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DESIGNETTES: NEW APPROACHES TO MULTIDISCIPLINARY ENGINEERING DESIGN EDUCATION

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ABSTRACT
Teaching of design and other fundamental topics in engineering is often isolated to dedicated courses. Thus, an opportunity is missed to foster a culture of engineering design and multidisciplinary problem solving throughout the curriculum. Designettes, defined as brief, vignette-like design challenges, exploit opportunities to integrate design learning experiences in class, across courses, across terms, and across disciplines. When courses join together in a designette, a multidisciplinary learning activity occurs, demonstrating how different subjects are integrated and applied to open-ended problems and grand challenges. Designettes help foster a culture of design, and enables the introduction of multidisciplinary design challenges across all core courses in each semester. These challenges combine problem clarification, concept generation and prototyping with subject content from curricula such as biology, thermodynamics, differential equations, and software with controls. This paper investigates the use of single and multidisciplinary designettes at SUTD. From pre- and post-surveys of junior college students, designettes were found to increase students' awareness of applications and learning of content. From 321 third-semester students across six cohorts, designettes were found to increase students' self-perceptions of their ability to solve multidisciplinary problems.

1 INTRODUCTION
Designettes, as originally coined at the Singapore University of Technology and Design (SUTD), use the concept of vignettes or "brief, evocative descriptions, accounts or episodes" to teach engineering design thinking through short-term design experiences [1]. Designettes employ fundamental engineering subject matter in combination with design to provide students with creative pedagogical experiences. Although the movement towards more design-centric and project-based learning approaches in engineering curricula recognizes the motivational and practical potential of design, it typically focuses on the longer-term and iterative aspects of design processes. Conversely, designettes teach modules of design learning objectives in conjunction with other learning objectives and courses such as biology or thermodynamics. This paper introduces a methodology for creating designettes in addition to exploring the success of three unique designettes, with different levels of learning objectives. The designettes reviewed in this paper are based on problems from a broad domain of topics: systems, circuits, robotics, kinematics, biology and thermodynamics. The effects of designettes are evaluated for learning objectives in design, single course topics (1D) or multiple course topics (2D). Designette principles and examples within this paper foster a culture of creativity and design thinking.

Engineering and design are inextricably linked. According to ABET, "Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs" [2]. The ABET accreditation criteria include many skills inherent to design, such as understanding of fundamental principles in a multidisciplinary and global context. Employers and research institutions seek graduates ready to engage in design, open-ended problem solving, communication, team-work, and life-long learning [3]. The aerospace industry considers systems-level understanding and design as fundamental attributes of a good engineering [4].

Although design projects in dedicated capstone and cornerstone courses help meet the learning objectives of engineering as a discipline, integrating the practice of design across the curriculum can enhance teaching of other fundamental engineering principles. Lee *et al.* [5] did a longitudinal study of students in years and curricula with and without design courses and found that time spent on re-formulating a design problem increases in years with design focused content. Klukken *et al.* [6] interviewed practicing engineers who are recognized for creativity by their peers. The interviewees expressed frustration at the lack of open-endedness in each of their courses and a need for problems with multiple possible solutions and solutions paths, as well as more interdisciplinary thinking. Such challenges promote more creativity and better reflect real-world projects and teams [6–9].

Designettes address these needs for understanding of the practice of engineering and approaches to open-ended and multidisciplinary problems. At the Singapore University of Technology and Design (SUTD), a 4-dimensional pedagogy has been conceived, developed and implemented making use of the practice of designettes. The 4D pedagogy employs design challenges at four levels or dimensions: the 1D, single course design activities; the 2D, multiple concurrent course activities; the 3D, multi-year thematic activities; and the 4D, independent and extra-curricular activities. This research presents studies of designettes applied at the 1D and 2D levels through open-houses, outreach, and sophomore curriculum.

At the 1D level, SUTD continually engages students in desktop experiments, designettes, hands-on demonstrations, and collaborative learning activities in each of the courses. These concrete experiences enhance active learning of individual concepts and fundamentals in every course, from humanities to mathematics, physics, and chemistry.

At the 2D level, SUTD engages students in short term, from hours to one-week, design challenges that integrate concepts, coursework, and faculty across their current term courses. During a dedicated week, for example, student teams design their own unique approaches to the 2D challenge while all instructors from the subject matters are available and engaged to guide and facilitate the student teams. This lateral approach fosters a culture of design within the curriculum and enables student success in multidisciplinary problem solving while limiting the scope to current fundamental learning objectives.

At the 3D level, SUTD engages students in concept vignettes and design challenges with themes that continue across all four years of study. These themes reflect important grand challenges that create strong societal and global impacts. Specific 3D strategies are still being developed as the first class of students has only reached its third year.

At the 4D level, students at SUTD participate in extracurricular design activities with faculty, other students, clubs, and industry during the term and in between terms during the independent activities period (IAP). For example, SUTD students designed and constructed the 2012 and 2013 Chinese New Years decorations for Chinatown in Singapore as an extracurricular activity. These decorations incorporate architectural, artistic, cultural, electrical and mechanical elements with the community and its leaders as customers.

The following sections introduce the pedagogical theory and method for creating designettes and present results of designettes used at outreach events and in the classroom. Section 2 reviews the pedagogical theories and state-of-the-art in short-term design education and multidisciplinary learning. Section 3 presents a structured method for creating a well-scoped designette that addresses Kolb's learning cycle. Section 4 presents the research approach to measuring the learning results of designettes. Finally, Section 5 presents the results for three designettes carried out at SUTD. Results from each of the designettes reveal learning of engineering design through practice and artifact generation. By comparing several activities, it can be seen that designettes are flexible and remain effective across domains. A biologically inspired robot, or MechAnimal, designette embodies design learning objectives at the 1D level. Additionally, a 1D interactive music designette embodies design learning objectives and fundamental electromechanical principles such as electrical resistance. Then, a milk delivery designette embodies multidisciplinary problem solving at the 2D level. These examples and outcomes demonstrate the efficacy of 1 hour to 1 week long designettes for engaging and motivating students while teaching design, fundamental concepts, and multidisciplinary problem solving.

2 LEARNING THEORIES AND STATE-OF-THE-ART

Bloom's learning taxonomy posits that creative experiences unlock the highest level of learning and that memorization and understanding of less far-field problems are not pre-requisites for creative understanding. Related research indicates that such active learning experiences help students take ownership of the learning experience. This section reviews the fundamental motivations for designettes grounded in Bloom's taxonomy and findings from previous studies of active learning. Additionally, inspiring examples of design experiences internationally are presented.

2.1 Bloom's revised taxonomy

Bloom's revised taxonomy describes multiple levels of learning, all of which are important, but designettes are one of the few techniques for achieving creative learning, the highest of these levels. Bloom's taxonomy is a multi-tiered model of classifying thinking according to six cognitive levels of complexity: *remembering* information, *understanding* concepts, *applying* concepts in familiar situations, *analyzing* information, *evaluating* hypotheses, and *creating* new ideas. [10–12]. In general, a higher level corresponds to a more advanced or mature learning process and engages in a cyclic learning pattern with the other levels of learning [13].

Designettes benefit students by engaging them in a cycle that advances from a stage of merely acquiring information to more advanced stages in which they learn to analyze information and ultimately to synthesize information and apply what they have learned in different situations. As found in prior work [14], introducing fundamental concepts is essential to enabling higher levels of learning. Introducing designettes as part of current fundamental curricula further enables this cycle by reducing the time between practicing memorization and application, as in lecture and homework, and practicing creativity, as in a designette. These benefits are in addition to the motivational and learning improvements found in using other active learning techniques.

2.2 Active Learning

Active learning improves students' overall learning by transferring responsibility to the student while the instructor acts as a guide. Active learning or interactive engagement does not comprise a single approach, but many approaches may be executed through a variety of modes and media. Exemplar delivery modes supported by research include experimentation [15], cooperative groups [16,17], Socratic dialogue inducing labs [18,19], interactive demonstrations [20], peer instruction [21], think/pair/share [22], jeopardy-type problems [23], tutorials [24,25], and hands-on activities [26–28]. Designettes satisfy the requirements of active learning by handing the responsibility of creation and design to the students, either as individuals or teams, at the level of problem exploration, participatory design, concept and prototyping.

By extensively reviewing the current research, Prince [29] finds that incorporation of active learning, such as designettes, into the classroom increases student performance, including understanding and retention of content. Student motivation is simultaneously enhanced through active learning [15,22,23,30,31]. In the freshman cornerstone design course at the University of Maryland, student appreciation for learning fundamentals was enhanced through integration of "anchor lectures" on fundamental topics [14]. At North Carolina State University, a longitudinal study of an experimental and control group of students found that the use of active learning in chemical engineering curricula increased retention and graduation rates and reduced anxiety about professional prospects [32]. A survey by Hake [33] of pre- and post- test data found that the use of active learning in introductory physics courses significantly increased conceptual understanding and problem solving in comparison with more traditional lecture formats. Active, hands-on learning was also found to increase scores on quizzes and exams in trials at the University of Texas at Austin and the U.S. Air Force Academy [26–28,34,35].

2.2 State-of-the-Art

Many faculty report on efforts to integrate multiple disciplines through design and small scale projects, similar to the designettes discussed here. The pedagogical opportunities within designettes are multidisciplinary, and three aspects of that are described in this paper: design, single subject, and integrated subject learning.

At a similar 1D and 2D level, Roedel *et al.* detail small-scale projects of four to five weeks used at Arizona State University to integrate calculus, physics and English topics in the freshman year [36]. The projects include a catapult, a trebuchet, and a bungee drop mechanism designed to demonstrate the relationship between all four disciplines [36]. Beaudoin and Ollis [37] employ three-day design projects wherein students play the roles of user, assembler and engineer in series as they explore every day engineering products, including a bar coder, photocopier, water purifier and optical fibers. Learning objectives of the course include a sense of student responsibility and involvement as an engineer. Chesler *et al.* [38] use "computer-based professional practice simulator" to teach management of trade-offs and client conflict in re-design and design selection processes. Students are able to solve the next-generation dialyzer problem in 11 hours. Wood, *et al*. [39–42] utilize reverse engineering, dissection, and every day systems and products to explore design methods, variant design, and adaptive design.

Aikens *et al.* [43] have created an extensive, 40 hour guitar design workshop that teaches topics from Physics (wave motion, magnetics, frequencies), Chemistry (finishes), CNC, Laser, Electronics, Woodworking, Tool usage (power and hand), Design, analysis (CG), material properties, Ergonomics, Geometry, algebra, logarithms, and calculus. It is administered by faculty from over six colleges and universities with workshops around the United States. Additionally, Hussman and Jensen [44] report favorable design improvement from incorporating international design competitions, specifically an autonomous race-car competition, into the undergraduate curriculum. Although the competition was initially appended to the yearly curriculum, it has become an integral motivator for learning content throughout the year.

3 DESIGNETTES APPROACH

In this section, a general framework for developing designettes is introduced. While some of these examples report on the process of developing a particular design-based or project-based learning exercise, none of these efforts include a generalized approach to creating designettes. Contemporary design processes may be employed to design and develop designette concepts [45–48]. Figure 1 provides the suggested flowchart for designette development. It is the experience of the authors, that creation of a designette requires a series of steps, and must be carefully designed and tested to be successful. For example, the designettes studied in this research required 2-5 iterations before being implemented in courses and open-houses.

This methodology begins with clear definitions of the learning objectives, outcomes, and desired mindset and skill set exercised during the designette activity. Table 1 illustrates the different parameters to be selected and chosen as well as possible components that can embody a designette. In the case of learning objectives, these can be at the 1D, single course level or including multiple course topics from 2D, concurrent courses or 3D across terms. Skill sets can be within the realms of system processes, technologies, and experimentation.

Based on these learning objectives and expected outcomes, a set of possible prototyping tools are chosen for experiencing the designette. The design and prototyping activities can be limited to creating variants of a pre-existing design, adapting designs and technologies, or creating more original or disruptive designs. The type of design will lend itself to prototyping within a virtual realm, including programming, CAD, or simulation, or the physical realm, including cardboard structures to electronic circuits, or the paper realm, including sketching. Foster *et al.*[49] proposed a method for creating software-based, computational design modules to integrate design across the curriculum. The use of software tools has been found to reduce the time required for the iterative nature of design, especially in more complex design problems. Such tools can comprise a portion of designettes, as in the use of spreadsheets or statistical packages for teaching design of experiments.

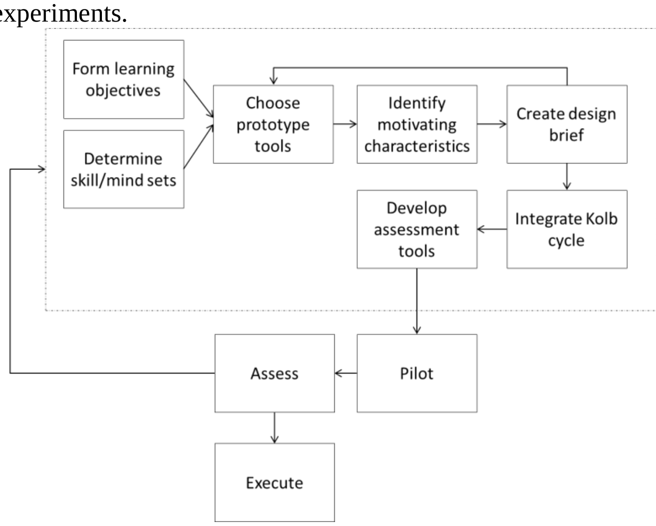

Figure 1: Flowchart for Designette Development

Once the learning objective and viable hands-on tools are scoped, possible motivational characteristics can be identified to create the design brief. The design brief is the problem statement and design goals that the student solves through creative design. Research by Linnerud and Mocko [50] indicates that the goal of an elegant design itself is a strong motivator for creating innovative design solutions. Nevertheless, engagement of the students is also strongly motivated by topics and applications of technology, specifically humanitarian needs-based design [51]. Motivational characteristics used in this work include needs-based motivation through rescuing hurricane victims and expressive cultural and play interests through musical instruments. In conjunction with the scoping of tools and motivational characteristics, the process of ideating and designing the designette brief is necessarily iterative as the prototyping method, design brief, and motivational characteristics of the designette cannot be decided in isolation.

After creating the design brief, the structure of the designette will generally include four parts that correspond to aspects of the design process (exploring the problem, generating concepts, prototyping concepts, and evaluating concepts.) Each task can be performed individually, as teams or in some combination. Table 1 includes a few suggestions for tasks and relates these to Kolb's learning cycle phases in the footnotes. The types of activities that can be implemented, such as interactive discussions, presentation, or video, to achieve each portion of the learning experience are reviewed by literature on Kolb's learning cycle [52]. It is recommended that these different types of learning be interspersed throughout the designette. For example, opportunities for reflection occur after learning, before ideation, and during and after prototyping.

Kolb's learning model [52] describes the cycle of learning experiences in four stages and provides the foundation for learning in designettes. The four stages do not necessarily begin at any particular stage, but are generally ordered as follows: *concrete experience*, *reflective observation*, *abstract conceptualization* and *active experimentation*.

Table 1: Parameter Choices for Designettes

	Explore subject - 1D - 2D - 3D	**Explore concept** - Process - Technology - Experiment - System	
Prototype at low-cost/time - Physical - Virtual - Paper	**Design** - Variant - Adaptive - Original - Disruptive	**Motivate** - Needs-based - Toy -Self-expression	
Introduce fundamentals - Lecture[3] - Demo[1] - Podcasts[1] - Reading[1]	**Plan concepts** - Discussion[2] - Ideation[2] - Questioning[2]	**Evaluate concepts** - Building[3,4] - Role Play[4] - Simlation[4]	**Reflect on design** - Discussion[2] - Critique[2] - Journal[2]

Kolb's Learning Cycle
1. Concrete Experience
2. Reflective observation
3. Abstract conceptualization
4. Active experimentation

To engage an active learning progression, the Kolb model generally starts with a *concrete experience* or task in the subject matter. Such experiences range from readings and problem sets to motivational films. After such an experience, a *reflective observation* of that experience engages the student in taking a time out to think, ask questions, and verbalize. Following reflection is the main pedagogical mode of coursework, *abstract conceptualization* of theory and principles to provide comparisons and deeper understanding. Finally, students engage in an *active experimentation* stage to practice and apply their new knowledge. All or some of these stages can occur during a designette, and many of these may overlap. In this context, each of the learning objectives may be experienced differently. Examples of types of teaching activities and their corresponding Kolb learning stages are given in Table 1.

Once a full procedure of the designette is created, assessment and evaluation instruments can be constructed. Options include pre- and post- testing, verbal examinations, presentations, competitions, and other forms. The assessment should include the relevant learning objectives for engineering design and any other subjects required for the designette.

After the designette and assessment tools are designed, they are then tested in a pilot instruction environment and iteratively improved for deployment in the classroom or other environment. Testing is a best practice for any pedagogical activity, but is essential for the development of a designette. As the variety of solutions or possible creations increases, the probability of unexpected results increases. As in the design of products, software, services, processes, and integrated systems, testing plays a key role in understanding and evolving a user-centered designette. Without appropriate testing, the potential of a designette may not be realized. In fact, a designette idea may fail, before it has an opportunity to succeed.

4 RESEARCH APPROACH

This research represents the findings from three years of designettes experience at SUTD in developing the 4D pedagogy. The subject of study includes three designettes created for open-house and recruitment activities as well as the 2D design challenges within the freshman and sophomore curriculum. The research reported here seeks to describe the success of designettes for teaching design, single-course material, and integrated material. The evidence of these learning objectives takes four forms: post-surveys, paired pre- and post-surveys, paired pre- and post-concept quizzes, and the artifacts created during the designettes.

Each survey seeks to determine efficacy of the 1D and 2D designettes. In the case of pre- and post-surveys and pre- and post-quizzes, the students were asked (but not required) to complete identical questionnaires before and after the activity. For the surveys, Likert scale responses were used to indicate comfort level and interest in single, and multidisciplinary material from the designette. This type of assessment approach has been demonstrated and validated for similar applications by various authors [53–55].

The designettes studied include a MechAnimal robot, interactive music, and autonomous milk delivery system. In the MechAnimal designette, 136 attendees of an open-house, aged 11-62 years old, used animal analogies to sketch, evaluate and prototype concepts for robots to rescue hurricane victims. The MechAnimal robot designette provides numerous artifacts exemplifying how designettes achieve design learning objectives, such as sketching and prototyping, as well as a post-survey of the participants' capabilities designing independently and as a team following the activity.

In the interactive musical circuit designette, 34 students at a junior college designed speakers and a variable resistance circuit to produce sounds through those speakers. The interactive music designette included both post-surveys and paired pre- and post-concept quizzes. The quizzes provide evidence of learning basic electro-magnetic and circuit design concepts. The surveys provide evidence of the same design learning objectives as the MechAnimal designette. The surveys additionally query about learning objectives regarding Lorentz force law and the application of physics principles.

Finally, the milk delivery designette was a 2D exercise undertaken by sophomore students at SUTD. This designette integrated biology, thermodynamics, differential equations, and software with controls by challenging students to design an insulated shipping container for milk to prevent spoilage as well as the algorithm and software for delivering the milk. Paired pre- and post-surveys and the artifacts created demonstrate that not only did students engage in and learn design phases of concept generation, prototyping and evaluation but students also gained understanding of how to integrate and apply disciplines such as thermodynamics and biology.

These studies and examples of designettes provide evidence that designettes teach design in concert with single and multidisciplinary learning objectives. The following section presents each designette and the results in more detail.

5 DESIGNETTE RESULTS AND DISCUSSION

The results were collected during three different designettes carried out at SUTD. This section is organized by three levels of learning objectives: design learning objectives, 1D learning objectives, and 2D learning objectives. These levels of learning objectives are introduced alongside results for a specific designette. Beginning with solely design learning objectives at the 1D level, the MechAnimal designette and results are introduced. Then, 1D learning objectives that include electronics are introduced using the interactive music designette. The design learning objectives of the interactive music designette are addressed as well. Finally, the potential of 2D learning objectives are discussed through introduction of the auto-milk designette results.

5.1 Design Learning Objectives: MechAnimal

The needs-based MechAnimal designette presented a design challenge focused on using ideation, concept selection, prototyping, and testing for a robotics application. The results in this subsection come from 136 participants between the ages of 11 and 62 years old at open house sessions for potential applicants and visiting students and parents. The design brief read as follows: **"**In natural disasters, there is a need for automatic devices to provide sensing, reconnaissance, and search capabilities. You are tasked with creating a novel automated system to enter a disaster site and provide these capabilities. Your analogy is an animal, insect, or other life-form from nature..."

Students then selected one or more living creatures to use as an analogy while sketching ideas individually over a ten minute period. They were given tasks to identify major components of a robotic rescue device, such as actuators, sensors and support structures, while thinking about the algorithm for controlling their mechanical robot. Then, students joined their teams to evaluate and select a concept during a five minute period. As a reflective experience, the teams were tasked with presenting this concept to the entire section of participants. After reflection, teams were given ten minutes to choose and prototype a subsystem of their MechAnimal, such as a leg or other moving part, shown in Figure 2. Finally students had an additional ten minutes for testing this prototype. The designette took a total of one and a half hours.

As the students were not graded, the central evidence of learning design lies in the sketches and prototypes created during the brief session. Students encountered some basic principles of control systems, mechatronics, robotics, kinematics, and biologically inspired design within the practical environment of constructing a system that incorporates these aspects. Figure 2 shows students successfully constructing components of their concepts, while Figure 3 shows a sketch of an exemplar scorpion-inspired MechAnimal. Evident in Figure 3 is the students' application of mechanical and electrical components to their system, successfully labeling drills, batteries, sensors, and actuators with the associated functional parts of the animal inspiration.

Figure 2: Students Prototyping MechAnimal Concepts

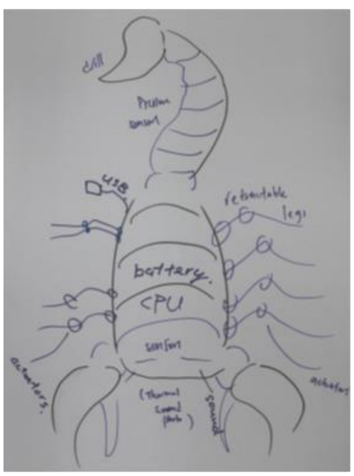

Figure 3: Sketch from the MechAnimal activity shows ability to identify components, exercise creativity and employ biological inspiration

Over 140 sketches revealed over 40 different types of animal inspirations, ranging from monkeys to unicorns and even popular cartoon characters. All sketches included the types of components required, including creative additions such as oxygen and food supply storage and power tools.

Participants of the MechAnimal activity were also provided with a post-survey to quantify their perceived learning and comfort in design after the designette. Shown in Table 2, the respondents indicated a strong sense of achievement from engaging in the designette. This indicates that they took the design process seriously, and felt that they were successful in addressing the design brief. Furthermore, participants felt that the MechAnimal activity allowed them to pursue their own learning. This result indicates that active learning, in which the participants take increased ownership of the material, took place. The bulk of this material focused on the process of sketching, selecting and prototyping novel concepts.

Table 2: MechAnimal post-survey results indicate learning of design, 136 respondents

	MechAnimal Survey Questions	Number of Responses					Average Rating
		Strongly Disagree 1	2	Neutral 3	4	Strongly Agree 5	95% CI
Q1	I have a sense of achievement from the rapid learning experience offered by the designiette	0	2	28	69	37	4.0 ± 0.67
Q2	The ways in which I was taught in the designiette provided me with opportunities to pursue my own learning	0	3	24	66	43	4.1 ± 0.69
Q3	The designiette experience enabled me to quickly connect and build relationship with fellow team members	0	7	29	66	34	3.9 ± 0.68
Q4	The designiette experience increased my interest in SUTD and its design centered technology curriculum	1	0	19	49	67	4.3 ± 0.78

Additionally, the designette required teamwork with a group of individuals who were generally strangers. The participants found that the designette, which involved both individual brainstorming and teamwork, allows them to connect and build relationships with other open house attendees.

Finally, the real test of if the open house attendees achieved a greater understanding and appreciation of design from the MechAnimal designette is their increase in interest in the SUTD design centered curriculum. The respondents overwhelmingly indicated that the designette increased their already present interest in SUTD, averaging a response of 4.3 out of 5 with a 95% confidence interval of 0.78.

As apparent from the mean responses of all 136 respondents, there is significant evidence that designettes: (1) increase students ability to engage successfully in design, e.g. Q1 (2) foster cooperative team problem solving skills, e.g. Q3; and (3) increase interest in learning more about design e.g. Q4. In combination the artifact evidence of over 140 sketches labeled with mechanical components over a diverse set of solutions, the MechAnimal designette succeeded in engaging students in a brief, yet powerful design learning experience.

5.2 1D Learning Objectives: Interactive Music

The interactive music circuit designette introduced the concepts of electro-magnetic force, electrical resistance, frequency, and basic circuit construction with a breadboard. Students received mostly completed circuits, completed the circuits, built a speaker, and drew a variable resistive element using conductive ink. After an interactive introduction to Lorentz force, resistance, frequency, and basic circuit elements, and the definitions of sound, students were given time to use their ink drawings to create a musical instrument on paper. By varying the points of connection between their drawings and the circuit, students varied the length of the connection, and thereby resistance and pitch from the speakers within their circuits. Students were provided with not only resistance to frequency mappings for designing their electronic instruments, but also the fundamental equations for creating their own mappings and understand the effect of widening and lengthening their ink paths. This designette took a total of two hours, with one hour for the speaker and one hour for the interactive musical circuit.

Table 3: Interactive music post-survey indicates learning, 34 respondents

	Interactive Music Circuit Survey Questions	Number of Responses: Disagree 1	2	Neutral 3	4	Agree 5	Average Rating 95% CI
Q1	I have a sense of achievement from the rapid learning experience offered by the designiette.	0	1	3	15	15	4.3 ± 0.71
Q2	The designiette provided me with opportunities to pursue learning as an individual.	0	0	2	19	13	4.3 ± 0.64
Q3	The designiette developed my understanding of concepts better than a traditional class would have.	0	0	5	11	18	4.4 ± 0.79
Q4	The designiette has developed my understanding on Lorentz force law.	1	3	16	7	7	3.5 ± 0.84
Q5	I have managed to link Physics with real life applications through the designiette	1	0	5	15	13	4.1 ± 0.75

Participants included 34 junior college students from local Singaporean schools in the range of 16-20 years old. The survey results of the designette are shown in Table 3. Question one of this survey asks students to evaluate their "sense of achievement" or how successful they were during the design process. The average rating for this question was 4.3 out of 5 with a 95% confidence interval of 0.71. This result shows that the students were satisfied with their creative endeavors and felt successful engaging in design. Furthermore, the students felt that the designette allowed them to pursue individual active learning, with a response of 4.3 ± 0.64. The students also preferred the designette to their traditional class activities.

Table 4: Musical circuit quiz results improved, 34 responses

Question	Answers	Pre- Responses	% Total	Post- Responses	% Total
What happens to a point charge (such as an electron) when it passes through a perpendicularly applied magnetic field?	It continues unaffected	0	0%	0	0%
	Increases speed	4	12%	4	12%
	Slows down	2	6%	2	6%
	Stops	0	0%	0	0%
	Deflects to one direction	**28**	**82%**	**28**	**82%**
Music 'pitch can be measured in…	**Hertz**	**26**	**76%**	**34**	**100%**
	Joules	0	0%	0	0%
	Seconds	0	0%	0	0%
	Ohms	0	0%	0	0%
	Decibels	8	24%	0	0%
Which wire shape offers the least resistance?	Short-thin	8	24%	1	3%
	Long-thin	2	6%	0	0%
	Short-wide	**24**	**71%**	**33**	**97%**
	Long-wide	0	0%	0	0%
	All the same	0	0%	0	0%
Change in the pitch of a musical note can be achieved by tuning the wire's…	**Length**	**5**	**15%**	**13**	**38%**
	Tension	12	35%	3	9%
	Density	1	3%	1	3%
	All of the above	**16**	**47%**	**16**	**47%**
	None of the above	0	0%	1	3%
The higher the frequency of the waveform, the pitch of the sound you hear becomes…	Lower	2	6%	1	3%
	Higher	**30**	**88%**	**33**	**97%**
	Unaffected	2	6%	0	0%
	Zero	0	0%	0	0%
	Infinite	0	0%	0	0%
Sound waves are different from light waves because…	Can be measured with frequencies	3	9%	0	0%
	Has amplitude	1	3%	0	0%
	Does not require energy	0	0%	0	0%
	Requires a medium	**30**	**88%**	**34**	**100%**
	All of the above	0	0%	0	0%

For the 1D content learning objectives, the students indicated that the designette increased their understanding of real world physics applications. This response speaks to the motivational aspects of designettes placing theory into context. A specific learning objective in the post-survey was Lorentz force law, introduced through lecture and building the speakers. The design of the speakers included selecting the number of wire coils to create the vibration of the magnet in their speakers. While 40% of students felt that they increased their understanding of Lorentz force law, the general response to this learning objective was neutral.

Considering the pre- and post-quiz results, it appears that students already possessed some understanding of Lorentz force law before the designette. Shown in Table 4, 82% of the pre-quizzes selected the correct answer for the Lorentz force concept question. This indicates that while only 18% of the students were unfamiliar with the concept of electromagnetic forces, 40% found the designette to increase their understanding.

The additional results in Table 4 show improved learning for a number of concepts taught in the circuit designette. Most notably, 100% of students learned the correct metric for pitch with a statistically significant increase from the pre-test. A student t-test yielded a *p-value* of 0.003 for this second quiz question. All but one student learned the relationship between a wire's length, width and resistance with a statistically significant *p-value* of 0.0059 for question three. The enforcing relationship between pitch and frequency in question five, and difference between sound waves and light waves also show significant increases with *p-values* of 0.04 and 0.02, respectively. The students exhibited a modest understanding of these concepts before the designette and a stronger grasp after completing the design of their instruments.

The fourth question of the quiz was phrased confusingly and had two correct answers, but yielded the important observation that learning strongly reflects the creative parameters of the design activity. One third of students responded that tuning a wire's tension is the only way to change the pitch of a musical note. This answer is partially correct for acoustic vibration of a guitar wire, but density and length of guitar wires are also important. 47% of students selected the correct answer, reflecting an understanding of either acoustic or electrical properties of wires. After engaging in the activity, many of the students changed their response to length, reflecting a now electrical understanding of the question and the design activity modifying length and width of their conductive ink drawings. Nevertheless, a split similar to the pre-quiz occurred with 85% of students answering the correct or partially correct response. While tension is not correct for an electrical system, density is still important. Eleven out of 12 students who selected tension in the pre-test changed to the correct answer (all of the above OR length). Six of the students who answered "all of the above" during the pre-quiz switched to "length" in the post-quiz. Therefore, the results are likely a mix of the influence of the designette and interpretation of the question as referring to electrical or acoustic wires. Nevertheless, the designette had a clear impact on the learning and understanding of the concept.

5.2 2D Learning Objectives: AutoMilk

While the previous two designettes were created for open-house and recruitment activities, the 2D "AutoMilk" autonomous milk delivery designette was developed for the 3rd Term of the freshmore (freshman and sophomore) year for the SUTD students of the Class of 2015. This designette had to integrate the current term courses and remain relevant to both engineering and architecture, as the students' majors were still undeclared. The pedagogical objectives of the four subject courses in the term included: Engineering in the Physical World**,** a course in thermodynamics, heat transfer, and fluids. Introduction to Biology. The Digital World, a course on circuits, programming and controls. And, The Systems World, a course on matrix equations and optimization.

The 2D designette developed to meet these course topics was called "AutoMilk" and challenged students to develop, in teams of 4-5, an autonomous personalized delivery system of perishable milk for Singapore. Teams were given regularly scheduled lecture and recitation periods to work on their projects. The deliverables included reports for each course and a proof of concept in three prototypes for an autonomous unmanned ground vehicle (UGV) transport system that delivers milk. This proof of concept included:

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.

Integration was achieved by creating one design requirement per course and ensuring that each requirement nominally combines material from at least two subject matter courses. No deliverable could be completed without integrated multidisciplinary thinking, and each deliverable drew upon theory and practice from design methodology, including systematic brainstorming, and concept selection tools.

For the insulated carton deliverable, students had to employ principles from both thermodynamics and biology. The biological shelf life of milk is well established as a function of temperature, with a shelf life of less than a few hours when unrefrigerated [56]. Students sized their insulated containers to meet delivery volume requirements and simultaneously maintain shelf life. Students had to determine the number of cartons to ship and the remaining shelf life after shipment using their understanding of bacterial growth rate curves and protein taste changes taught in their biology course. In their thermodynamics course, students also learned the heat transfer concepts required to select and size insulation materials.

For the set of dispatching algorithms, students tackled a traveling salesman optimization problem. Such problems were introduced in their systems engineering course, but the delivery time constraints were derived from the thermodynamics and biology course material.

Lastly, the UGV guidance control algorithms were introduced in the students' 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.

The pre- and post-surveys administered to the students aimed to evaluate the effectives of deliverables that required simultaneous consideration of material from at least two of the four courses. One learning objective of interest was the level to which a designette can teach integration and contextualize natural sciences, such as biology, with engineering courses. The first survey question, shown with results in Figure 4, was designed to detect any change in comfort at working with engineering design problems that incorporate biology. In this case, the 2D designette combined thermodynamics and biology to place constraints on the engineered systems design.

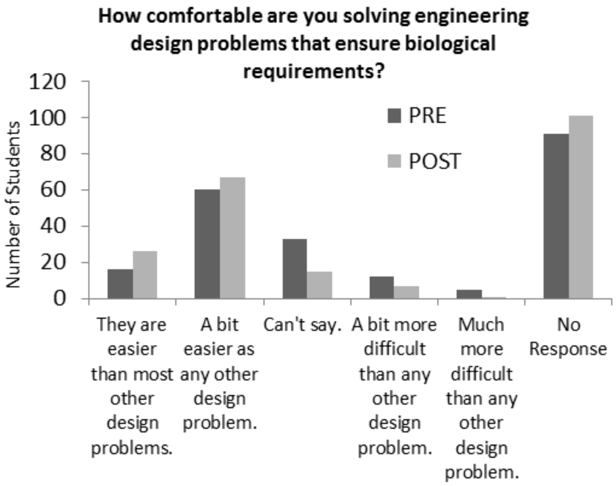

Figure 4: Student comfort in applying biology to engineering design problems increased

The student responses reflect a statistically significant increase in the level of comfort in solving engineering problems with requirements from biology. Approximately 15% of the class shifted from responding that biology increases the difficulty or responding that they are unsure to responding that such problems can be easy to solve. 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.

A second pre- and post- survey question asked students how effective the 2D design challenge would be (was) at teaching multidisciplinary design. This question, shown in Figure 5, was designed to detect any change in perceived learning about solving multidisciplinary design problems.

The results also show a statistically significant increase in perceived learning after experiencing the 2D multidisciplinary engineering designette. Approximately 10% of the class shifted from being unsure (or very negative) to feeling that the 2D designette increased their understanding of multidisciplinary engineering design problems. 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 the pre- and post-survey.

The 2D designette was successful at teaching multidisciplinary engineering concepts. The survey also questioned students on their understanding of 1D, single subject engineering problems. After one week of a 2D designette within a semester long course, a significant change in perceived ability to solve 1D engineering problems was not expected. The results did not provide a statistically significant shift in students' perceived ability to solve thermodynamics problems before and after the 2D experience. Further, students initially rated multidisciplinary knowledge as important in their planned disciplines, and the designette did not result in a significant change of this understanding of engineering and architecture practice. The students seem to be aware of the multidisciplinary need in today's modern world and were able to learn and practice design of such solutions through the 2D designette experience.

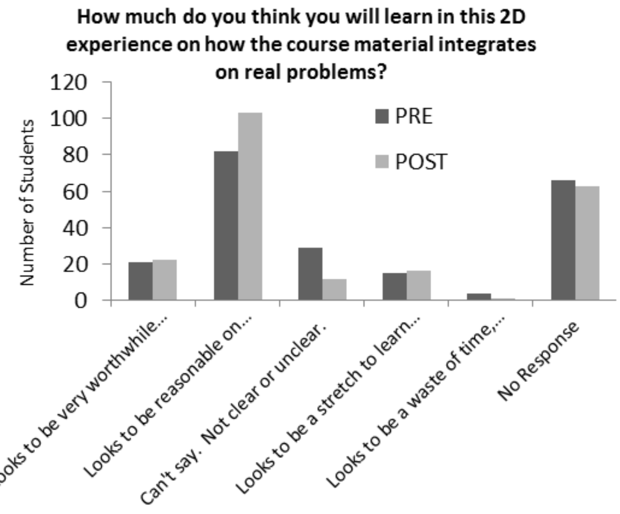

Figure 5: Students understanding of solving multidisciplinary problems increase.

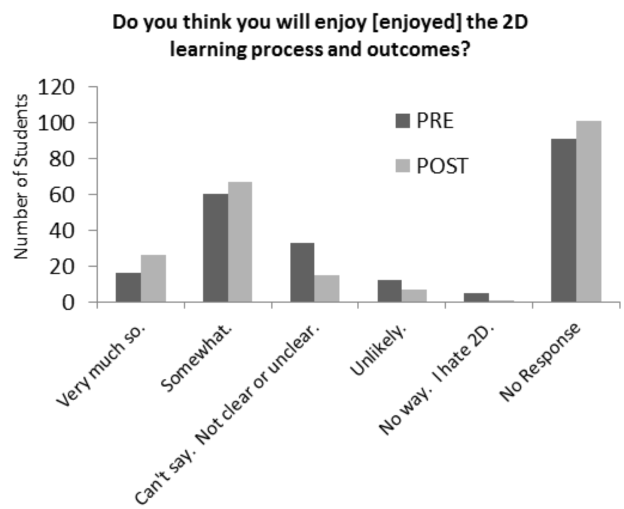

Figure 6: Students enjoyed the multidisciplinary designette

Finally, students were asked if they thought they would enjoy (pre) and did enjoy (post) the 2D challenge as shown in Figure 6. Initially, 23% of the students expected a neutral or negative experience. After the designette, only 10% reported such an experience. This observed change yields a *p-value* result of 9.4e-07 in a t-test with the pre-survey responses. There was also an increase of 5% in the number of students who rated the 2D challenge in the highest category and really enjoyed the experience. Overall, the students not only enjoyed the 2D designette's multidisciplinary design challenge, but also increased their understanding of applying material from courses they are currently taking.

6. CLOSURE

This paper presents the pedagogical underpinnings and research results of *designettes*, a new approach to integrating design experiences and multidisciplinary learning into engineering curricula. The three designettes presented, AutoMilk, interactive musical circuit, and MechAnimal provide evidence in the forms of designed artifacts and student surveys and quizzes to verify single subject, multidisciplinary and design learning.

Significant findings at the 1D level show that designettes help students appreciate and feel comfortable in applying concepts in real world problems. Results suggest that learning is closely tied to the creative parameters of the designette. Those design variables left open-ended for creative exploration are the focus of learning, and understanding of more complex or broader concepts may be incomplete. Certainly, the designette aids and does not inhibit learning.

In the context of multidisciplinary 2D learning, knowledge of integration of subjects was significantly increased. Students gained appreciation for subjects, specifically biology, which may not traditionally be well-integrated or understood when scoping design objectives. The 2D AutoMilk designette did not significantly contribute to understanding of a discipline in theoretical fundamentals beyond those equations or concepts used as creative design variables in the designette.

Most importantly, all of the designettes were enjoyed by the students. At the open houses and outreach activities in particular, students were engaged and having a blast. SUTD students engaged in the AutoMilk designette increased their appreciation for the multidisciplinary activity after one-week of engagement in what was an involved, demanding, and open-ended design process.

Future work can consider the longitudinal effects of the 4D curriculum and the implementation of 3D. The impact of dedicated design courses and project-based learning is still uncertain [3,5]. It is hypothesized that the 4D approach focusing on design thinking and the integration of designettes will help students internalize best practices and more creative thinking. The first class of students graduates in 2016, and the curriculum and 3D are still under development.

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