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Designettes: An Approach to Multidisciplinary Engineering Design Education

Design and other fundamental topics in engineering are often isolated to dedicated courses. An opportunity exists to foster a culture of engineering design and multidisciplinary problem solving throughout the curriculum. Designettes, charette-like design challenges, are rapid and creative learning tools that enable educators to integrate design learning in a single class, across courses, across terms, and across disciplines. When two or more courses join together in a designette, a multidisciplinary learning activity occurs; multiple subjects are integrated and applied to open-ended problems and grand challenges. This practice helps foster a culture of design, and enables the introduction of multidisciplinary design challenges. Studies at the Singapore University of Technology and Design (SUTD) demonstrate learning of engineering subject matter in a bio-inspired robotics designette (MechAnimal), an interactive musical circuit designette, and an automated milk delivery (AutoMilk) designette. Each challenge combines problem clarification, concept generation, and prototyping with subject content such as circuits, biology, thermodynamics, differential equations, or software with controls. From pre- and post-surveys of students, designettes are found to increase students' understanding of engineering concepts. From 321 third-semester students, designettes were found to increase students' perceptions of their ability to solve multidisciplinary problems.

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1 Introduction

Designettes, coined at the SUTD as a contraction of design charette, use the concept of charettes or “intense periods of design or planning activity” to facilitate learning through short-term design experiences [1]. Designettes are pedagogical tools for teaching fundamental engineering subject matter in combination with design processes and methods to provide students with creative pedagogical experiences across courses, time, and disciplines. The movement toward more design-centric and project-based learning (PBL) approaches in engineering seeks to facilitate learning that are expected by students, employers, faculty, and society, but are not necessarily fulfilled by traditional lecture-based curricula. Dedicated design courses, however, typically focus on the longer-term and iterative aspects of design processes and do not significantly contribute to traditionally lecture-based courses. In contrast, designettes teach modular design learning objectives, such as ideation or prototyping, integrated with other engineering subject matter. This paper introduces a methodology for creating designettes and reports on the success of three unique designettes. The designettes reviewed in this paper are based on problems from a broad selection of subject matter: systems, circuits, robotics, kinematics, biology, and thermodynamics. The effects of designettes are evaluated for learning objectives in design, single subjects (1D) and multiple subjects (2D).

Designettes enable achievement of learning differently from dedicated capstone and cornerstone design courses because they can integrate the desired open-endedness and skill sets of design throughout the curricula. A review committee of the National Academy of Engineering reported 50% of undergraduate students leave science and engineering, and the research suggests that poorly designed lecture-based instruction is a contributing factor [2]. Lectures, reading assignments, note-taking memorization, and laboratory activities with predetermined results contribute to stifled understanding and adoption of concepts. Rather, they suggest “peer-led team learning” and other collaborative exercises are needed. From the interviews by Klukken et al. [3], engineers recognized for creativity by their peers desired more open-endedness in their undergraduate courses, including more interdisciplinary thinking. Similar observations are reported by engineers and instructors in Kazerounian and Foley’s study of creativity in engineering education [4].

Professional engineering requires graduates who are ready to engage in design, open-ended problem solving, team-work, and life-long learning [5]. The aerospace industry, for example, has voiced a need for graduates with a strong understanding of design and systems-level thinking [6]. Bilén et al. [7] argued that the increasingly global nature of engineering and product development requires engineers with significant prior education in the design process. Design-based learning can teach theoretical underpinnings (facts and knowledge) while enabling development of practical and innovation skills (process) [8–12].

Designettes also tackle the problem of teaching engineering and design fundamentals differently from traditional PBL pedagogies. PBL emulates long-term industry or research projects to provide real-world importance to the application of knowledge, as in Refs. [5] and [13–15]. Designettes instead introduce design tasks such as sketching, prototyping, or other design tools, methods or processes into lecture-based and PBL-based courses. These design tasks allow students to engage in and learn subsets of the design process without being consumed by the goals of a product [16]. The core foci of PBL courses are often semester-long projects resulting in a single product [5]. In contrast, designettes do not need to be the focus of a course; they can be engaged merely as an active learning technique.

The SUTD uses designettes as part of a four-dimensional pedagogy. 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, across term (time) activities; and the 4D, independent and extracurricular activities.

This research presents studies of designettes applied at the 1D and 2D levels through open-houses, outreach, and across courses in the 2013 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 design challenges, from hours to one-week that integrate concepts, coursework, and faculty across their current term courses [17]. During a dedicated week, for example, student teams design their own unique approaches to the 2D challenge while all instructors from the courses 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 that are revisited and deepened throughout all 4 years of study. 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. For example, SUTD students designed and constructed the 2012, 2013, 2014, and 2015 Chinese New Year’s 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.

Designettes are used throughout the curricula at the SUTD, and this paper focuses on early results from three studies. Two are outside of the curricula and one integrated in a full week of the third semester. Sections 3–6 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 state-of-the-art in short-term design education and multidisciplinary learning. Section 3 presents a structured method for creating a designette as well as a brief description of the studied designettes. Section 4 presents the research approach to evaluate the designettes. Section 5 presents the results for three designettes carried out at the 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, MechAnimal, designette embodies the design learning objectives at the 1D level. Additionally, a 1D interactive music designette embodies design learning objectives and electromechanical principles. An automated milk delivery (AutoMilk) designette embodies multidisciplinary problem solving at the 2D level. These examples demonstrate the efficacy of 1 hr to 1 week long designettes for engaging and motivating students while teaching design, fundamental engineering subject matter, and multidisciplinary problem solving.

2 Design-Based Learning: Objectives and Prior Art

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 learning taxonomy posits that creative experiences unlock the highest level of learning and that memorization and understanding of less far-field problems are not prerequisites for creative understanding. Bloom’s taxonomy is a multitiered 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 [18–20]. 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 [21].

Designettes benefit students by engaging them in a cycle that advances from a stage of merely acquiring information to analyzing and ultimately synthesizing information to apply what they have learned in different situations. As in Ref. [22], 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 content learning, application, and creating new ideas. Designettes structurally provide open-ended problems and anchors for linking ideation techniques and methods within an engineering context.

2.2 Active Learning. Active learning describes an educational process where students are vigorously engaged in assimilating the material being taught rather than absorbing information passively [23]. It 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. Many approaches may be executed through a variety of modes and media. Exemplar delivery modes supported by research include experimentation [24], cooperative groups [25,26], Socratic dialog inducing labs [27,28], interactive demonstrations [29], peer instruction [30], think/pair/share [31], and hands-on activities [32–34]. 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.

Prince [23] reviewed the findings in active learning research and concluded 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 [24,31,35–37]. 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 [38]. A survey by Hake [39] of pre- and post-test data found that the use of active learning in introductory physics courses significantly increased conceptual 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 [32–34,40,41].

2.3 Prior Art. Over the past two decades, faculty have developed design and small-scale projects to integrate multiple disciplines, similar to the designettes discussed here. Techniques, such as product dissection, are being introduced in universities as state-of-the-art [42,43]. Additionally, dedicated capstone and cornerstone design courses remain the primary modes of design education [43,44] and designettes offer opportunities to expand upon these advances. The examples in this section provide inspiration for the development of the designettes framework (Sec. 3) that utilizes partial design processes and can be integrated throughout the curriculum with fundamental engineering subject matter.

Roedel et al. [45] detailed small-scale projects of 4–5 weeks used at Arizona State University to integrate calculus, physics, and English subjects in the freshman year. The projects include a catapult, a trebuchet, and a bungee drop mechanism designed to demonstrate the relationship between all four disciplines [45]. Beaudoin and Llis [46] employed 3-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. Rowan and Harvey Mudd incorporated engineering clinics to engage students in design thinking

and professional practice [8,47]. Chesler et al. [48] used a “computer-based professional practice simulator” to teach management of tradeoffs and client conflict in redesign and design selection processes. Students are able to solve the next-generation dialyzer problem in 11 hrs. Wood et al. [49–52] utilized reverse engineering, dissection, and every day systems and products to explore design methods, variant design, and adaptive design.

Aikens et al. [53] have created an extensive, 40 hrs 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 U.S. Additionally, Hussmann and Jensen [54] reported 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.

2.4 Engineering and Design Learning Objectives. A review of research in design and design education provides six overarching sets of learning objectives for engineering students across courses. The 2014–2015 ABET accreditation criteria [55] define engineering design as “the process of devising a system, component, or process to meet desired needs.” Furthermore, Dym et al. [5] described a good designer as able to embrace convergent and divergent thinking, accept uncertainty and ambiguity, contextualize within a bigger picture, reason about dynamics of systems, make multicriteria decisions under uncertainty, think as a team, think and communicate in varied design languages. A review of design learning objectives conducted by Wood et al. [1] adds that designers are able to creatively use resources, including prototype and experimentation, and that designers draw from existing knowledge, such as examples and analogies. All of these experts additionally recognize the importance of strong engineering fundamentals in design. By combining the literature reviews and perspectives of Crismond and Adams [56], Dym et al. [5], Wood et al. [1], and ABET [55], one can define six overarching sets of learning objectives for students to develop an innovative mindset and skill set:

2.4.1 Learning Objective Set 1: Engineering Subject Fundamentals. In order to perform engineering design, students must have knowledge of the fundamentals of mathematics and science at the level of engineering applications. Engineers generally learn subject matter related to their broad field of applications and specialize as their career progress and requires. Specific objectives within this set include knowledge of: chemistry; physics; thermodynamics; mechanics; and other fundamental engineering subject matter.

2.4.2 Learning Objective Set 2: Reflect, Observe, and Hypothesize. Innovators actively observe and reflect regarding their circumstances, activities, and societal needs. Specific objectives within this set include the ability to: recognize and identify inventive problems or opportunities; adapt innovation processes for varying problems and problem domains; correlate a course's subject matter to current and real-world events, and apply such relationships to exciting problems in society; understand the history of key innovations in a field and how they came about; and hypothesize and carry out novel research in a chosen field or area.

2.4.3 Learning Objective Set 3: Assess Contexts, Opportunities, and Needs. Bringing results to market requires understanding elements influencing reception, such as the user, competitive environment, technology forecasting, prior art, and financial feasibility. Specific objectives within this set include the ability to: develop system contexts and product contextual analysis; perform lead user and empathic lead user analyses; develop technology

forecasting; perform background research in a given field or area; develop quantified metrics and specifications; develop market and user descriptors; to analyze user activities; and perform benchmarking of a field or area.

2.4.4 Learning Objective Set 4: Ideate and Abstract Using Multiple Representations. Convergent thinking seeks to specify and detail concepts, while divergent thinking seeks to widen the scope of alternatives to expand and relate concepts. Similarly, students believe mathematics to be “the language of engineering,” but design language takes many different forms from verbal and textual to graphical representations, analytical models, and shape grammars [5]. Specific objectives within this set include the ability to: recognize analogies and adapt analogies to a design problem; perform ideation and concept generation; apply principles and physical models from multiple fields to explore new concepts; learn and apply knowledge from a variety of fields; and develop functional models.

2.4.5 Learning Objective Set 5: Make Decisions for Open-Ended, Design Problems. The ability to make decisions under uncertainty and multiple criteria is essential. Students should employ both inductive and deductive reasoning to inform and improve process understanding and the experimental approach [57]. Specific objectives within this set include the ability to: solve open-ended problems where a “correct” or singular solution may not exist; identify criteria from multiple approaches and concepts; apply knowledge from multiple fields as part of analysis and decision making; consider multiple competing objectives from stakeholders and physical constraints; embrace different perspectives and ideas among stakeholders and team members; and identify independent, dependent, and interdependent variables within a problem and its context.

2.4.6 Learning Objective Set 6: Creatively Utilize Resources Within a Complex System. Creative resource utilization is developed in various situations, such as overcoming limited resources. Creative resource utilization is crucial for sustainable development and requires big picture and system level thinking that is also useful for delegating tasks within the design process and working in teams [58]. Specific objectives within this set include the abilities to: execute and realize concepts in a physical form; design, develop, and execute systematic testing and experimentation approaches; understand the entrepreneurial process of transforming a concept to prototype and to market; adapt prototyping strategies to constraints; understand the concepts of efficient resource utilization and sustainability; and develop environmentally, socially, and economically sustainable systems and products.

Although categorized into six distinct sets, these learning objectives exhibit overlaps and synergies. The challenge then becomes the integration of these skill sets into engineering theory courses through designettes.

3 Designette Framework

While most PBL focuses on a product, we present a framework and approach to creating designettes independent of the product [46,48,53,59]. One can develop designettes as standalone modules or sequences to be revisited days or years in future after the students are ready for more advanced concepts. 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, shown in Fig. 1. For example, the designettes studied in this research required 2–5 iterations with pilot groups to determine the timings and learning obstacles before being implemented in courses and open-houses.

Creation of a designette begins with clear definitions of the learning objectives, as well as the desired mindset and skill sets to explore. Learning objectives can include a subset of the design skills outlined in Sec. 2.4, as well as learning objectives from

other engineering knowledge sets. For example, the designette may teach students use reflection and observation (learning objective set 2) in thermodynamics or ideation and abstraction using multiple representations (learning objective set 4) in robotics. The exploration of these concepts can occur within a variety of design realms including system processes, technologies, and experimentation.

After selecting learning objectives and skill sets, relevant prototyping or modeling tools are chosen. The design and prototyping can be limited to designing variants of a pre-existing design, adapting design and technologies, or creating more original or disruptive designs. The type of design will lend itself to prototyping within the virtual realm, including programming, CAD, or simulation, or the embodied physical realm, including cardboard structures or electronic circuits, or the paper realm, including sketching. For example, Foster et al. [60] 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 be used

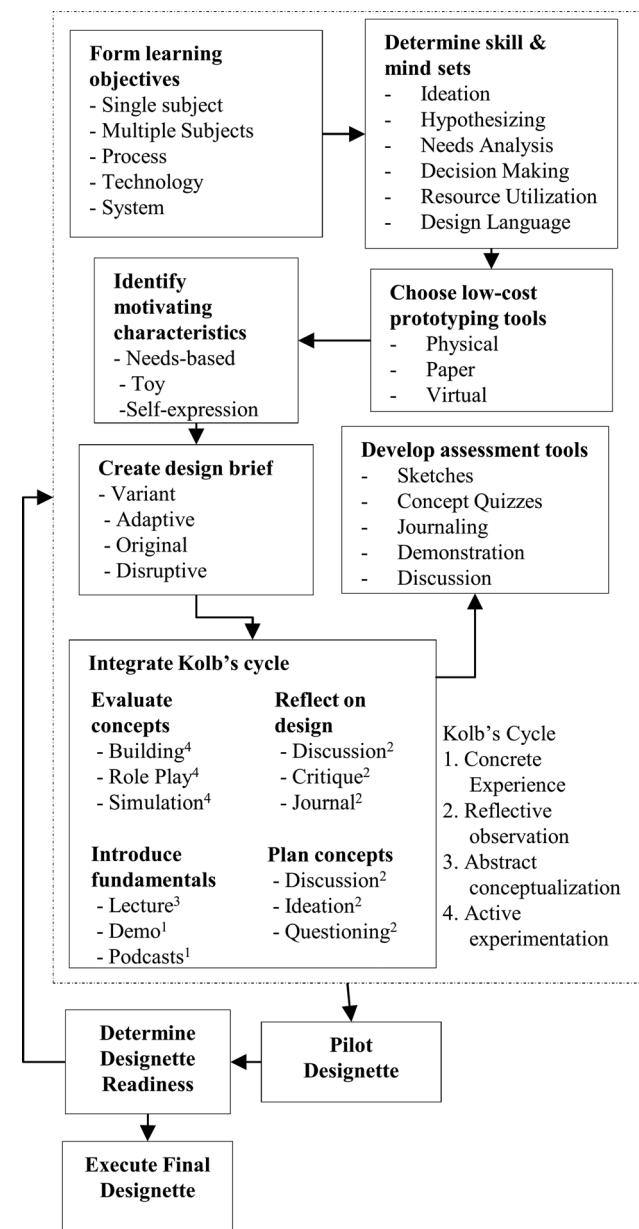


Fig. 1 Flowchart for designette development

in designettes, as in the use of spreadsheets or statistical packages for teaching design of experiments.

Once the learning objectives 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 goals that the student addresses through creative design. Research by Linnerud and Mocko [61] indicates that the goal of an elegant design itself is a strong motivator. Other motivators include social applications of technology, such as humanitarian needs-based design [62]. The MechAnimal designette in this paper, for example, is motivated by rescue of hurricane victims and the interactive musical circuit engages self-expression and play. In conjunction with the scoping of tools and motivational characteristics, the process of refining 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 correspond to aspects of the design process, such as ideation, modeling, and evaluation. Each task can be performed individually, as teams or in some combination. Usually, timing is constraint-based. Generally, we find that ideation and low-fidelity prototyping tasks can each be carried out in as few as 10 min, or as long as needed to address the chosen learning objectives. Actual times may vary based on the tasks and the content and tools being taught. Figure 1 includes a few suggestions for tasks and relates these to Kolb's learning cycle phases, shown by footnotes.

Kolb's learning model [63] describes the cycle of learning experiences in four stages and can provide a foundation for planning designettes. The four stages are generally ordered as follows: *concrete experience*, *reflective observation*, *abstract conceptualization*, and *active experimentation*. 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 [63]. It is recommended that these different aspects of the learning cycle be addressed throughout the designette. For example, a short lecture introduction can occur before a designette or students can conceptualize a task and obtain information through a question and answer forum. Many learning theories can be applied in this area, Kolb in particular employs an entire learning cycle to engage different types of learning and provide a foundation for planning activities.

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, discussions, and other rubrics [64]. 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 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 core designette idea.

3.1 Designette Examples. The subject of this study is three designettes formed at the SUTD using the above framework. Two covered single subject matter, one on robotics design (MechAnimal) and the second on circuit theory (Interactive musical circuit). The third (AutoMilk) integrated subject matter from courses in thermodynamics, biology, programming, controls, and optimization.

The MechAnimal designette on design of robots was created to introduce design to young students, typically at the secondary or freshman levels, and in particular, it was used as part of Open House sessions to recruit students to engineering curricula in higher education. The design brief is 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 10 min 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 5 min period. As a reflective experience, the teams were tasked with presenting this concept to the entire section of participants. After reflection, teams were given 10 min to choose and prototype a subsystem of their MechAnimal, such as a leg or other moving part, and an additional 10 min for testing this prototype. The designette took a total of one and a half hours.

The MechAnimal designette included elements from five of the six sets of learning objectives. The introduction of robotics and mechatronic components falls under learning objective set 1 from Sec. 2.4. The students were themselves able to identify functions and needs for the disaster victims (learning objective set 3). The practice in use of analogies, sketching and physical building of a subsystem addressed learning objective set 4. Finally, the process of evaluating and selecting designs falls under learning objective set 5 while working on a team and finding ways to represent their idea using the provided kit addressed learning objective set 6. The interactive music circuit designette introduced the physics concepts of electromagnetic force, electrical resistance, and frequency as well as basic circuit construction with a breadboard. Students received partially constructed 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 components (e.g., resistors and buttons), 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 resistance to frequency mappings for designing their electronic instruments and the fundamental equations for creating their own mappings and understanding the effect of widening and lengthening their ink paths. This designette took a total of 2 hrs, with 1 hr for the speaker and 1 hr for the interactive musical circuit.

The interactive music designette addressed three of the six sets of learning objectives. The fundamental engineering learning objectives were concepts related to variable resistance and electromagnetism. Students also used the relationship between length and resistance, represented by equations and charts, to play music (learning objective set 4). Finally, they engaged in creative use of materials, such as paper plates, to make their speakers (learning objective set 6).

The multidisciplinary "AutoMilk" autonomous milk delivery designette was developed for the third term of the freshman (freshman and sophomore) year for the SUTD students of the Class of 2015 [17]. 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 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 programming and controls; and The Systems World, a course on matrix equations and optimization.

The "AutoMilk" 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. Instructors acted as guides and advisors. 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: an insulated container for milk cartons, the software algorithms to dispatch UGVs, and the software to move a UGV over a scaled course representing Singapore.

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. The devices had to balance shelf-life, delivery time, and delivery volume. No deliverable could be completed without multidisciplinary thinking, and each deliverable drew upon theory and practice from design methodology, including systematic brainstorming, and concept selection tools.

The AutoMilk designette addressed five of the six sets of learning objectives. The fundamental learning objectives (set 1) were at a multidisciplinary level, representing each of the four courses. The students were provided with a set of requirements that demonstrated how students can combine disciplines in real-world problems (learning objective set 2). The students also performed ideation and prototyping (set 4) on an open-ended problem that required analysis to evaluate and choose design (set 5). Additionally, the task was a complex, systems-level problem that the students need to work on as teams (set 6).

4 Research Approach

This research represents the findings from 3 years of designettes experience at SUTD in using the designettes framework. The designette interventions in this study were introduced in Sec. 3.1: single subject MechAnimal and Interactive Circuit designettes, and the AutoMilk design challenge integrating the third semester curriculum. Figure 2 shows the research methodology design, addressing three research questions: (1) Do designettes encourage students' self-concepts in design? (2) Do designettes improve students' understanding of single subject material? (3) Do designettes improve students' self-concept in integrating concepts from multiple disciplines of study through multidisciplinary problems? The success of the designettes is evaluated by postsurveys, paired pre- and postsurveys, and paired pre- and postconcept quizzes, shown in Fig. 2. Results describe success in design concepts collectively (learning objectives 2–6 as outlined in 3.1), single-course material, and integrating material from multiple disciplines.

In the case of pre- and postsurveys (AutoMilk) and pre- and postquizzes (circuit), the students were asked (but not required) to complete identical questionnaires before and after the activity. The musical circuit and MechAnimal employed only postsurveys, but recent informal pre- and postsurveys provide similar insights as those reported here. For the surveys, Likert scale responses were used to indicate self-perceived competency level in the subject domain (self-concept [65]) 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 [65–68]. Self-concept in design was indicated by asking students to rate their sense of achievement from the designette and interest in the design-based curriculum. Self-concept in physics concepts, for example, was indicated by student responses to perceived ability to link physics with real-world problems. Self-concept in multidisciplinary learning was indicated by pre- and poststudent responses regarding the ease of solving engineering problems that integrate biology. The results and average responses with intervals were calculated using a Student's T distribution with alpha level of 0.05. *P*-values were calculated using a paired *t*-test and a permutation test of 1000 samples. Section 5 presents the results in more detail.

5 Designette Results and Discussion

The results were collected during three different designettes carried out at the SUTD. This section is organized by three

dimensions of learning objectives: self-concept in design, self-concept and performance on concept quizzes for 1D (single subject) learning objectives, and self-concept on 2D (multidisciplinary) problem solving. Each designette addressed different subsets of learning objectives from Sec. 2.4. The self-concept in design collectively evaluated these learning objectives for each designette. The self-concept in subject matter addressed the first set of learning objectives, fundamental engineering subject matter.

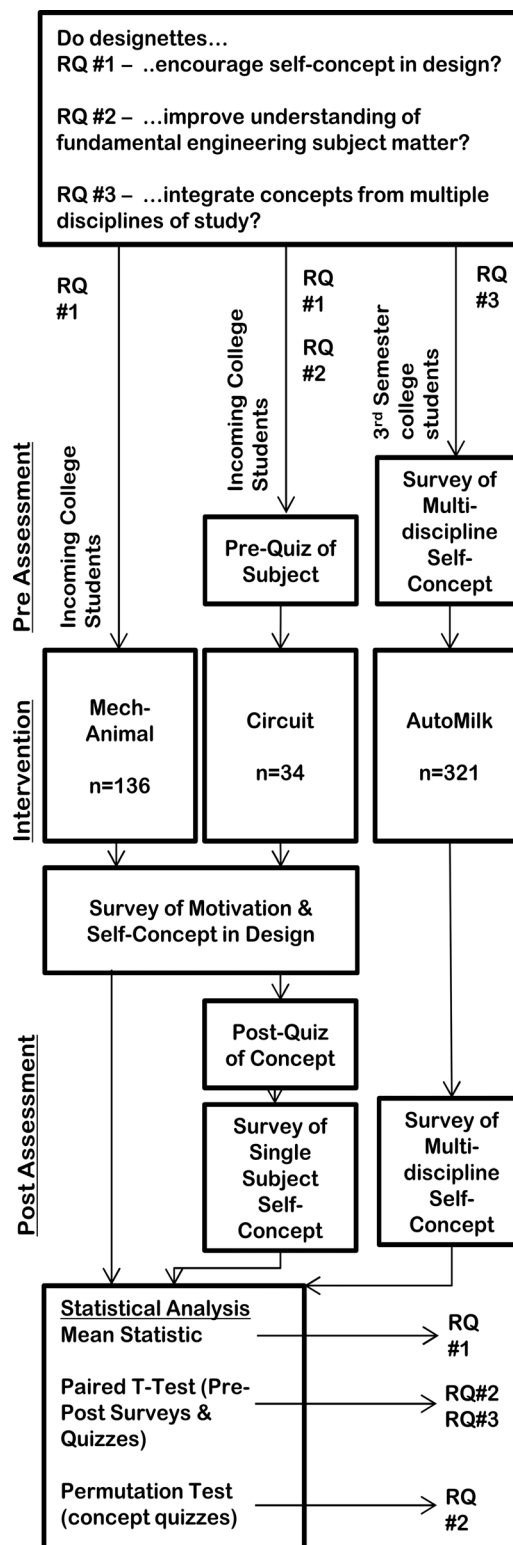


Fig. 2 Research study of three designettes

These occurred at two levels, single subject and multidisciplinary. 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. Finally, the potential of 2D learning objectives are discussed through introduction of the AutoMilk 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. Participants were 136 attendees of an open-house, used animal analogies to sketch, evaluate and prototype concepts for robots to rescue hurricane victims. Students selected one or more living creatures to use as analogies, an established approach to creativity [69,70], and were able to identify major components of their robotic rescue device, such as actuators, sensors, and support structures. Postsurveys evaluated their perceived learning and self-concept in design after the designette.

Table 1 shows the students indicated a strong sense of achievement from engaging in the designette. This indicates that they took the design process seriously, and felt 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.

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, allowed them to connect and build relationships with other open house attendees.

Finally, the real test of 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 0.13.

Evidence of learning design also lies in the sketches and prototypes created during the brief session. Students were introduced to 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 3 shows students successfully constructing

components of their concepts, while Fig. 4 shows a sketch of an exemplar scorpion-inspired MechAnimal. Evident in Fig. 4 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.

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.

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 (2) foster cooperative team problem solving skills; and (3) increase interest in learning more about design. 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 physics concepts of electromagnetic force, electrical resistance, and frequency as well as basic circuit construction with a breadboard. 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 2. One question of this survey asked 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 0.26. 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 ± 0.20 . The students also preferred the designette to their traditional class activities.

For the single subject 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. One question in the postsurvey asked students' about their understanding of 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.

Table 1 MechAnimal postsurvey results indicate learning of design, 136 respondents

MechAnimal survey questions	Number of responses					Avg (1–5)	95% CI
	Strongly disagree		Strongly agree				
	1	2	3	4	5		
I have a sense of achievement from the rapid learning experience offered by the designette	0	2	28	69	37	4.0	± 0.12
The ways in which I was taught in the designette provided me with opportunities to pursue my own learning	0	3	24	66	43	4.1	± 0.13
The delivery fashion of the designette developed my understanding of concepts better as compared to traditional classes	0	1	16	55	64	4.3	± 0.12
I have received feedback that is constructive and helpful during the designette	0	7	30	61	38	4.0	± 0.14
The designette experience enabled me to quickly connect and build relationship with fellow team members	0	7	29	66	34	3.9	± 0.14
Overall I was satisfied with the quality of the designette	0	0	12	62	62	4.4	± 0.11
The designette experience increased my interest in SUTD and its design centered technology curriculum	1	0	19	49	67	4.3	± 0.13

Table 2 Interactive music postsurvey indicates learning, 34 respondents

Interactive musical circuit survey questions	Number of responses					Avg(1-5)	95% CI
	Strongly disagree				Strongly agree		
	1	2	3	4	5		
I have a sense of achievement from the rapid learning experience offered by the designette	0	1	3	15	15	4.3	±0.26
The designette provided me with opportunities to pursue learning as an individual	0	0	2	19	13	4.3	±0.20
The designette developed my understanding of concepts better than a traditional class would have	0	0	5	11	18	4.4	±0.25
I received feedback that was constructive and helpful during the designette	0	0	4	20	10	4.2	±0.21
Overall I was satisfied with the quality of the designette	0	0	1	12	21	4.6	±0.19
The designette experience increased my interest in SUTD and its design centered technology curriculum	0	1	2	19	12	4.2	±0.23
The designette has developed my understanding on Lorentz force law	1	3	16	7	7	3.5	±0.34
I have managed to link Physics with real life applications through the designette	1	0	5	15	13	4.1	±0.30

Considering the pre- and postquiz results, Table 3 shows high scores for the pretest but improved learning for most concepts covered by the circuit designette. Hundred percent of students learned the correct metric for pitch, a statistically significant



Fig. 3 Students prototyping MechAnimal concepts

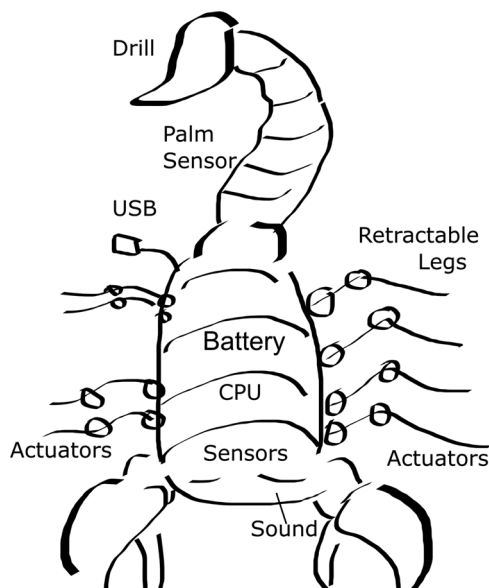


Fig. 4 Sketch from the MechAnimal activity shows ability to identify components and exercise creativity

increase from the pretest result of 76% correct. A Student's *t*-test yielded a *p*-value of 0.002 and a 1000 sample permutation test of the null hypothesis both yielded a *p*-value of 0.003 for this quiz question. All but one student correctly identified the relationship between a wire's length, width, and resistance, an increase from 75% to 97% and a *p*-value of 0.004 using a permutation test, and 0.002 using a *t*-test. The rest of the questions had higher *p*-values using the permutation test. The null hypothesis could not be rejected, although an additional 9% of students correctly predicted an enforcing relationship between pitch and frequency with a *p*-value of 0.233 between the pre- and postresults (0.09 using a paired *t*-test). Furthermore, the number of students correctly identifying the primary distinction between sound waves and light waves increased by 12% with a *p*-value of 0.081 using a permutation test (0.02 using a paired *t*-test). The students exhibited a modest understanding of these concepts before the designette and a stronger grasp after completing the design of their instruments.

5.3 Two-Dimensional 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 third term of the freshman (freshman and sophomore) year for the SUTD students of the Class of 2015 [17]. This designette, as described in Sec. 3.1, integrated material from thermodynamics, biology, programming, and controls and optimization courses. The students were tasked with designing a milk delivery system that balanced insulation and path planning to keep milk fresh.

The pre- and postsurveys asked students to evaluate multidisciplinary teaching and contextualizing of natural sciences, such as biology, with engineering courses. The first survey question, shown with the results in Fig. 5, was designed to detect any change in self-concept. In this case, the 2D designette combined thermodynamics and biology to place constraints on the engineered systems design.

The student responses yield a statistically significant increase in the level of self-concept. 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 postquestionnaire.

A second pre- and postsurvey question asked students how effective the 2D design challenge would be at teaching multidisciplinary design. This question, shown in Fig. 6, was designed to detect any change in perceived learning about solving multidisciplinary design problems.

Table 3 Musical circuit quiz results improved, 34 responses

Answers	Pre		Post	
	#	%	#	%
<i>What happens to a point charge (such as an electron) when it passes through a perpendicularly applied magnetic field?</i>				
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
<i>Music 'pitch can be measured in...</i>				
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
<i>Which wire shape offers the least resistance?</i>				
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
<i>Change in the pitch of a musical note can be achieved by tuning the wire's...</i>				
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
<i>The higher the frequency of the waveform, the pitch of the sound you hear becomes...</i>				
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
<i>Sound waves are different from light waves because...</i>				
Can be measured with frequencies	3	9	0	0
Has amplitude	1	3	0	0
Do not require energy	0	0	0	0
Requires a medium	30	88	34	100
All of the above	0	0	0	0

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 postsurvey.

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 1 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.

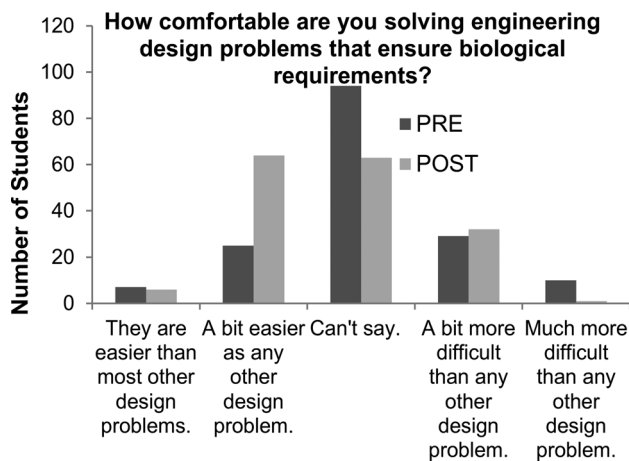


Fig. 5 Student self-concept in applying biology to engineering design problems increased

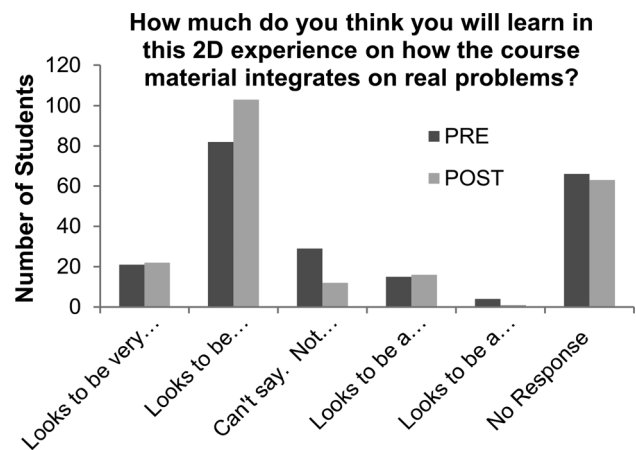


Fig. 6 Students understanding of solving multidisciplinary problems increase

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.

6 Limitations

Results from Likert scales are vulnerable to several biases: central tendency bias, acquiescence bias, and social desirability bias. Central tendency bias would result in fewer responses in the "extreme" areas. Nevertheless, more than one-third of the responses were at the "extremes" indicating lack of such bias. Acquiescence bias would result in more positive responses to please the designette practitioners. To help mitigate this bias, surveys were anonymous. Social desirability bias would result in more students providing the socially acceptable answers. The questions were posed in more personal terms to mitigate a social bias.

Section 2.4 lists a number of learning objectives for design, and these were assessed collectively through the self-concept questions. Two of the three studies rely on student and instructor perceptions of learning based upon the surveys and prototypes or sketches created. Self-concept and self-efficacy, or perceived ability, is linked to performance. Confidence and sense of achievement are imperfect measures, but correlation to performance increases when students report on confidence and achievement related to specific and identical skill sets as used in the intervention [65]. Although the interactive musical circuit designette includes pre- and postconcept quizzes, the AutoMilk designette has no point of comparison of learning for fundamental subject matter. The primary objective point of evidence of integration of concepts in the AutoMilk is that students utilized the concepts in design. Direct assessment within each set of learning objectives can be addressed in future studies.

Additional limitations to this study lie in the novel nature of the experience and the narrow demographic. Most participants in the 1D designettes had no learning experiences like designettes. Furthermore, most participants were 17–20 years old. A longitudinal study of the continued use of designettes and studies in different institutions would help understand the effects of novelty, culture, and age in addition to other long-term effects of designettes.

Limitations also exist for the designette framework proposed. Although the results show that the framework produces useful activities, the framework itself can be more rigorously assessed. For example, questions regarding how to integrate learning objectives, match objectives to design parameters, and coordinate among instructors have yet to be fully addressed.

7 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 single-subject level show that designettes help students appreciate and increase their self-perceived ability to apply subject matter to design problems. Results also suggest that learning is closely tied to the creative parameters of the designette. Those design variables left open-ended for creative exploration may be 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 learning, knowledge of integration of subjects 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 provides an example of how this integration may be achieved.

Most importantly, all of the designettes were enjoyed by the students. At the open houses and outreach activities in particular, students were engaged and, while challenged, were encouraged and motivated by the activities. SUTD students engaged in the AutoMilk designette increased their appreciation for the multidisciplinary activity after 1 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 PBL is still uncertain [5,71]. 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. Future work can also compare best practices in timing of designettes, how often they occur and the duration of the activities. The first class of students' graduates in 2016, and the curriculum and 3D are continually being evolved.

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