrary scope from individual lectures to individual courses to multidisciplinary courses. We here similarly propose learning objectives for the one week 2D design challenge, against the pedagogical framework of the 2D Design Experience and subject matter courses. The learning objectives of the 2D Design Activity include the following set, as adapted from that proposed by Wood et al[30]:

1. Ideation and concept generation. These outcomes consider divergent thinking and expansive idea generation.
2. Opportunity and needs analysis. These outcomes consider analyzing need and context, to clarify why the problem exists and what the problem is.
3. Quantification of open-ended problems. These outcomes consider on convergent thinking, modeling and analysis, reduction and simplification.
4. Effective resource utilization. These outcomes consider prioritization and trade-offs with limited or unused resources such as schedulable time, finances, or resources.
5. Reflection, observation and hypothesizing. These outcomes consider reflective practice, including personal responsibility and professional growth.

In summary, we seek a one week multi-disciplinary design activity that either motivates or exercises the course subject matters, and also challenges the students on design thinking. Means for student progress against these objectives can all be incorporated into the 2D Design Activity. Doing so increases the active learning effectiveness of the activity.

Literature Review

Others have reported on the need and progress for incorporating design into the engineering curriculum, notably into the traditional engineering courses[6,7,11,25,26,31]. This paper presents a novel implementation approach against these goals.

It is also well established that active learning improves student outcomes as supported here[1,2,3,12,15,19,20,21,24,28]. Wood et al[30] report a survey of global engineering educators indicating 90% seek more active learning in their courses.

Knight[17] reports on the many factors that explain the increased outcomes from active learning compared to traditional lecture and problem set based learning, including that lectures are not conducive to good listening given the inability to actively listen (e.g., repeat back what was spoken), critical thinking is not exercised when following the logical progressive derivation approach of lectures, the human limited attention span of 10-15 minutes, the repeated nature of lecture and course book material, and the focus of most lecture materials on the abstraction phase of learning.

Others also report on efforts to integrate multiple disciplines in the early undergraduate years through small scale projects, similar to that discussed here. Roedel et al.[29] report on a Freshman year effort to integrate calculus, physics and English through projects lasting over 5 weeks. These include a catapult, a Trebuchet, and a bungee drop mechanism. The pedagogical challenge included keeping the project material difficulty aligned over the time period with student material being taught. Beaudoin and Ollis[4] report on efforts to develop short, 3 day design projects on common technical products, including the bar code, photocopier, water purifier and optical fibers. The projects aim to engage and motivate students with individual confidence in the learned materials. Chesler et al.[9] report on an introduction to design course where they make use of virtual epistemic games focused on design trade-offs and client conflict management. In groups of 5, they solve the design projects in 11 hours. Wood et al[30] discuss effective practices in designettes, similar to charettes in architecture studies, or small scale design problems inserted at arbitrary points in the engineering curriculum. Guidelines are presented for effectiveness.

Others also report on effects to use design projects as the basis for learning multidisciplinary engineering. Hussman and Jensen[16] report on using a small autonomous vehicle competition as a motivator for designing a UAV to which several courses provide necessary engineering skills and understanding. Material to contribute to the design of the UAV became an integral aspect of the course subject matter. Gomez-Puente et al[13] provide a literature review of design based learning of engineering subjects, and how reports of such courses relate or not to good professional design practice. Hassan et al[14] (2008) report on a multi-course methodology to coordinate all projects undertaken throughout the undergraduate years to build throughout toward solving industrial problems. The approach here is less ambitious in curriculum coordination and planning structure than these efforts; we rather seek to provide a multidisciplinary experience in the courses offered in the term alone. We find this more practical, requiring more limited coordination of four courses rather than an entire sequence of courses.

The SUTD 2D Design Challenge

In this section we focus on the details of 2D Design Activity carried out during the 3rd Term of the Freshmore year for the SUTD students of the Class of 2015. This activity has been proposed in the form of a design challenge to the entire class (318 students in total). It is worth highlighting that the SUTD Freshmore year is a common core curriculum year for the students of the four undergraduate degree programs offered: Engineering Product Development (EPD), Engineering Systems Design (ESD), Information Systems Technology and Design (ISTD), and

Architecture and Sustainable Design (ASD). These constitute the so called four “pillars” of study at SUTD.

In that framework, our 2D Design Challenge takes place at the pivotal moment when students have to declare their future major, i.e. the pillar of their choice. It is quite clear that running this 2D Design activity at such an early stage in the students’ engineering training presented the team of instructors with clear challenges for developing and selecting a problem:

- Identity a theme cutting across all three engineering science subjects and biology
- Make the activity challenging despite the limited technical grounding of the students
- Ensure that this engineering design project has a certain level of real-life relevance
- Make the project relevant to engineering, hardware, software, and architecture students

Simultaneous with these challenges, we had the pedagogical objectives stated earlier to provide experiential active learning of the subject course materials as well as experiences in design thinking.

The four subject courses in the term included:

- Engineering in the Physical World: a course in thermodynamics, heat transfer, and fluids.
- Introduction to Biology: a course in biology, from biochemistry to ecology.
- The Digital World: a course on circuits, programming and controls.
- The Systems World: a course on matrix equations and optimization.

A design project was sought that simultaneously exercised the subject matter of all four courses.

The design problem developed was called “AutoMilk” and asked the students to develop an autonomous personalized delivery system of perishable milk for the city state of Singapore. The problem statement was to provide proof of concept prototypes for several key aspects of this system. The problem statement included that the Government of Singapore was interested in developed an autonomous unmanned ground vehicle (UGV) transport system for home food delivery, including milk. The system was to be composed of battery powered UGVs operating on dedicated paths throughout the city.

Student teams typically consisted of five members. The teams were highly interactive during the problem solving process. Teams developed a report for each course that highlights the relevant aspect of the multidisciplinary design problem to that course. The same team members worked together throughout the entire project. Teams met during scheduled lecture and recitation periods to work on their projects. There was a high degree of camaraderie, and sharing of test equipment along with other resources between teams.

The students were obviously not asked to deliver a complete system, but rather aspects of the problem directly related to the subject matter courses. The students need to demonstrate three key prototypes:

1) an insulated container for holding milk cartons,
2) the software algorithms to dispatch UGVs on deliveries, and
3) the controls software to move a scaled UGV over a scaled course representing the Singapore city.

In addition, the problem solving process employed by students drew upon theory and practice from design methodology; including systematic brainstorming, and concept selection tools.

Further, however, each of these deliverables could not be completed without integrated multidisciplinary thinking. We find this construction amongst deliverables the key to a successful 2D design challenge. That is, we find it critical to ensure all subject matter courses have a requirement that must be met in the 2D design project, and to meet that requirement the students must minimally make use of material from at least two subject matter courses. This is shown in Figure 3 for the example discussed here.

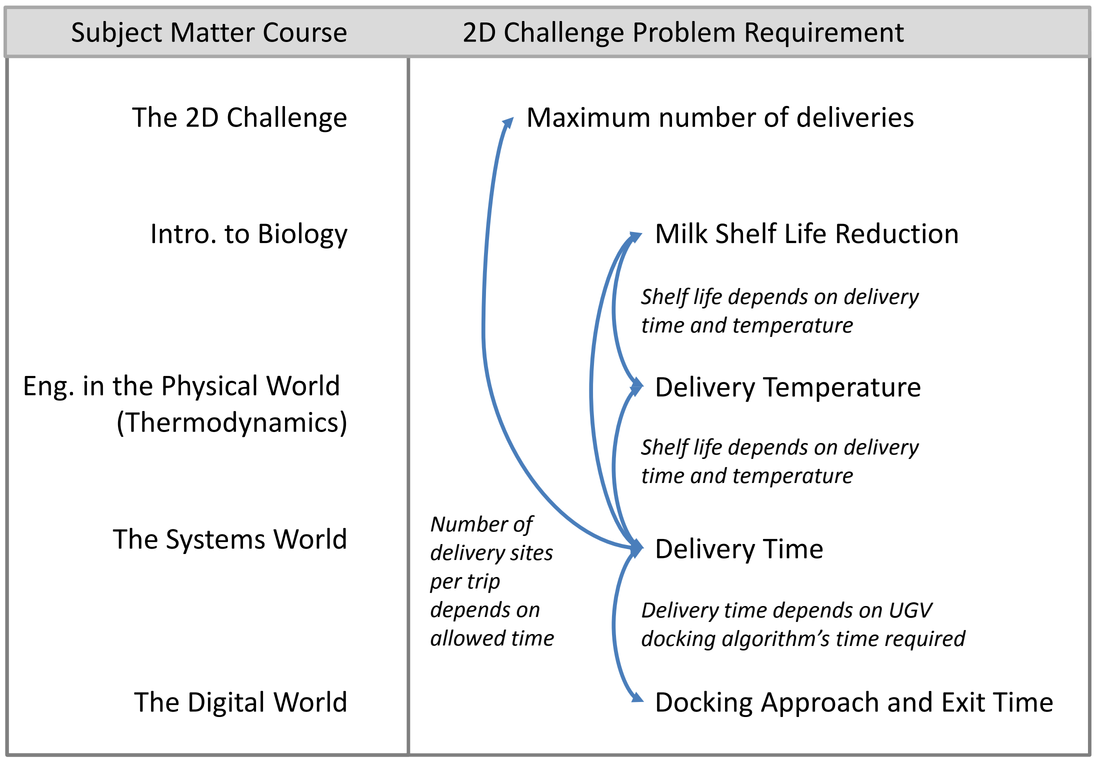


Figure 3: Relation amongst key design requirements of the project compared with the associated subject matter courses. It is critical that each subject matter requirement be codependent amongst at least two courses to ensure multidisciplinary learning.

To complete the first deliverable, one could conceivable isolate this to two subjects, the biology and thermodynamics courses. As shown in Figure 4, the biological shelf life of milk is well established as a function of temperature, with an approximately 2 week shelf life when well refrigerated. This 2 week shelf life period reduces to hours or less at elevated temperature[10]. To make a delivery in an unrefrigerated battery powered UGV, an insulated container must be designed with adequate insulation and/or ice to maintain the milk at a low temperature. This presents a thermodynamics and heat transfer design problem, to size the thermodynamic elements. However, to ensure efficient delivery dispatching, the delivery container must be also sized in terms of the number of cartons of milk per container, to permit multiple delivery sites per UGV delivery trip. Depending on delivery distance, the number of cartons can vary from as low as one for single house delivery to the maximum size of the container.

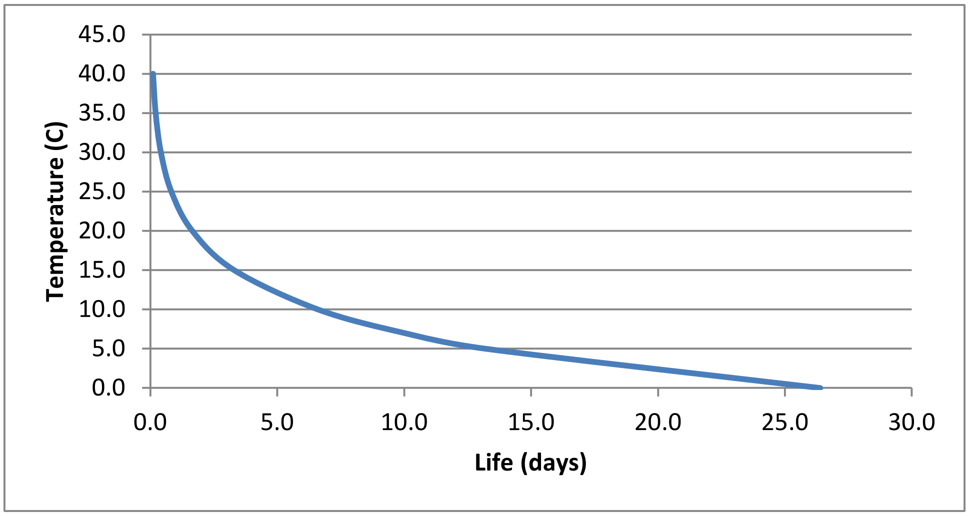


Figure 4: Biological Shelf Life of Milk.

Resolving this is an exercise in problem reduction and analytic engineering thinking. A percentage of the 2 week shelf life lost to the higher temperature delivery must be defined, such as 1% loss. Using Figure 4 this thereby defines a maximum time allowed at any elevated temperature, which is the maximum delivery time at that elevated temperature during delivery. This set of material was discussed before the 2D week in the biology course. Figure 4 was developed, including the underlying mechanisms generating the curve including bacterial growth and protein taste changes underway within the milk as spoilage progresses.

Thermodynamics and heat transfer materials can then be applied by the students to analyze the various thermodynamic design concepts generated. Temperature as a function of time equations can be derived to select and size alternative insulation materials. This set of material was discussed before the 2D week in the thermodynamics course.

From this, a maximum delivery time can be assured for a peak temperature during delivery to ensure a minimal impact of the biological shelf life. Using models and equations, the students developed models to trade-off these quantities as part of the project design process. The resulting maximum delivery time and temperature was required to be demonstrated in a thermal prototype of the student crate design. Examples are shown in Figure 5 from the course.

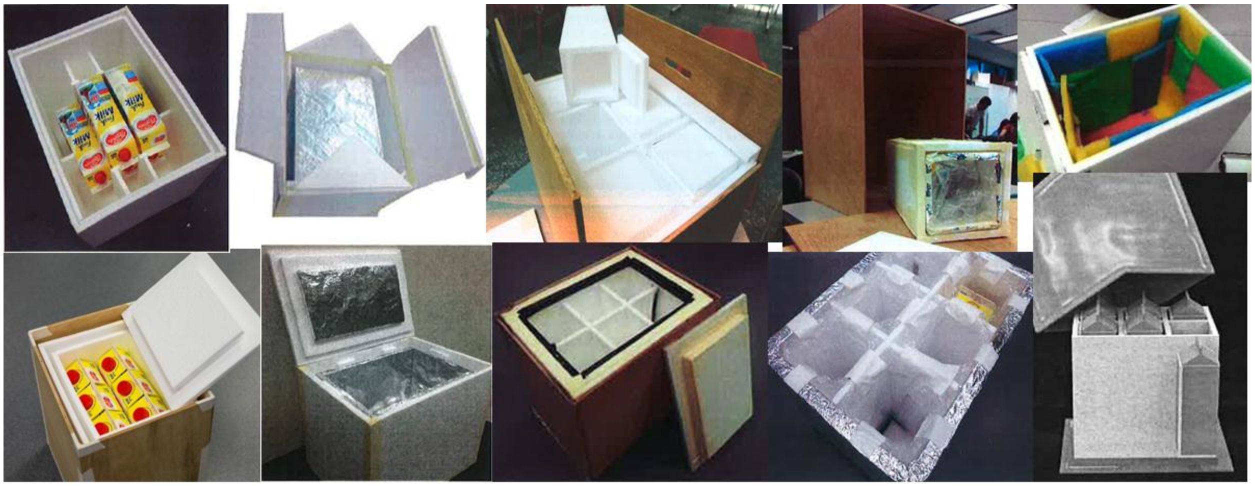


Figure 5: Example thermal crate designs, required to demonstrate adequacy of the insulation material thickness. Note the variety in design concepts against a single thermal insulation requirement.

Given this first deliverable, the next 2D design activity was to develop a set of dispatching algorithms to complete all milk deliveries in minimal time using a minimal number of UGVs. These traveling salesmen optimization problem formulations were discussed in the systems course. Notice, though, the maximum delivery time determined from the thermal crate design has a direct impact on the dispatching problem. Multiple delivery sites cannot be completed by a single UGV if the delivery time becomes excessive, and so multiple individual site deliveries become required. This is another example of the multidisciplinary constitutive problems that students faced in this challenge.

Lastly, demonstration of the UGV guidance control algorithms was the final deliverable of the 2D design activity. This material again had been covered in a subject course, this time in the digital world course. Again, there is a chain of dependency between the delivery time and the efficacy of the UGV controls algorithms developed and how long the UGV take to perform various maneuvers including docking and loading.

Overall, the 2D design challenge problem was constructed to have deliverables that each required simultaneous consideration of material from at least two of the four courses. Providing all of the deliverables therefore required consideration of the materials from all four subject courses, and an approach to structure and sequence the interdependent decisions amongst the deliverables.

2D Outcomes and Assessment

The question exists over how effective 2D challenges are at student learning. It is not clear they are more or less effective than not doing the 2D challenge and instead use the historically applied methods of standard lecture and recitations as a means to train engineers. To scrutinize this, we planned several assessment methods of the 2D challenge approach. First, we planned for the students to complete pre- and post- questionnaires of their perceived knowledge and comfort level at solving engineering problems, including multidisciplinary, disciplinary, and problems outside their discipline. Secondly, we also planned to compare these results with graded outcomes of the 2D challenge project. For each course included in the challenge, the students received a grade for the constitutive aspects of the total challenge related to that course. Within each course, this independently assessed 2D grade contributed to 10% of each total course grade.

2D Outcomes and Assessment: Student Self-Efficacy

For the first assessment to determine efficacy of the 2D design approach, the students we asked (but not required) to complete identical survey questionnaires before and after the one week activity. Likert scale type questions were posed as to comfort level and interest in combined materials from inside and outside the course. This type of assessment approach has been demonstrated and validated for similar applications by various authors[5,8,27].

The first survey question concerned the integration of disciplinary material often considered far from engineering, namely biology. The degree to which the biology subject matter was exercised in an integrated manner with the remaining engineering courses was of particular interest.

> *How comfortable are you solving engineering design problems that ensure biological requirements?*
> *a) They are easier than almost any other design problems.*
> *b) A bit easier than almost any other design problem.*
> *c) Can't say.*
> *d) A bit more difficult than almost any other design problem.*
> *e) Much more difficult than almost any other design problem.*

This question was designed to detect any change in comfort at working with design problems that incorporate both biology and thermodynamics. The students were given such a problem in the 2D week, and so if the students were capable, their comfort level should increase. The results are shown in Figure 6.

Responses		
	PRE	POST
A	7	6
B	25	64
C	94	63
D	29	32
E	10	1
No Answer	52	51

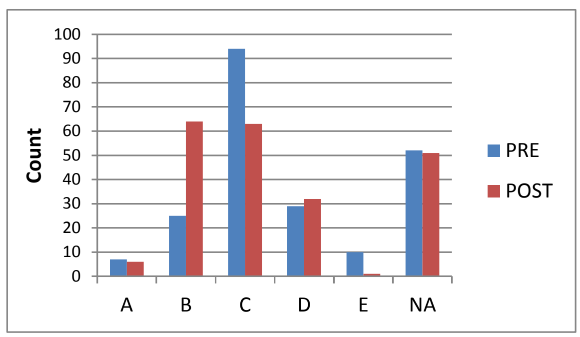


Figure 6: Comfort level differences in solving engineering design problems with biology requirements from 1 week of 2D challenge problem solving, showing a clear shift to higher comfort levels A and B.

The results show a clear shift upward in comfort levels in solving engineering problems with biology requirements. After 1 week of 2D activity, roughly 15% of the class shifted up a level from being unsure to realizing they can solve such multidisciplinary design problems as easily as any other single-discipline engineering design problem. Statistically, a paired t-test analysis for mean shift in the data results in a p-value of 0.0092, indicating a rejection of the null hypothesis of no difference between in mean between the pre and post questionnaire. There was a statistically significant improvement in outcome.

A second question was asked about how effective the students felt the 2D design challenge would be at creating learning of multi-disciplinary design. The question asked was:

How much do you think you will learn (did learn) in this 2D experience on how the course material integrates in real problems?

a) Looks to be very worthwhile on understanding how the 4 courses' material integrates in real problems

b) Looks to be reasonable on understanding how the 4 courses' material integrates in real problems

c) Can't say. Not clear or unclear.

d) Looks to be a stretch to learn how the 4 courses' material integrates in real problems

e) Looks to be a waste of time, and will provide very little understanding how the 4 courses' material integrates in real problems

As asked before and after the 1 week 2D activity, this question was designed to detect any change in perceived learning about solving multidisciplinary design problems. The results are shown in Figure 7.

Responses		
	PRE	POST
A	21	22
B	82	103
C	29	12
D	15	16
E	4	1
No Answer	66	63

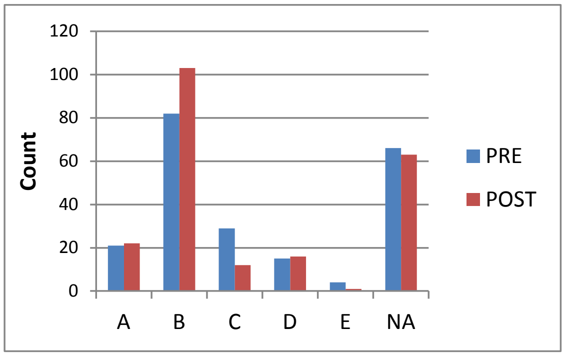


Figure 7: Differences in self-stated ability to solve multi-disciplinary engineering design problems from 1 week of 2D challenge problem solving, showing a clear shift to higher capability levels A and B.

The results show a clear shift upward in how the students felt the 2D challenge exercised multi-disciplinary engineering problems. Roughly 10% of the class shifted a level up from being unsure about the 2D experience to feeling reasonable that the 2D experience helped them learn about solving multi-disciplinary engineering design problems. Statistically, a t-test analysis for mean shift in the data results in a p-value of 0.013, indicating a rejection of the null hypothesis of no difference between in mean between the pre and post questionnaire. There was a statistically significant improvement in perception that the 2D design challenge provided learning on multidisciplinary engineering design.

We also asked the students additional questions as checks on the survey. After one week of 2D, one would not expect a significant change in students' perceived ability to solve 1D engineering problems within the course subject. Questioning this, there was no statistically significant shift in students' perceived ability to solve thermodynamics problems before and after the 2D experience. This is as you would expect. Further, when similarly questioned, there was also no significant shift in students' perception of how much nondisciplinary expertise is needed by engineers in their discipline. This is not surprising and as one would expect, the students are aware of the multidisciplinary need in today's modern world; they had already given this question a high initial rating.

Finally, we also asked if the students will enjoy (pre) or did enjoy (post) the 2D challenge. We observed a statistically significant shift in response, with a t-test p-value result of 9.4e-07. The students significantly changed their minds about the 2D challenge, from 23% of the students expecting a neutral or negative experience before 2D shifting down to 10% at the end of the exercise. There was an associated increase of 5% of the student body who rated the 2D challenge in the highest category and really enjoyed the experience. Overall, the students very much enjoyed the 2D challenge. Forming a one-week multidisciplinary design challenge restricted to the materials from the courses they are currently taking is an effective means to motivate students to learn multi-disciplinary engineering.

2D Outcomes: Grading

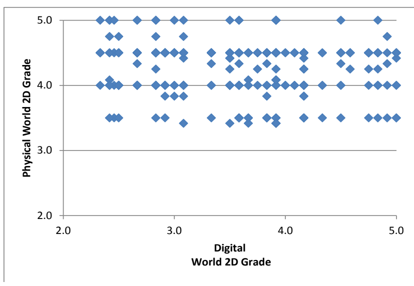
While the survey questionnaires point to students perceptions of learning, a question might be to determine the efficacy of the 2D design approach at solving multidisciplinary problems. 2D was fun, but did they learn anything? This is more difficult to assess, and will likely take a much longer time period to assess reflectively in future years of undergraduate education or even in the first years of working practice. On the other hand, subject matter course grading is perhaps a natural first point of assessment. Students with higher grades on the 2D project presumably can express information about the subject more exactly.

Our grading approach was based on letting the project itself drive multidisciplinary integration, and to complete the 2D project grading in separate tracks. Each course graded their portion of the 2D project in isolation from the other courses, and in isolation from the remainder of the subject matter course grading activities. For example, the biology course evaluated all student understanding of biological processes of milk spoilage, including sugar breakdown, taste change, and bacterial growth levels. This portion of 2D was graded in isolation of the thermodynamics course, which graded the project on the thermodynamics and heat transfer design.

Notice as designed by the instructors, the project naturally allowed for subject matter course grading in isolation from each other course in a natural way using the requirements flow (Figure 3). For example, the biological analysis formed a biological requirement, which then provided constraints on thermodynamic variables, as a shelf life versus temperature equation. The thermodynamics course simply graded the use of this equation to design the thermodynamics and heat transfer properties, without need for much consideration of the biological basis of the equation, and vice versa for the biological course grading.

Unfortunately, it must be reported that this isolated grading approach perhaps proved to not be as effective as had been hoped. Individual course contribution grading to 2D perhaps proved a questionable means of assessing understanding of the integrated, larger context of multidisciplinary engineering. To see this, consider if a student understands the integration of the materials of two courses on a design problem. Then presumably that student must have done well on the project in both courses. Similarly, students who did not understand the integrated context would do poorly. Such a distribution of students would be supported by evidence of correlation among the grades of the independently assessed disciplinary course contributions to the project.

No such correlation was generated among the 2D grades. The 2D project grades from each course bore near zero correlation, as shown in Figure 8. While some students did well in all courses and understood the project, apparently equal numbers of students understood only the project content of one course well and the project content of other courses not all.



r^2	Bio	Sys	DW	PW
Bio	1	0.26	0.00	0.13
Sys		1	0.00	0.18
DW			1	0.01
PW				1

Figure 8: Lack of correlation amongst grading of 2D projects across the different subject matter courses when 2D is graded on individual subject matter content of the 2D experiences.

This grade-based argument logic would then assert the students did not learn multidisciplinary skills. However, that conclusion is in direct conflict with the student self-assessed results and the opinions of the faculty who observed students effectively engaging materials from multiple courses.

Alternatively, another explanation of the lack of grading correlation is the grading does not reflect student understanding of what must be known from the disciplinary course to complete the project. Based on scrutiny of the grading rubrics form each course, this appears the much more likely the case, and reinforces guidance and commentary on methods to grade projects in courses.

The grading for the 2D courses typically followed a grading rubric assigning points for various features of the project deliverables. For the thermodynamics course, a report was required for grading purposes. The report was graded on 7 aspects: objectives, performance requirements, design concepts, concept selection, design sizing equations, prototype build results, and experimental validation. While seemingly logical, these criteria are not strictly necessary for an effective thermodynamic design, and only 1 of 7 points ensure the students understand the biological basis for the design requirement. The grading schemes therefore reflected the individual course objectives (learning thermodynamics) and did not reflect the 2D objective of integrated learning. The 2D grading did not grade multi-disciplinary design; it graded the small disciplinary content of the large multi-disciplinary design problem.

This was confirmed when studying the correlation of the 2D grades assigned in each subject with the overall final grades in each subject. In the systems course, the correlation was 44%, and in the thermodynamics course the correlation was 30%, which is about what one would expect between hands on laboratory grades and overall subject matter grades. When each subject course grades a 2D project alone on the subject matter contribution to 2D, then those grades will not correlate, and do not grade the multidisciplinary nature of the 2D exercise.

In hindsight, this result gave pause to the course instructors on grading. All felt 2D was worthwhile, and all could point to projects demonstrating the students did well understanding integration amongst the courses. The correlation result, however, speaks to the need for individual course instructors to jointly define and grade the projects. Overall, we found that grading integrated multidisciplinary design courses will require more than the standard approach to grading disciplinary materials we applied.

Conclusions

We find the 2D Design Activities a useful approach to introducing students to effective multi-disciplinary engineering problem solving early in the undergraduate curriculum. Beyond single course 1D design problems, it allows more difficult problems to be presented that address issues outside of the scope of a single course. Yet, it is not completely open ended in scope, the design problems must be contained to that within the current enrolled courses.

We find that to for implementation to be successful, the instructors must create a chain of project requirements amongst the course subject matter. Design requirements from all covered courses must be defined such that accurately fulfilling them requires incorporating analysis from at least one other discipline. The requirements must be co-dependent across disciplines.

An example of such a 2D requirement is to develop thermal properties (coolness) such that the biological aspect (freshness) is also met. This was actually one of the challenges for students in approaching the Automilk design problem; students discovered that translating the biological health and safety requirements into a thermodynamic design requirement was difficult. This type of design requirement translation is a very real-world scenario and highlights the criticality of 2D type design projects, as this was also a new type of problem for students.

We also find it useful to contain the activity to a dedicated single week. More than this allotted time generates excess activity away from the disciplinary courses, and creates a design problem that is unnecessarily large against the real need for active learning of technical course subject matter.

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References

1. Aglan, H. and S. Ali, (1996). "Hands-on Experiences: An Integral Part of Engineering Curriculum Reform," *Journal of Engineering Education*, October, pp. 327-330.
2. Barr, R., Schmidt, P., Krueger, T., and C. Twu, (2000). "An Introduction to Engineering Through an Integrated Reverse Engineering and Design Graphics Project," *Journal of Engineering Education*, 89(4):413-418.
3. Bean, J. C. (2001). *Engaging Ideas: The Professor's Guide to Integrating Writing, Critical Thinking, and Active Learning in the Classroom*. San Francisco, CA:Wiley.
4. Beaudoin, D. and D. Ollis,. (1995). "A product and process engineering laboratory for freshmen," *ASEE Journal of Engineering Education*, July, pp. 279-284, Vol. 84, No. 3.
5. Beghetto, R. A., Kaufman, J. C. and J. Baxter, (2011) "Answering the unexpected questions: Exploring the relationship between students' creative self-efficacy and teacher ratings of creativity." *Psychology of Aesthetics, Creativity, and the Arts* 5, Vol. 4: 342.
6. Bilén, S., Devon, R., and G. Okudan, (2002). "Core methods in teaching global product development," *ICEE* 2002, Manchester, 22 August.
7. Blessing, L. (2002). "What is this thing called design research?" *International CIRP Design Seminar*, Hong Kong, 16-18 May.
8. Carberry, A. R., Hee‐Sun Lee, and M. W. Ohland. (2010) "Measuring Engineering Design Self‐Efficacy." *Journal of Engineering Education* 99, Vol. 1 pp. 71-79.
9. Chesler, N., D'Angelo, C., Arastoopour, G., and D. Shaffer, (2011). "Use of Professional Practice Simulation in a First-Year Introduction Engineering Course," *American Society for Engineering Education Conference* (ASEE), Vancouver, BC.
10. Duyvesteyn, W., Shimoni, E. and T.P. Labuza, "Determination of the End of Shelf-life for Milk using Weibull Hazard Method," *LWT - Food Science and Technology*, Vol. 34, Issue 3, May 2001, Pages 143-148.
11. Dym, C., Agogino, A., Eris, O., Frey, D., and L. Leifer, (2005). "Engineering Design Thinking, Teaching, and Learning," *Journal of Engineering Education*, Vol. 94, issue 1, pp. 103-120.
12. Eder, W. E. (1994). "Comparisons – Learning Theories, Design Theory, Science," *Journal of Engineering Education*, April, pp. 111-119.
13. Gomez-Puente, S., van Eijck, M. and W. Jochems (2011), "Towards characterising design-based learning in engineering education: a review of the literature," *European Journal of Engineering Education* 36(2): 137–149.
14. Hassan H., Domínguez, C., Martínez, J, Perles, A., Albaladejo, J. and J. Capella, (2008), "Integrated Multicourse Project-based Learning in Electronic Engineering," *International Journal of Engineering Education*, 24(3):581-591.
15. Holzer, S., Andruet, R. (2000). Experiential Learning in Mechanics with Multimedia, *Int. Journal of Engr. Education*, Vol. 16. No. 5.
16. Hussman S. and D. Jensen (2007), "Crazy Car Race Contest: Multicourse Design Curricula in Embedded System Design," *IEEE Transactions on Education*, 50(1):61-67.
17. Knight, R. (2004). *Five Easy Lessons: Strategies for Successful Physics Teaching*, Addison-Wesley, San Francisco, CA.
18. Kolb, D. (1984) *Experiential learning: Experience as the source of learning and development*. Vol. 1. Englewood Cliffs, NJ: Prentice-Hall.
19. Linsey, J., Cobb, B., Jensen, D., Wood, K., and S. Eways, (2006). "Methodology and Tools for Developing Hands-on Active Learning Activities," *Proceedings of 2006 American Society for Engineering Education Annual Conference*, Chicago, IL.
20. Linsey, J., Talley, A., Jensen, D., Wood, K., Schmidt, K, Kuhr, R., and S. Eways, (2007). "From Tootsie Rolls to Composites: Assessing a Spectrum of Active Learning Activities in Engineering Mechanics," *Proceedings of 2007 American Society for Engineering Education Annual Conference*, Honolulu, HI.
21. Linsey, J., Talley, A., White, C. K., Jensen, D., and K. Wood, (2009). "From Tootsie Rolls to Broken Bones: An Innovative Approach for Active Learning in Mechanics of Materials," *ASEE Journal of Advances in Engineering Education (AEE)*, 2009, Vol. 1, No. 3, pp. 1-23.

22. Magee, C., Pey, K., Chen, J., Luo, J. and D. Frey (2011). Beyond R&D: What Design adds to a Modern Research University, *International Journal of Engineering Education.*
23. Magee, C., Wood, K., Frey, D. and D. Moreno, Advancing Design Research (2013). A "Big-D" Design Perspective, in Proc. ICoRD'13, *International Conference on Research in Design*.
24. Mayer, R. (2002). "Using Illustrations to Promote Constructivist Learning from Science Text," in J. Otero, Leon, J., Graesser, A. and N. Mahwah, eds., *The Psychology of Science Text Comprehension*, pp. 333-356.
25. Otto, K. and K. Wood, (1998). "A Reverse Engineering and Redesign Methodology," *Journal of Research in Engineering Design*, Vol. 10, No. 4, pp. 226-243.
26. Otto, K. and K. Wood, (2001). *Product Design: Techniques in Reverse Engineering, Systematic Design, and New Product Development*, Prentice-Hall, NY.
27. Pajares, Frank. (1996) "Self-efficacy beliefs in academic settings." *Review of educational research* 66, no. 4, pp. 543-578.
28. Prince, M. (2004), "Does Active Learning Work? A Review of the Research," *Journal of Engineering Education*, Vol. 93, No. 3, pp. 223-231.
29. Roedel, R. , Evans, D. Kawski, M., Doak, B. Politano, M., Duerden, S., Green, M., Kelly J. and D. Linder. (1995). "An integrated, project-based, introductory course in calculus, physics, english, and engineering," *Proceedings ASEE/IEEE Frontiers in Education Conference*, Atlanta, GA.
30. Wood K., Rajesh, M., Kaijima, S., Dritsas, S., Frey, D., White, C., Jensen, D. and R. Crawford, (2012), "A Symphony of Designiettes Exploring the Boundaries of Design Thinking in Engineering Education," *ASEE Annual Conference*, San Antonio, AC 2012-4004.
31. Wood, K., Jensen, D., Bezdek, J. and K. Otto, (2001). "Reverse Engineering and Redesign: Courses to Incrementally and Systematically Teach Design," *Journal of Engineering Education*, Vol. 90, No. 3, pp. 363-374.
32. Wood, K., Rajesh, M., Kaijima, S., Dritsas, S., Frey, D., White, C., Jensen, D. and R. Crawford (2012). "A Symphony of Designiettes Exploring The Boundaries of Design Thinking in Engineering Education," in *Proc. ASEE Annual Conference*, San Antonio, TX 10-13 June, AC 2012-4004.