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## Clive L. Dym Mudd Design Workshop XII: Designing Through Making Sketches, Drafting in Campus Facilities and Remotely

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**The Key Ideas of MDW XII: A Summary** 1694–1703
*Gordon G. Krauss*

This paper provides a high-level summary of the presentations and associated discourse from the Clive L. Dym Mudd Design Workshop XII, "Designing Through Making: 2-D and 3-D Representations of Designs in Campus Facilities and Remotely," conducted online and coordinated from Harvey Mudd College from May 27 to 29, 2021. An attempt is made to encapsulate the key ideas that emerged from both the presentations and discussions of the participating engineering design educators, practitioners and researchers.

**Iterating Overnight: Using Cardboard to Teach Audio During a Pandemic** 1704–1711
*Colin M. Gray, Christopher Wolford and Davin Huston*

Prototyping is a core element of engineering and technology activity, giving form to design concepts and facilitating iteration and testing. With the rise of the "maker movement," higher fidelity forms of prototyping have often been privileged, without deep investigation into prototyping activities that support materially-focused exploration across different levels of fidelity. In this paper, we describe how students in an interdisciplinary undergraduate audio engineering course adapted to a loss of fabrication equipment and the COVID-19 pandemic, relying more heavily on cardboard prototypes as they "iterated overnight" at home to realize the design of their loudspeaker. We analyzed a range of iterative prototypes using a prototyping framework we operationalized from Lim, Tenenberg, and Stolterman, describing the filtering and manifestation dimensions across a range of student projects. We reflect upon the trajectories of prototyping, considering strengths and weaknesses of different types of materials in supporting student exploration and the pedagogical supports that may be needed to encourage this exploration.

*Keywords:* prototyping; cardboard; engineering technology; loudspeaker design

**Student Perspectives of the Nature and Purpose of "Deep Modeling" as Situated Knowing** 1712–1729
*Robin S. Adams and Asem Aboelzahab*

Deep modeling is a practice of representing ideas in a way that is amenable to inquiry. In engineering, deep models often take the form of drawings or physical and digital prototypes. These models are created and used throughout a design process to discover, analyze, evaluate, and validate ideas about problems and possible solution approaches. This paper is an exploratory study into student perspectives about the nature and purpose of deep modeling. The study context is an interdisciplinary design sequence where students created a personalized Interdisciplinary Design Playbook as a means for documenting their evolving design knowledge. We pursued two questions through a situated knowing lens: (1) How do students describe the nature and purpose of deep modeling as a design practice – what is it, why is it important, when is it useful, and how to do it? and (2) What associations do students make across these dimensions of knowing that reveal conditionalized logics for how and why deep modeling is meaningfully employed? By taking a situated knowing perspective, analysis focused on the conditions under which students perceive deep modeling practices can be employed in meaningful and relevant ways. We present three cases of rich narratives and representations, illustrate similarities and differences across cases, and discuss findings. We conclude by speaking to the benefits of our approach for understanding student learning – moving from the behaviors we see students doing towards the meanings these behaviors hold for students.

*Keywords:* modeling; prototyping; informed designing; situated knowing; design playbook

**The Impact of Appropriate Prototyping Tool Choices on Achieving Functionality for Novices** 1730–1746
*Joshua D. Brandel, Andersen Chang and Matthew A. Wettergreen*

Balancing coverage of design process, teaming, and prototyping is a challenge for instructors in their pursuit of creating the perfect engineering design course. Previous studies have demonstrated that teaming and process-based skills can be acquired in a short period of time by applying a training model. Prototyping skills can also be taught but there is a quandary regarding *which* tools and machines are critical to student success. In this study we evaluated prototypes produced in a first-year team-based engineering design course. Pre- and post-course surveys on prototyping skill and evaluations of end-of-semester prototypes were used to explore which prototyping tools meaningfully contribute to producing *functional* final prototypes. Several fascinating results have been uncovered through this exploration of student prototyping, including student skills growth and overreporting skill growth, as well as prototyping progress as a critical factor determining design functionality. Our study shows that when considering which prototyping skills to teach in a first-year design course the question is not how many prototyping skills to teach, but how few an instructor can get away with.

*Keywords:* prototyping; novice; design process

**CAD as a Virtual Prototyping Method: Uses and Timing of Computer-Aided Design Artifacts in Hardware Design** 1747–1760
*Hannah Budinoff and Julia Kramer*

Prototypes are critical learning tools in the design and development of innovative products. Computer-aided design (CAD) models are most closely associated with detailed design, but emerging research suggests a role for CAD to create virtual prototypes earlier in the design process. In this study, we explore the use of CAD as a prototyping method throughout the design process. We conducted a literature review of scholarly works that described designers using a 3D CAD model to learn about their design. A total of 24 studies were included in our review and were coded to identify common uses of CAD as a prototyping method. CAD was used as a virtual prototyping method from early conceptual design through detailed design but was most frequently used to create operational prototypes when a design was substantially developed, rather than as a simple mock-up. The most common use of CAD prototypes was to assess feasibility of technical aspects of the design. We also observed several examples of CAD models that were used to explore the design solution space and as means of communication with stakeholders. The benefits and limitations of using 3D CAD models as virtual prototypes are also summarized.

*Keywords:* CAD; virtual prototyping; engineering design process

**Engineering Students' Performance of Prototyping: Process, Purpose, and Perception in the Design Classroom** 1761–1778
*Todd Fernandez and Martin Jacobson*

Learning to design is important to engineering students. Learning to prototype and use prototyping as part of the design process is a critical part of learning to design. Prior research shows that students prototype in different ways and towards different goals than professionals during the engineering design process. In this study we explore students' use of prototyping from a lens of prototyping as performance of the design process, as opposed to looking at professional purposes for prototype creation. We use a mixed-methods approach consisting of survey data across an undergraduate biomedical engineering curriculum and interviews with juniors and seniors in the program. Our results suggest that students attach their prototyping to the context in which it occurs. Prototyping to our participants is a goal of the design process, seen as necessary to demonstration of course accomplishment, and involves purposeful but a-professional goals such as learning to build things as a relevant factor in their prototyping. We discuss the implications of different but purposeful student prototyping for researchers and instructors through links to information literacy and prototyping as a source of design information.

*Keywords:* perception; design process; prototyping; classroom

**Building Confidence and Embracing Failure Through Sketching Practice** 1779–1790
*Madhurima Das and Maria Yang*

There is a growing movement in engineering for students and practitioners to learn to embrace failure and develop resilience. The design process is inherently full of iteration and failures that can be leveraged as learning opportunities for students. This paper presents a preliminary study that introduces a sketching practice intended to provide students with opportunities to experience low-stakes failure and space to build their confidence in sketching. The study analyzes the resulting sketches for attributes such as line smoothness, accuracy/proportion, and understandability to identify potential links with sketch confidence and student perspectives on failure. 47% of students reported finding the sketching activity to be effective in making them feel more comfortable with failure. The study found that students' sketch smoothness showed signs of improvement during the course of the class and students' confidence in sketching increased. Additionally, the study found that women were initially more confident in sketching but men experienced greater growth in confidence over the course of the class and bridged that confidence gap. This gender difference persisted in sketching performance as well, as women scored higher in sketch smoothness and proportion/accuracy.

*Keywords:* sketching; design education; engineering confidence

**Student Perception of Construction Problems and their Process Design Strategies** 1791–1803
*Ali Shafaat and Farshid Marbouti*

The construction process is an ill-structured complex problem that needs to be designed based on multiple constraints. Typically, construction engineering students have difficulties understanding the complexity of the process and treat the problem similar to well-structured problems. This paper has utilized a systems thinking framework to enhance construction engineering students' design thinking. This protocol takes into account critical aspects that students can address in their solutions. The protocol consists of six consecutive levels; each level should be built on the previous levels. Forty-eight construction engineering students participated in this study over five sessions. Student teams designed two construction projects, one with and one without using the introduced framework. They also reviewed and provided feedback on their peers' designs. The results show that the framework reduced the time for most students to reach a higher level of thinking. In addition, students were more successful in connecting different aspects of the project process by using the framework. Thus, it is expected that using the framework helps the students better understand the relationship among materials, systems, structures, and processes, which is the second most important competency for construction management students. In summary, this systematic framework shows potentials to speed up the transformation from novice to expert designers for construction students.

*Keywords:* construction process; engineering design; design education; systems thinking; novice-experts

**Community-Engaged Learning, Prototypes and Requirement Development** 1804–1814
*William C. Oakes, Andrew Pierce, Jorge Martinez and Paul Leidig*

A challenge facing many institutions is how to bring "real" design experiences into the curriculum. Industry-inspired projects are often used in design classes, but the community can offer a plethora of compelling projects that challenge students in many ways and offer opportunities for students to make an impact in their local and global communities. One engineering engagement program has used community-engaged learning to create a human-centered design learning experience that benefits students and creates tangible benefits to community organizations. This paper explores two interrelated elements of this design learning experience: how students use prototypes in the design process, and how students perceive project specifications and use those specifications in the evaluation of prototypes. Prototyping is emphasized through the design process and different ways that prototypes are used are described. Examples are provided to demonstrate the breadth of projects and the roles of prototyping within the program. The understanding of the Specification Development phase of the design is explored with three different interventions to enhance student awareness of requirements. Representations of the design process created by students showed inconclusive results for the interventions. The representations pointed to the dominance of the learning in the actual design experience and implies that interventions would be more effective within the context of their specific designs.

*Keywords:* human-centered design; community; prototyping

**Designing a Design-Driven Human-Centered Engineering Program** 1815–1823
*Avneet Hira, Sunand Bhattacharya, Glenn Gaudette and Siddhartan Govindasamy*

In this paper, we take a systemic design approach to the design and development of the undergraduate Human-Centered Engineering program at Boston College, a Jesuit, Liberal-Arts University. We provide details on how the program is evolving and how we are weaving human-centeredness, design, and reflective practice into the program. We share a 2-D representation of our approach to the program's design in the form of a GIGA map using systemic design principles. In doing so, we adopt the metaphor of the tree of life to represent the program design, comprising human-centeredness as a design value, design as a mode of engagement and thinking, and reflection as a mode of thinking and becoming. Human-centeredness has been a guiding design

value of this project. Being situated in a liberal arts university provides unique opportunities to converge the technical and human in engineering. Design as a mode of engagement allows us to introduce students to engineering in an applied context using thinking, ideation, and prototyping for problem exploration and idea refinement. Reflective exercises will support students in integrating their learnings in engineering with the liberal arts contextually as they develop their own identities and understandings of engineering.

*Keywords:* undergraduate engineering; systemic design; program development; human-centered design

**Understanding the Anchors Associated with Secondary School Students' Engineering Design Experiences** 1824–1835

*Adam R. Carberry, Medha Dalal and Olushola Emiola-Owolabi*

Many students do not truly encounter engineering education during their school years despite numerous calls to increase focus on engineering-centric knowledge and skills in pre-college education. This study uses a Social Cognitive Career Theory framing to examine the nuanced experiences of pre-college students who learned the engineering design process through multiple, progressively complex project experiences in an introductory engineering course designed for all. Data was collected from 80 students within eight schools across the United States using multiple focus groups. Iterative thematic analysis revealed four themes that collectively depict how design experiences provide an anchor or a comprehensive knowledge base for engineering pathways. The study provides insights into the complex interplay of learning activities and wider educational contexts that influence students' higher education and career choices. Understanding the anchors associated with students' design experiences has the potential to impact future motivation and design of pre-college engineering experiences that can lead to improved student recruitment and retention in higher education.

*Keywords:* pre-college engineering education; engineering design; prototyping; social cognitive career theory

**Improving Engineering Sketching Education Through Perspective Techniques and an AI-Based Tutoring Platform** 1836–1850

*Morgan B. Weaver, Samantha Ray, Ethan Clark Hilton, Denis Dorozhkin, Kerrie Douglas, Tracy Hammond and Julie Linsey*

Freehand sketching equips engineers to rapidly represent ideas in the design process, but most engineering curriculums fall short of equipping students with adequate sketching skills. This paper is focused on methods to improve engineers' sketching skill through type of instruction, length of instruction, and delivery of and feedback for assignments using Sketchtivity, an intelligent sketch-tutoring software. We answer several key questions for providing better sketching education for engineers. Does perspective training improve freehand drawing ability? Can an intelligent tutoring software improve education outcomes? And how much sketching instruction is necessary for engineers? Analyzing the changes in sketching skill from pre- to post-sketching instruction between different instruction types ($n$ = 116), we found that perspective sketching instruction significantly improved freehand sketching ability compared to traditional engineering sketching methods. When comparing pre to post sketching skill of students using Sketchtivity ($n$ = 135), there was no significant difference in improvement between students using the intelligent tutoring software and those that exclusively practiced on paper – both groups improved equally. However, completing sketching tasks on tablets did not hinder students' skill development even when measured on paper. Future work will more directly explore the influence of Sketchtivity on sketching skill development. Additionally, we found that five weeks of sketching instruction greatly improves sketching skill compared to only three weeks of instruction ($n$ = 108), but both approaches significantly improve sketching self-efficacy. These outcomes support more extensive sketching instruction in engineering classrooms, and changes in instruction type to promote more freehand sketching skills.

*Keywords:* sketching; freehand sketching; visual communication; engineering curriculum

**Predicting Success of Engineering Student Makers: Relationships Between Makerspace Involvement, Academic Performance, and Engineering Design Self-Efficacy** 1851–1861

*Morgan B. Weaver, Ethan Hilton, Melissa W. Alemán, Robert Nagel and Julie Linsey*

Makerspaces are common in engineering programs around the country and around the world. As universities invest more into these spaces, researchers investigate more the impacts of making in the educational setting. As more students across more educational contexts get involved in making and makerspaces, there is a greater need for educators to gain a more wholistic understanding of the impacts of making on the academic environment, both positive and negative. In this paper, we look at the critical relationship between makerspaces and academic performance at a unique university with a design-centric approach to engineering education. This study presents three key findings: First, more involvement in making early in the curriculum is related to increased retention. Second, increased anxiety towards engineering design is connected to both lower retention and lower involvement in academic makerspaces. Third, GPA and makerspace activity are largely independent at this university where the engineering curriculum prescribes engineering students' engagement in making. As impacts of academic makerspaces are unfolding before us, these findings shed a positive light on their contribution to engineering education.

*Keywords:* makerspaces; engineering design; engineering education; academic performance

**Experiences with Prototyping and Making in Virtual Classes** 1862–1874

*Reid Bailey, Bethany M. Brinkman, Greg C. Lewin and Matthew Shields*

The pandemic caused people to teach classes virtually that they never imagined could be taught virtually. Hands-on classes are among the most challenging to move from in-person to virtual. In this paper, we focus on how prototyping in engineering classes was handled when those classes were taught virtually during the COVID-19 pandemic. Four engineering educators from a diverse set of four schools were engaged on this topic through written reflections and two focus groups. Learning from this experience has implications for these classes as they remain virtual and shift to hybrid and back to in-person. The four educators each found ways to make prototyping work in virtual classes. Shifting closed-ended prototyping from in-person to virtual classes was found to require less change than shifting open-ended prototyping. Within open-ended prototyping, the instructors generally narrowed scopes and took on less ambitious projects, with students engaging in new ways that produced impressive prototypes that surprised some the educators. Access to materials and tools was handled through different approaches, with curated sets of materials that maintain design freedom being important for open-ended projects while a standard set of materials for all teams worked for closed-ended projects. Students expressed more interest in doing projects individually. For those that worked on teams, approaches included having the whole team produce one prototype and having each person produce a prototype. Having each person produce their own prototype opened up the possibility that students would not truly collaborate. Even though they were all virtual, teams of students who had to make a single prototype generally worked better than expected.

*Keywords:* prototyping; distance learning; virtual classes; design

**A Small Rebellion: How to Catalyze Innovation Through Self Actualization** 1875–1890

*Ade Mabogunje, Larry Leifer and Phillip Wickham*

How do you teach creativity? In this paper, we explore ways to create an environment in which students do more than learn – they innovate. The Non-hierarchically Organized Design Engineering (NODE) model creates a new kind of faculty community – one that is collaborative and guided by humanistic values – and one that is able to create the conditions for students to self-actualize i.e., develop autonomy, self-awareness, and self-acceptance. And once they have acquired those attributes, they will have the freedom and the courage to innovate, be that in a prototyping exercise or in their personal lives. Students who are self-actualized will be more creative, more fulfilled in their work, and in the rest of their lives. They will have the ability to achieve peak experiences more frequently – and live with a sense of wonder.

*Keywords:* creativity; innovation; design; prototyping environment

**Semantic Fluency in Design Reasoning** 1891–1903
*Jenny Quintana-Cifuentes and Senay Purzer*

During design, different forms of reasoning shape the designers' decision-making. As a result, the ability to fluently transition across various forms of reasoning is essential. The purpose of this study is two-fold: first is to introduce and explain the concept of *Semantic Fluency in Design Reasoning*, as the ability to transition across multiple forms of reasoning fluently. To identify these transitions, this study used the Design Reasoning Quadrants framework, which represents four quadrants: experiential observations (reasoning based on observations and experiences), trade-offs (reasoning recognizing multiple competing design requirements), first-principles (reasoning requiring disciplinary understandings), and complex abstractions (reasoning in envisioning new situations). The second purpose of this study is to illustrate semantic fluency in a design review conversation. We selected and presented three different forms of transitions identified through our analysis of conversations between students and design reviewers. Our analysis revealed evidence of semantic fluency in young designers. Mike, one of the students, demonstrated fluency across three quadrants (experiential observations, trade-offs, and first-principles). Lisa and David demonstrated two-quadrant transitions. Lisa had fluency from experiential observations to trade-offs, and David transitioned from experiential observations to first-principles. We recommend the intentional use of design reviews to elicit student reasoning in design and adopt questioning strategies to promote fluency across different forms of design reasoning.

*Keywords:* design reasoning; first-principles; trade-offs; engineering design; K-12; pre-college engineering

**The SmithVent Experience and a Framework for Collaborative Distributed Design and Fabrication** 1904–1922
*Susannah Howe, Eleanor Ory, Devin Carroll, Sarah Chu, Kalifa Clarke, Beatrix Dalton, Claire Dudek, Adrienne Horne, Nicholas Howe, Sangye Kazi, Astrid Landeau, Dan Lin, Phoebe Degroot, Emily Dixon, Farida Sabry and Alex Widstrand*

This paper addresses the collaborative journey of the SmithVent team, a 30-person distributed group of volunteers, who designed, fabricated, and tested a simplified and cost-efficient ventilator over a three-month period, and won the CoVent-19 Challenge in July 2020. The paper first presents the SmithVent experience through a co-constructed narrative that describes the team's approaches to collaborative distributed design and fabrication. The paper next reviews frameworks from five theoretical lenses and then details the process of extracting, synthesizing, and organizing relevant factors to create a new and emergent framework reflective of the SmithVent experience. Lastly, the paper discusses educational implications of the SmithVent experience and proposed framework, emphasizing that the team's strategies provide a model for educational and industry settings for future collaborative and distributed design and fabrication.

*Keywords:* distributed fabrication; collaboration; distributed design; virtual teams; remote making; remote learning; Scrum; ventilator; SmithVent; CoVent-19 Challenge; COVID-19

**Using Practitioner Strategies to Support Engineering Students' Intentional Use of Prototypes for Stakeholder Engagement During Front-End Design** 1923–1935
*Ilka B. Rodriguez-Calero, Shanna R. Daly, Grace Burleson, Marianna Coulentianos and Kathleen H. Sienko*

Engaging stakeholders early and throughout design processes is necessary for product success as it supports the alignment of design decisions with user and stakeholder needs and preferences. Leveraging prototypes to engage stakeholders can help designers develop common ground with stakeholders, especially during "front end" design activities, such as problem scoping and product requirements development. While design practitioners intentionally use prototypes to engage stakeholders in a variety of ways including during the earliest stages of design, research suggests that novice designers are not as intentional or comprehensive in their approaches. Therefore, we developed in-depth narratives constructed from practitioners' real design experiences to demonstrate to novice designers how design practitioners use prototypes for stakeholder engagement during the design front-end. Further, we described strategies that could be incorporated into engineering classrooms and suggested ways to support more intentional uses of prototyping strategies by students to engage stakeholders during the design front-end, including through the use of a novel prototyping planning tool.

*Keywords:* prototyping; stakeholder engagement; front-end design; design practice; engineering education

**Cultural Influence on Providing Peer Feedback in an Engineering Design Course** 1936–1952
*Gordon G. Krauss*

This study evaluates cultural differences between students based in Austria (n = 20) and the United States (n = 6) around providing fast, frequent team feedback evaluation during an engineering product development course. Both cohorts consist of self-selected teams working on project topics and products of their own choosing. Students were required to provide feedback on the performance of their teammates by indicating if their work was complete and on time for each assignment and through the ordinal ranking of the contributions of each team member to the individual assignment submission over five assignments and after the final project. The perceptions of the students are recorded following the final feedback submission of the course to understand how effective they perceived the feedback tool, including the authenticity of their participation, noted behavioral change in themselves and others, opportunities to increase the impact of the feedback information, and the overall effectiveness of the feedback process. Significant differences were noted in the approach and attitude of students to team member issues that might inform instructors attempting to gather information on teams and increase awareness of cultural differences to the approach to feedback preferred by students.

*Keywords:* project-based learning; peer feedback; team member evaluation; team feedback

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