2012

The Key Ideas of MDW VIII: A Summary

Aaron Altman
University of Dayton, aaltman1@udayton.edu

Clive L. Dym
Harvey Mudd College

Ray Hurwitz
Harvey Mudd College

John W. Wesner
Carnegie Mellon University

International Journal of Engineering Education Vol. 28, No. 2, pp. 501–511, 2012
Printed in Great Britain
0949-149X/91 $3.00+0.00

The Key Ideas of MDW VIII: A Summary*

AARON ALTMAN
Department of Mechanical and Aerospace Engineering, University of Dayton, 300 College Park Avenue, Dayton, OH 45469-0238, USA.
E-mail: aaron.altman@notes.dayton.edu

CLIVE L. DYM
Department of Engineering, Harvey Mudd College, 301 Platt Boulevard, Claremont, CA 91711-5990, USA. E-mail: clive_dym@hmc.edu

RAY HURWITZ
Harvey Mudd College, 301 Platt Boulevard, Claremont, CA 91711-5990, USA. E-mail: ray_hurwitz@hmc.edu

JOHN W. WESNER
Institute for Complex Engineered Systems, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213-3890, USA.
E-mail: wesnerj@asme.org

This paper summarizes and highlights the presentations and discussions that took place during Mudd Design Workshop VIII, 'Design Education: Innovation and Entrepreneurship,' at Harvey Mudd College. This paper also describes both the key ideas that emerged from the presentations and discussions of the participating engineering design educators, practitioners and researchers, and the methodology used to capture and retain those ideas. Additionally, this paper proposes a framework of design competencies that were created and evolved by the workshop's participants as a response to a question posed at one of the workshop sessions: 'What are the minimum design competencies students should learn from our programs?'

Keywords: design education; innovation; entrepreneurship

1. Introduction

The eighth Mudd Design Workshop (MDW VIII), supported by Harvey Mudd College's Center for Design Education and the National Science Foundation, was held at Harvey Mudd College during 26–28 May 2011 and titled as 'Design Education: Innovation and Entrepreneurship.' The Workshop was organized in much the same way as its predecessors. Dym, the Workshop organizer and host, opened the Workshop by citing classic definitions of the Workshop's two key terms [1]:

- **innovate** (v) to bring in or introduce novelties; to make changes in something; to introduce innovations
- **entrepreneur** (n) the director or manager of a public musical institution; one who undertakes an enterprise; a person who takes the risk (of profit or loss)

Dym went on to share the roots of the Harvey Mudd Engineering curriculum, which puts experiential learning on an equal footing with 'book learning,' as a testament to the innovation and entrepreneurship exhibited by the visionaries who founded the Engineering program [1].

In a similar vein, the traditional keynote format was forgone in favor of two reflective and retrospective talks on how the speakers found their success as engineering design professors. Berkeley's Alice Merner Agogino spoke about her own unique journey and how she forged her own path [2]. She framed much of her academic life's voyage in terms of her own students' experiences and how much she learned and evolved through them, citing as one example a former engineering graduate student, Catherine Newman. Agogino plotted out her overall story path with a mind map on the whiteboard, illustrated in real time by another graduate student, Lora Oehlberg. The story centered around living one's own life and doing engineering on one's own terms, or in other words, living life within the constraints of the resources provided rather than trying to fit into a profile of what an engineer should be.

Stanford's Larry J. Leifer used a hunting analogy to describe engineering design [2]. He drew a visual depiction of a meandering path to a target and the associated return path to the village representing the steps required reaching a goal. His accompanying slides emphasized the point that there is no map to success in life.

The keynotes related strongly to the overall theme of the workshop as they focused on employing creativity to find one's way in life, as well as in successful innovation and entrepreneurship. Both of the talks also indicated an uneasy ambiguity associated with defining what it means to be a design engineer. From the perspective of the workshop goals, these themes dovetailed naturally into initial discussions on the most basic level of the

* Accepted 20 August 2011.

definition of innovation, as the central topic of the first session was *characterizing innovation*. The remaining six sessions of presentation and discussion were also devoted to various articulations of that theme. Each session started with four 10-minute 'position talks' that were followed with about 75 minutes of vigorous open discussion. The moderated discussion was organized around a panel comprised of each session's speakers* (and often their co-authors). This Workshop also included a poster session for the very first time, highlighting eight more papers. MDW VIII ended with an affinity diagramming exercise and a closing luncheon.

As was done at the previous Mudd Design Workshops, an effort was made at the end of MDW VIII (and afterward) to identify the most important ideas and themes that emerged over the course of the Workshop. The intent was to provide both Workshop participants and others with ideas or action items that they can incorporate into their own teaching, and thus implement things they learned at the Workshop. This was implemented by asking each session chair to capture a small number of 'key ideas' that were brought up in their session, either in the prepared presentations or in the ensuing discussion. At the end of the Workshop, all of the participants were asked to cluster these key ideas (using a methodology to be described in more detail in a later section) by common themes. Interestingly enough, many of these key ideas are really rather specific action items.

The next section of this paper summarizes the presentations and ensuing discussions of each of the seven formal Workshop sessions. It is followed by a description of the methodology used to pull together the main concepts of MDW VIII, an articulation of those main concepts and the key ideas and action items behind them, and then closes with a list of the relevant design competencies that educators should foster in their students' development, as identified by the workshop participants.

2. Session presentations and discussions

The themes of innovation and entrepreneurship were focused on some important modern challenges, as can be seen in the following descriptions of the seven formal sessions.

2.1 Session I: characterizing innovation

Ferguson [4] promoted much thought and discussion on what the profession considers 'engineering innovativeness.' Many different perspectives on what differentiates innovation from ordinary design and product realization were offered and no consensus definition surfaced. Clearly, if innovation must be taught, some established definition of its meaning must be arrived upon!

McKenna [5] discussed how modeling relates to both design process and analysis, as well as how students do not always recognize the full and nuanced ways that these two interact. The presentation explored the roles that computational, analytical and modeling abilities play in innovation, in the context of engineering design education. It highlighted faculty and students' conceptions on the variations in how they describe how to model a design idea or solution, and the different ways each group perceives how models can be useful/helpful in the design process. The (later) discussion focused on the heightened role of meta-cognition in the identification of the different manners in which modeling and analysis interact with process. Additionally, a recurring theme emerged: how and where do students learn when it is appropriate to apply a specific set of skills?

Currano [6] concentrated on reflective practices used by designers in idea generation. A variety of reflective practices used by design students in originating new insights and ideas were presented. A clarified definition of reflective practice was offered, derived from Donald Schön's concept of reflection-in-action. A framework for characterizing reflective practices was assessed and validated. The following discussion of this presentation complemented the next presentation as both delved more deeply into the value of reflection and the different manners in which reflection can be assessed or documented. In particular, the idea of using reflection as a tool for ideation in innovation was discussed.

Burton and Vanasupa [7] finished the formal presentations of this session by positing that the disposition required for transformational innovation relies on interrupting existing patterns. This requires the conscious recognition of patterns, which necessitates an active practice of self-observation. Unlike the processes of problem solving and process improvement, transformational innovation requires insight into the individual and collective attention of the designers. It also allows access to unexamined mental models and apparent cause and effect relationships. It was also noted that transformational innovation within organizations requires reflection, experimentation and learning within the human system. It is the human component that is the most often neglected component in the innovation process.

The concept of 'out-of-action reflection' generated conversation related to the idea that few allow

* In the case of multi-authored papers, the session description lists the name of the actual presenter, while the reference identifies all of the papers' authors.

themselves time for reflection outside of their problem-solving environments, with the example of the morning shower 'Eureka' revelation being shared by many. How can students be expected to find the time for out-of-action reflection? The concept of refocusing design around the variable of the human system also generated further discussion related to the environmental factors that influence that system and were revisited in later sessions. It was generally agreed that all of these factors contribute to making more creative approaches to design and innovation available.

2.2 *Session II: students seeing innovation*

Bigelow [8] opened the second session by talking about student perspectives in an all-female first-year engineering innovation class. She detailed the perceived benefits and consequences of having an all-female section of the class as found through reflective papers. She expanded on the results by suggesting ways in which mixed gender classes could be more inclusive to all students. One classic point made was the reflection from one of the students stating that they didn't understand why they had access to band saws and drills and not a sewing machine!

Lau [9] articulated the role of diversity in design team performance and how diversity factors affect the dynamics and success of a design team. Kolb's Experiential Learning Theory was used as a framework from which to evaluate diversity in learning styles, and other demographic factors such as discipline and gender were considered. The results offer insights into how students with different learning styles contribute to design team performance as well as their own ability to assess that performance.

Rhee [10] described a pilot multidisciplinary senior project combining sustainability, innovation, and entrepreneurship. The influence on individual student performance of personality domains described by the 'big five' (extraversion, agreeableness, conscientiousness, emotional stability, and openness), the group experience, and attitudes towards multi-disciplinarity, were explored at the end of the first semester of a two-semester experience.

McKenna [11] discussed the use of a hierarchical coaching model in educating and guiding undergraduate engineering design teams in innovative design projects. The coaching model incorporated the use of graduate students as coaches of design teams and faculty as mentors of the graduate students. Two underlying themes were attributed to the successful execution of this model: the development of human connections between the coach and undergraduate design team, and the need for mentorship of the graduate student coach.

All papers in this session related to some aspect of team-based design, while the first three directly addressed diversity of gender, learning styles and personality traits. This was a data intensive session and the discussion focused mostly on ensuring a proper understanding of the data. The audience was intrigued by the result that teams made up of students with similar traits were less effective (and less able to assess their own performance) than most of the more diverse teams. The discussion also emphasized that the personal connection between instructor/mentor and design team was highly advantageous. The mentoring of design teams would be continued in the next session.

2.3 *Session III: improving innovation learning (I)*

Gerber, Olson and Komarek [12] continued the discussion of a peer-mentored design process: a student-directed approach to engineering education called Extracurricular Design-Based Learning (EDBL) that aims to foster innovation design self-efficacy was described. EBDL focuses on peer mentored human-centered design and innovation for social and local impact in extracurricular settings. One implementation of EDBL through Design for America (DFA), a student-centered extracurricular development program, was described. In the ensuing discussion it was noted that similar environments are often seen in the more informal extracurricular design competitions in which many schools participate. The idea that design students are frequently paralyzed into inaction by facing too many choices was also raised, and the possibility that it isn't always necessary to choose one or the other was suggested, and that incorporating elements of multiple approaches can be achieved. It was noted, however, that students may need to be guided through these choices.

Thompson [13] described a model for encouraging innovation in a required cornerstone design course. The opportunities for students to continue their work after the end of the semester were described, and innovation indicators resulting from the course, such as publications and patents, were noted. It was shown that the faculty members′ comfort and familiarity with innovation, intellectual property, and entrepreneurship were a major factor in whether or not patents were filed after student projects. It was suggested that a follow-up course on innovation and entrepreneurship may help to incubate promising student projects, while at the same time it might increase faculty and TA knowledge about innovation and entrepreneurship and help establish a culture of innovation and entrepreneurship. In the subsequent discussion the issue was raised that whether or not the design projects continued depended quite strongly on the associated faculty mentor's comfort level and familiarity with the process of dealing with IP and had little to do with the relative merits of the resulting designs.

Strong [14] described a series of multidisciplinary design courses at a Canadian university, the initial difficulty in gaining acceptance for the courses across the faculty and participating departments, and their continued high success and popularity. He stated that as a form of validation, client response has typically been outstanding and is reinforced with a very high rate of year-over-year client return. Finally, student surveys and a design skills assessment have provided statistical evidence of increased competency.

Goldberg [15] focused on how the needs identification and problem definition phases of design are frequently bypassed in design courses when students are provided with a list of potential projects from which to choose. It described a junior-level biomedical engineering course designed specifically to address these shortcomings: the students had to observe medical and surgical procedures in various clinical environments. This helped develop their clinical literacy and their listening and ethnographic observation skills. Subsequent discussion focused on details of the observation environment and process, as well as the structure within which the work was performed. Issues about the learning environment and its impact on innovation emerged again in the next session.

2.4 Session IV: improving innovation learning (II)

Brunhaver and Lande [16] described a course to prepare students for high technology entrepreneurship, or 'technopreneurship.' The factors that comprise the course's enterprising learning ecology were described, including laboratory space, course structure, teaching staff, and peer environment. Situated learning theory was leveraged to describe how the social interactions influence learning taking place within a 'community of practice.'

Beckman [17] described how students struggle with design regardless of the process used to teach them. The reasons for the struggle result from the facts that design is a messy and ambiguous process, students lack the basic skills needed to engage in the process, and students' learning orientations don't support the key activities needed to do design. Storytelling was offered as a new way of thinking about the design process. In this context, five basic skills need to be developed if students are to become better at design: empathizing, generating insights, diverging, iterating and performing. The skill of empathizing generated subsequent discussion that built on the previous session on the subject of needs identification and problem definition: empathy was identified as being critical to the good listening skills deemed necessary to perform good needs identification and problem definition.

Johri [18] introduced a novel approach to design education that draws on advances in open innovation to reorganize design learning in both formal and informal settings. The extension of design education to external clients increases the authenticity of projects and makes the design task the cornerstone of the learning activity.

Schaefer [19] discussed an innovative approach to design education that represents a transformation from traditional in-class education to a globally distributed collaborative distance learning setting that mirrors real-world design experience. Techniques such as collaborative and collective learning, the creation of a 'learning organization,' scaffolding, reflective practice based on *observe-reflect-articulate*, learning essays, threshold concepts and transformational learning were implemented and discussed.

The idea that peer learning is a powerful tool in developing strategies to foster innovation was raised in the audience discussion that centered on a consensus that teamwork and critical thinking should be integrated progressively, across the entire curriculum: not just in a single capstone course. A familiar point was raised that there is a distinction between teaching necessary design skills and teaching design processes. This led to discussion about the structure within which design and disciplinary coursework are taught, and the revelation that it is difficult to ask students to innovate when they are surrounded by the structure endemic to the present curricular system. This provided an excellent transition to the next session that started with the creation of a new engineering school from a clean slate.

2.5 Session V: views from on top

Magee [20] talked about launching a new university, the Singapore University of Design and Technology (SUTD), striving to establish a 21st century innovation paradigm that recognizes a synergy between research and design. He addressed the challenge of conflicting agendas between design-centric education and the norms of a leading research-intensive university, and provided an overview of research intended to address this conflict. One example highlighted the 'feeling' that design is highly non-systematic: thus some in academia question whether it can be taught or even whether it has value in the curriculum. The second challenge discussed in some depth was the setting of 'culture' for the new institution that encourages bold attempts to improve the world through technical innovation ('innovation culture') with breadth in national cultures ('global culture') bridging from Western to Asian perspectives.

Jorgensen [21] discussed various conceptualizations of innovation and entrepreneurship. Engineering educators and researchers in Denmark identified three different response strategies to emerging challenges in the education of engineers: a technology driven promotion response; a business selection response strategy; and a design intervention response strategy. The need to further develop and strengthen a robust notion of innovation and entrepreneurship was emphasized, to overcome naïve hopes that traditional, narrow engineers can keep pace with innovation in a global economy.

Trevisan [21] described a web-based professional responsibility instrument and accompanying rubric that was used to assess students' understanding and their skill at identifying and discussing areas of strength and opportunity in an ethics case taken from the students' projects. Students completing the instrument most frequently rated work competence as both highly important and as a team strength, while issues of sustainability were least frequently cited. The scored results of this instrument showed students were moderately effective at relating ethical issues to situations within their projects, as well as addressing them responsibly.

Discussion in this session had an underlying theme heavily influenced by the international nature of the presentations. The highly collaborative—and often international—environments in which engineers practice produced a consensus that engineering students should be taught how to work in teams. The success of team-based engineering rather than individual, isolated work was thought by some to be due to the complexity of the problems being addressed by engineers today. The discussion then turned to more socio-cultural influences on engineering design. There was a belief that helping students to understand the social culture and environmental significance of their work should be an integral part of teaching problem-solving skills. This could also be connected to earlier discussion on the utility of empathy in the early stages of design. Finally, there was discussion on the manner in which ethics is synthesized by different cultures and how it might be part of a more general, personal, legal or social aspect of other cultures.

2.6 Session VI: entrepreneurship

Reed-Rhoades [23] provided a good high-level perspective on entrepreneurship in engineering education. She explored a broad array of attitudes toward and outcomes of entrepreneurship education on engineering students in order to understand: the characteristics of students participating in related courses and activities, the nature and extent of their involvement, entrepreneurship's role in their career plans, and its impact on entrepreneurial self-efficacy.

Yasuhara [24] discussed an extension of the Academic Pathways Study (APS), beginning with a brief discussion on how engineering entrepreneurship demands a broad range of skills and knowledge, such as motivation and proactive behavior, professional skills (*e.g.*, communication, leadership, business), and creativity in problem solving. The APS results showed positive relationships between entrepreneurial attributes and involvement in engineering and non-engineering extracurricular activities. These activities generally fostered entrepreneurial attributes and contributed to students engineering education experiences. The subsequent discussion centered on how teaching students to become good entrepreneurs helps them become better engineers because it adds emphasis to traits such as creativity and persistence that are valued in engineering and design in general.

Sinfield [25] drew parallels between advanced design problem-solving skills and those employed by entrepreneurs: to help engineering students develop such skills, educators must provide educational experiences that motivate students at both a cognitive and meta-cognitive level and enable them to recognize potentially flawed paradigms so that they can tackle ambiguous and ill-structured problems. Entrepreneurs routinely employ the same skills as they seek to break with accepted norms and pioneer new approaches to problems they observe in their environment. With this analogy in mind, the implementation of an entrepreneurially oriented case study was presented as a means to enhance engineering student attitudes and perspectives on problem solving and learning. This presentation and related discussion built upon earlier comments about the value of varying perspectives and shifting paradigms in entrepreneurship and innovation (Session II), as well as about relating to the environment and how it relates to innovation and creativity (Session IV).

Oden [26] described the efforts and early outcomes in incorporating entrepreneurship concepts into an interdisciplinary capstone design program. Elements such as an 'elevator pitch' competition, business planning, intellectual property, project management and planning, and others are taught in modules and are now available to be taught in any capstone design course. Some 'nuts and bolts' component elements of an entrepreneurial curriculum were mentioned, contrasting with the opening talk in the session which was much more global in nature. This session dovetailed well into the banquet lecture in which the president of the new SUTD, Thomas L. Magnanti, provided both high-level and curricular-level views of the creation of a new design-oriented university.

One aspect of the discussion that didn't seem directly inspired by any of the sessions talks related to how students could learn from both successful and unsuccessful entrepreneurship. A caveat was noted that the lessons learned are typically valuable on a case-by-case basis.

2.7 Session VII: curriculum matters

Daly [27] returned attention back to the course level, and to the tools that can be utilized to improve the quality concepts proffered early in the design process. She and her colleagues studied the use of design heuristics as prompts that encourage design space exploration during concept generation. Students were given a short design task and a set of twelve design heuristics cards and were then asked to create new design concepts using the heuristics. The results showed that design concepts created without design heuristics were less developed, and were often either replications of known ideas or minor changes to existing products. However, concepts created using design heuristics resulted in more complex, creative designs. The study also showed that some students readily applied the heuristics, while others struggled to understand how to apply them.

Silva [28] described two independent experiences in teaching design in two courses of an Mechanical Engineering Integrated MSc degree, suggesting that different approaches to design teaching need to coexist for students to get a grasp of what engineering practice is. One case study focused on the role of entrepreneurship and intellectual property in design teaching, highlighting the duality of perceived challenges and attitudes of engineers and entrepreneurs and other areas of similarity and difference between standard engineering practice and the entrepreneurial process. A second case study described a design-led approach to a structural mechanics course that explores the relationships between mechanical design and engineering analysis. In that case, the exploration was undertaken with the task of designing a folding umbrella, with all of its underlying complexity while also addressing the challenge of knowing how much analysis was appropriate, an issue that had been raised in earlier sessions.

Oehlberg [29] described two educational programs which engaged undergraduates from multiple disciplines in design education: '{design.},' a student-initiated course on the basic human-centered design process and philosophy; and a 'human-centered design course thread,' a certificate program in which students took multiple courses across departments that were thematically linked to human-centered design. The impacts these programs have had on participating students' multidisciplinary design education was explored, particularly: pursuing design as a career, participating in the multidisciplinary design community, and broadening perspectives of design.

Butler and Goff [30] explored the educational impact of utilizing realism and simulation to introduce the aircraft design process with the aim of determining if such an approach could help remedy the academia-industry disconnect while simultaneously creating an engaging design experience for the students. Early results indicated that the use of simulation was welcomed by the participants of the study and can help prepare students to think as working design professionals and to not be limited by the generic design solutions often found in academic de-contextualized design problems.

Much of the discussion related to specific interventions that could be undertaken to guide students in better implementing analysis in design. Heuristics were raised as one of the means, which led to discussion on how best to implement, teach and evaluate their use. Some discussion focused on advanced rubrics in design. The main idea that percolated up from the discussion was a revisit of conclusions drawn in earlier sessions relating to the need to better understand relationships and methods to integrate design and analysis.

3. The main concepts and the key ideas behind them

Each of the Workshop's session moderators was charged with capturing what s/he believed to be the three or four most important or *key ideas* and issues brought out in their session, either from the presentations or in the ensuing discussion. These key ideas (which are collected in the next section) were printed onto index cards, one key idea per card, as a prelude to the end-of-Workshop affinity diagramming exercise. After the last session, the Workshop participants were broken into several teams, each provided with an identical set of cards, and challenged to gather the key ideas into common categories or affinity groups according to common themes [31, 32]. This affinity diagramming activity was designed to obtain a compiled set of the *main concepts* on which future discussion and efforts pertaining to engineering education research and curriculum attention could be centered. The construction of affinity diagrams by teams is intended to be a silent exercise in which everyone in a team works together to cluster related items (affinities). Once the clusters are finalized names for the assembled categories can be chosen through discussion amongst team members [31]:

> The purpose of this exercise is to identify natural groupings of items by silently and simultaneously,

everyone working at the same time, placing the Post-It® notes with other Post-It notes that belong together. No discussion is allowed. Anyone can continue to move Post-It notes around until everyone is content with the groupings (or tired, whichever comes first).'

In this case, index cards were used in place of Post-It notes.

The results of each team's work were blended together using a spreadsheet, to identify common groups. The titles assigned to the affinity groups were used as the basis for identifying the Workshop's main concepts. This process required visual inspection to identify clusters of similar repeat occurrences within and across groupings. These clusters were then given titles based on their content and the result of this clustering process as well as the clustered ideas can be seen below.

4. Summary of main concepts

As described above, based upon input from the Workshop participants, the key ideas or issues gleaned from the formal sessions were used to identify the most important core concepts which were further refined into a set of seven *main concepts* that emerged at MDW VIII: methodologies for teaching and learning design; the promotion of design education within academe; enabling students to experience the value of teamwork; exposing students to the roles of culture and environment in design; providing students with entrepreneurial experiences; teaching students how, when and where to apply the fundamentals; and teaching students what innovation really means.

Many of the *key ideas* identified by the several Workshop teams also turn out to be useful *action items*. Both the seven actionable main concepts and underlying key ideas are detailed below. The letter and number in brackets following each key idea (e.g., '[S1]') identify the Workshop session from which this idea emanated.

(a) **Methodologies for teaching and learning** design combine two team clusters, with five shared key ideas:
- Stepping back to a more objective perspective, using metacognition, can be a useful critical thinking tool. [S1]
- Designers use a variety of reflective practices, many of which can be classified as 'out-of-action reflection.' These do not even appear on our radar or in textbooks, and yet they form a large percentage of the many reflective practices that lead to new ideas and insights. [S1]
- Apparently either/or conflicts are often resolved by realizing one can choose both. [S3]
- Alternatives should be mapped as an aid to help students make choices. [S3]
- Teaching necessary design skills is different than teaching design processes. [S4]

(b) **Promoting design education within the academic environment** combines three team clusters, with four shared key ideas:
- The knowledge and culture that faculty bring to a classroom matter. [S3]
- It is important that faculty recognize that it is difficult to ask students to truly innovate when they are surrounded with rather hard structure. [S4]
- Design faculty must recognize that they still must help their faculty colleagues to see and value the importance of teaching design-based engineering.
- Personal connections between students and project faculty facilitate a more productive engineering design process. [S2]

(c) **Students should experience the value of teamwork** combines three team clusters, with five shared key ideas:
- There is a consensus that teaching engineering students to work in teams is a valuable undertaking, especially considering the collaborative environments in which engineers practice the profession (e.g., outsourcing in virtual companies, collaboration without teaming, fully formed functional teams). [S5]
- Design teams with a balance of learning styles typically are better able to assess their own progress in the course. [S2]
- Learning teamwork and critical thinking must be emphasized across a series or progression of courses, rather than just in a single course. [S4]
- Peer learning is a very powerful tool in developing strategies to foster innovation. [S4]
- Due in large part to the increased complexity of problems addressed by engineers, engineers are much more likely to work (and to succeed) doing team-based engineering, rather than individual, isolated work. [S5]

(d) **Expose students to the roles of culture and environment in design** combines two team clusters, with two shared key ideas:
- While North American engineering education includes an explicit focus on ethics, European and Asian universities generally consider this to be part of a more general personal, legal or social aspect (perhaps related to notions of citizenship). This has implications for how international design activities are conducted. [S5]
- An integral part of teaching problem-solving

skills means teaching students to understand both social culture and environmental significance. [S5]

(e) **Provide students with entrepreneurial experiences** is based on a single cluster:
- Teaching students to become better entrepreneurs can help them become better engineers because it adds emphasis to traits such as creativity and persistence. [S6]
- Students can learn from both successful and unsuccessful entrepreneurship, although the lessons learned are typically valuable on case-by-case basis. [S6]

(f) **Teach students how, when and where to apply the fundamentals** is based on a single cluster, with a single unique key idea:
- Students should develop a better understand of relationships and methods to better integrate design and analysis. [S7]

(g) **Teach students the full meaning of innovation** is based on a single cluster, with one key idea that is an important educational step. This particular key idea appeared in other clusters, but in those other instances it was mixed with ideas that were shared in other main concepts:
- A major step in the process of teaching innovation is defining innovation. A shared concrete definition enables both its measurement and improvement. [S1]

5. Design competencies identified by MDW VIII participants

During one of the session discussions, Terpenny issued a challenge to the assembled participants to identify the core competencies necessary to performing design. This challenge was posed after an audience consensus emerged: students are, in general, ill prepared to do design when they start design classes. As a direct response to the challenge, Agogino organized an impromptu activity designed to identify the core competencies that students needed to enjoy success in design. A workshop replete with engineering design professors and students seemed an ideal environment to assemble such a framework of core design competencies. Just as technical skills and mechanical principles are important to design education, there are other, less-quantifiable core abilities that are vital to success in design. The purpose of this exercise was go one step further and to articulate these traits and capabilities with the aim of enabling proper assessment of them.

Agogino suggested a Post-It™ note affinity-type exercise to have Workshop participants write notes (and place them on a dedicated whiteboard) identifying the most important design competencies. The MDW VIII participants responded overwhelmingly, resulting in an abundance of notes that led to the list of design competencies presented below. The competencies were separated into affinity groups and then titled after multiple iterations as participants passed by the board throughout the Workshop refining their contributions. The final listings are divided into eight sections, and it is worth noting that the competencies are a mix of attributes—especially the first set of personal attributes—while the remaining seven are mixtures of attributes and of skills to be developed:

1. Personal Attributes
2. Evaluation and Testing
3. Creativity
4. Identifying Problems and Opportunities
5. Communication and Teamwork
6. Knowledge Creation and Thinking Processes
7. Making Things
8. Technical Fundamentals

The competencies within each of these sections, found below in the Appendix, illustrate some, but not all, valuable aspects of an engineering design student. While the expanded list of competencies is more wide-ranging than the basic Workshop theme, there are clearly a number of items in this list that support the Workshop's main concepts and were integral part of the Workshop conversation.

6. Conclusions

Innovation and entrepreneurship have become highly visible in academe these days and in engineering education in particular. From the proceedings and discussions at MDW VIII, it seems clear that these words do have a lot of import for engineering education, while at the same time they serve as overarching rubrics for a variety of concerns about how to help educate and raise good engineering designers. It is hoped that the issues and needs addressed at MDW VIII can further assist the ongoing conversations about design education.

Acknowledgments—We gratefully acknowledge the support provided by the National Science Foundation under Grant EEC-1102663, as well as by the Center for Design Education at Harvey Mudd College.

References

1. C. L. Dym, Engineering Design @ HMC: A Testament to Innovation and Entrepreneurship, *International Journal of Engineering Education*, **28**(2), February 2012.
2. Agogino keynote paper
3. M. Steinert and L. J. Leifer, Finding One's way: Re-Discovering a Hunter-Gatherer Model based on Wayfaring, *International Journal of Engineering Education*, **28**(2), February 2012.

4. D. M. Ferguson and M. W. Ohland, What is engineering innovativeness?' *International Journal of Engineering Education*, **28**(2), February 2012.
5. A. F. McKenna and A. R. Carberry, Characterizing the role of modeling in innovation, *International Journal of Engineering Education*, **28**(2), February 2012.
6. R. Currano and M. Steinert, A framework for reflective practice in innovative design, *International Journal of Engineering Education*, **28**(2), February 2012.
7. R. Burton, L. Schlemer and L. Vanasupa, On the use of pattern interruption and self-observation in human systems for transformative innovation, *International Journal of Engineering Education*, **28**(2), February 2012.
8. K. E. Bigelow, Student perspectives in an all-female first-year engineering innovation course, *International Journal of Engineering Education*, **28**(2), February 2012.
9. K. Lau, S. L. Beckman and A. M. Agogino, Diversity in design teams: An investigation of learning styles and their impact on team performance and innovation, *International Journal of Engineering Education*, **28**(2), February 2012.
10. J. Rhee, D. Parent and C. Oyamot, Influence of personality on a senior project combining innovation and entrepreneurship, *International Journal of Engineering Education*, **28**(2), February 2012.
11. M. V. Manuel, A. F. McKenna and G. B. Olson, The driving force behind student innovation in capstone design projects: Insights into the human connection, *International Journal of Engineering Education*, **28**(2), February 2012.
12. E. M. Gerber, J. M. Olson and R. L. D. Komarek, Rethinking how students prepare for careers in innovation: A case study of extra-curricular design-based learning, *International Journal of Engineering Education*, **28**(2), February 2012.
13. M. K. Thompson, Fostering innovation in cornerstone design courses, *International Journal of Engineering Education*, **28**(2), February 2012.
14. D. S. Strong, An approach for improving design and innovation skills in engineering education: The multidisciplinary design stream, *International Journal of Engineering Education*, **28**(2), February 2012.
15. J. R. Goldberg, Learning to identify unmet needs and new product opportunities, *International Journal of Engineering Education*, **28**(2), February 2012.
16. S. Brunhaver, M. Lande, S. D. Sheppard and E. Carryer, Fostering an enterprising learning ecology for engineers, *International Journal of Engineering Education*, **28**(2), February 2012.
17. S. L. Beckman and M. Barry, Design as a storytelling process: Implications for teaching, *International Journal of Engineering Education*, **28**(2), February 2012.
18. A. Johri and H. J. Teo, Levering advances in open innovation to re-design design learning.
19. D. Schaefer, J. H. Panchal, J. L. Thames, S. Haroon and F. Mistree, Educating engineers for the near tomorrow, *International Journal of Engineering Education*, **28**(2), February 2012.
20. C. L. Magee, K. L. Pey, J. Chen, L. Jianxi and D. D. Frey, Beyond R&D: What design adds to a modern research university, *International Journal of Engineering Education*, **28**(2), February 2012.
21. U. Jorgensen and A. Valderrama, Response strategies to new challenges to engineering and design education, *International Journal of Engineering Education*, **28**(2), February 2012.
22. J. McCormack, S. Beyerlein, D. Davis, M. Trevisan, J. Lebeau, H. Davis, S. Howe, P. Brackin, P. Thompson, R. Gerlick, J. Khan and P. Leiffer, Contextualizing engineering ethics in capstone projects using the IDEALS professional responsibility assessment, *International Journal of Engineering Education*, **28**(2), February 2012.
23. N. Duval-Couetil, T. Reed-Rhoades and S. Haghigi, Engineering students and entrepreneurship education: Involvement, attitudes and outcomes, *International Journal of Engineering Education*, **28**(2), February 2012.
24. K. Yasuhara, H. L. Chen, M. Lande and S. D. Sheppard, Educating engineering entrepreneurs: A multi-institution analysis, *International Journal of Engineering Education*, **28**(2), February 2012.
25. J. Garcia, J. Sinfield, A. Yadav and R. Adams, Learning through entrepreneurially-oriented case-based instruction, *International Journal of Engineering Education*, **28**(2), February 2012.
26. Z. M. Oden, M. K. O'Malley, G. Woods, T. Kraft and B. Burke, Outcomes of recent efforts at Rice University to incorporate entrepreneurship concepts into interdisciplinary capstone design, *International Journal of Engineering Education*, **28**(2), February 2012.
27. S. R. Daly, J. L. Christian, S. Yilmaz, C. M. Seifert and R. Gonzalez, Assessing design heuristics for idea generation in an introductory engineering design course, *International Journal of Engineering Education*, **28**(2), February 2012.
28. A. Silva and L. Faria, Two approaches to design teaching in a mechanical engineering curriculum, *International Journal of Engineering Education*, **28**(2), February 2012.
29. L. Oehlberg, I. Leighton, A. M. Agogino and B. Hartmann, Teaching human-centered design innovation across engineering, humanities and social sciences, *International Journal of Engineering Education*, **28**(2), February 2012.
30. Wm. M. Butler, J. P. Terpenny, R. M. Goff, R. S. Pant and H. M. Steinhauer, Improving the aerospace capstone design experience through simulation based learning, *International Journal of Engineering Education*, **28**(2), February 2012.
31. M. Brassard, *The Memory Jogger Plus, Featuring the Seven Management and Planning Tools*, Goal/PQC, Salem, New Hampshire, 1989.
32. J. W. Wesner, J. M. Hiatt and D. C. Trimble, *Winning with Quality: Applying Quality Principles to Product Development*, Addison Wesley, Reading, Massachusetts, 1994.

Appendix A

The following desired design competencies, organized by section, emerged during MDW VIII:

Personal Attributes: Comfort with and tolerance for ambiguity, resourceful, persistent, open-minded, can relax and have fun, sense of humor, be willing to step aside and be willing to step up, be sufficiently self-confident to lead, able to take risks, confident in asking questions and coming up with ideas, can recover from failure, is proactive and fearless, gives credit where credit is due, collegial and trusting, can identify and actuate passion, has humility, knows when to get help, knows when too much time and resources have been exhausted on one design step, can accept failure gracefully, can let go of ideas, is curious.

Evaluation and Testing: Can compare and evaluate solutions, can demonstrate modeling and analytical skills, has ability to 'listen to' tests, experiments with prototypes, exploits and interprets what is heard (for debugging).

Creativity: Can generate ideas and brainstorm, can offset decision-making tools to assess risk and potential failure, can generate a variety of solutions that are both novel and feasible, can think outside the box, has creative thinking skills, can create unexpected solutions that are innovative.

Problem and Opportunity Identification: Can discover or identify problems, can define the problem, can identify constraints, can identify a market and assess a market opportunity, can understand the context of the problem being solved, is optimistic and seeks opportunities (even among constraints), can identify customer needs and opportunities for innovation, making user centricity real.

Making Things: Has prototyping skills, knows when to model or prototype, builds (i.e., less talk, more action), uses tools to build, builds to learn, does iterative prototyping (i.e., build/ test, change, rebuild), is able to build or provide required information to be able to manufacture a product, implement an idea that can be built and mass-produced, can sketch and do drafting (e.g., CAD, SolidWorks).

Communication and Teamwork: Can communicate orally and in writing, can communicate with team and client and other stakeholders, can work on a team, can select the right kind of team members (i.e., can identify individual strengths), is able to listen to others and really hear what they have to say, can build collaboration instead of ownership.

Knowledge Creation and Thinking Processes: Realizes there are multiple repetitions of divergence and convergence in the process of idea generation, is able to abstract, is able to transfer knowledge from on area to another, asks good questions, can search the patent literature, knows how to recognize unknowns/ assumptions/limitations, can abstract and detail (i.e., can roll up/down in representations), can think on multiple levels (e.g., what is in front of me, what was I doing before, what do I do next, what is this process about, how do I change this process), can gather information, can recognize her/his own cultural lens, knows what to record/save/document/share (when, why, who, how . . .), can troubleshoot a non-functioning device or prototype to identify the root cause of a failure, can think critically, can capture and maintain knowledge, for re-use, can learn to learn (i.e., can teach themselves), can self-assess their core competencies so as to seek out opportunities for improvements, be willing to unlearn defunct/obsolete knowledge, be able to search for information and critically analyze it and categorize it and determine its relevance, can make innovation tangible and digestible.

Technical Fundamentals: Know 2nd order ODE's, know Bernoulli, know control volumes and transport, can use engineering fundamentals guide design and to model concepts to predict performance, can identify functions, must have technical competence—CORE to professional engineers—regardless of design or communication capability.

Aaron Altman is an Associate Professor in Mechanical and Aerospace Engineering and Director of the Aerospace Engineering Graduate Program at the University of Dayton. His interests include aircraft conceptual design, unsteady aerodynamics, low Reynolds number aerodynamics and vortex formation and shedding. Dr. Altman received his B.S.E. in Mechanical Engineering with a second major in Applied Mathematics at Tulane University (1990), an M.S.E. in Mechanical Engineering from the University of Texas at Austin (1994), and a Ph.D. in Aerospace Vehicle Design from Cranfield University in England (2001). After a few years working with Airbus France in Toulouse, France, he joined the faculty at the University of Dayton (2002) where he has been associated with the Design and Manufacturing Clinic (and now Innovation Center) ever since. Dr. Altman is an Associate Fellow of AIAA and a member of ASME, ASEE, AUVSI and AOPA. He has received the Pi Tau Sigma Teaching award at the University of Dayton (2008) and while at the University of Texas at Austin he received both the Texas Excellence Teaching award (1994) and the Lockheed Fort Worth Teaching award (1993)

Clive L. Dym has been Fletcher Jones Professor of Engineering Design at Harvey Mudd College since 1991, where he directs the Center for Design Education and was also department chair (1999–2002). His interests include design theory, knowledge-based (expert) systems for engineering design, and structural and applied mechanics. Dr. Dym completed the B.S.C.E. at Cooper Union (1964), an M.S. at Brooklyn Polytechnic Institute (1964), and the Ph.D. at Stanford University (1967). He has published some 85 refereed journal articles, was the Founding Editor of the Journal of Artificial Intelligence in Engineering Design, Analysis and Manufacturing, has served on the editorial boards of several other journals, including the ASME's Journal of Mechanical Design. In addition to editing eleven volumes, Dr. Dym has written thirteen books, including: *Engineering Design: A Synthesis of Views*, Cambridge University Press, 1994; *Principles of Mathematical Modeling*, 2nd ed., Academic Press, 2004; *Engineering Design: A Project-Based Introduction* (co-authored by P. Little, with

E. J. Orwin and R. E. Spjut), 3rd ed., John Wiley, 2008; and *A Continuum Introduction to Engineering Mechanics* (co-authored with J. S. Rossman), CRC Press, 2008. Dr. Dym is a Fellow of the Acoustical Society of America, ASCE, ASME, and the ASEE. Dr. Dym's awards include the *Walter L. Huber Research Prize* (ASCE, 1980), the *Western Electric Fund Award* (ASEE, 1983), the *Boeing Outstanding Educator Award* (first runner-up, 2001), the *Fred Merryfield Design Award* (ASEE, 2002), the *Joel and Ruth Spira Outstanding Design Educator Award* (ASME, 2004), the *Archie Higdon Distinguished Educator Award* (Mechanics Division, ASEE, 2006) and the *Bernard M. Gordon Prize* (co-winner, NAE, 2012).

Ray Hurwitz is a rising sophomore at Harvey Mudd College. He is an engineering major with an interest in mechanical and aerospace fields. He is a member of the Harvey Mudd Robotics Club as well as a writer and editor for the official student newspaper, The Muddraker. His awards include the CIF Statewide Scholar Athlete of the Year Award (2010), the Mission College Prep Valedictorian Award (2010), the MATE Monterey Regional Engineering Presentation Award (2009, 2010), and the Harvey S. Mudd Award (2010). Additionally, he plays baseball collegiately for the Claremont-Mudd-Scripps Stags.

John W. Wesner, PE, is Adjunct Fellow in the Institute for Complex Engineered Systems at Carnegie Mellon University. He is also affiliated with Carnegie's Entertainment Technology Center. His primary technical interests are Engineering Design and Product Development Processes. Dr. Wesner earned his BSME at the Carnegie Institute of Technology (1958), MSME at the California Institute of Technology (1959), and PhD in Mechanical Engineering at Carnegie Mellon University (1968). Prior to joining Carnegie Mellon nine years ago, he spent 31 years with Bell Laboratories (under AT&T and Lucent Technologies), doing and leading product design projects and implementing process management for quality improvement. A Fellow of the American Society of Mechanical Engineers, he is past ASME Vice President for both *System and Design* and *Programs and Activities*.