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Additive Innovation in Design Thinking and Making*

SHAWN JORDAN and MICAH LANDE
The Polytechnic School, Ira A. Fulton Schools of Engineering, Arizona State University, Mesa, AZ 85212, USA.
E-mail: shawn.s.jordan@asu.edu and micah.lande@asu.edu

A Maker is a modern-day tinkerer and hands-on builder of DIY artifacts. Makers create their inventions wholly out of their imaginations, with the support of a rich collaborative online and in-person community. This paper describes the results from a qualitative study of adult Makers and their characteristics of collaboration in the Maker community. Results indicate that Makers exhibit a mindset of Additive Innovation. This describes the open community of sharing and learning that is the Maker community. Connections between engineering and Making are also discussed.

Keywords: making; maker community; design thinking; innovation; design process

1. Introduction

Each weekend, in some corner of the world, groups of people convene at Mini Maker Faires and flagship Maker Faires to share technological novelties they have created. They also witness the technological wonders others have built on their workbenches. It is a community-focused version of the middle school science fair or college design project fair. People of all ages participate and display their mostly functional prototypes that solve problems that they care about to make impact in the world. They use their imagination, building skills, and apply design thinking to their Making work. These Makers show off qualities like *practical ingenuity* and *creativity* in their work, and exhibit a penchant for *self-directed* and *lifelong learning*. These qualities are useful for both participating in these Maker-related events *and* in the workplace. These qualities are also characteristics captured in the National Academy of Engineering's *Engineer of 2020* vision project [1].

We seek to understand design thinking and Makers and how they are inclusive or exclusive of what we expect from design thinking and engineering thinking activities of engineers and engineering students. Faced with a dynamic world of complex problems that cross disciplinary boundaries, our country needs this technical and engineering talent to solve challenges like the National Academy of Engineering Grand Challenges for Engineering [2]. The talent necessary to solve these problems largely comes from a formal engineering education system challenged with producing sufficient numbers of qualified engineers. However, there are useful qualifications beyond the expectation of the traditional. The nature of radical collaboration [3] within design thinking and making activities is illustrated in this work as *Additive Innovation*, with implications for how we do design thinking and teach design thinkers. With this work, we explore how design thinking overlaps with Makers in the Maker community, and engineering writ large. We are interested in how we might leverage the growing community of Makers to learn, inform, and redesign how we teach engineering in higher education.

2. Design thinking & making

Design thinking [4, 12] is a way of knowing, doing and acting with a central tenant of an empathy-led, user-centered engineering design process. User-centered design approaches focus on people as part of a system, and posit that the user can be the catalyzing starting point for innovation [5–11]. Design thinking is part of design education [12], and is at the root of business innovation [13–19]. Beckman and Barry [20] described design thinking as a learning process of observing, developing frameworks, creating new imperative (ideas), and providing solutions. Design thinkers use related steps in the engineering design process to *empathize, define, ideate, prototype,* and *test* [3]. With a focus on human values or desirability [21] before feasibility or viability, problem reframing and problem solutions generate and create new ideas or experiences that express insights connected to people, users, or customs. Design thinkers focus on the process to generate insights from users to produce an idea or a crude prototype that communicates that idea. Their exploration is more about the idea than its construction or realization. Mindsets for design thinking or "orientations to learning" have been identified as "human-centeredness, empathy, mindfulness of process, culture of prototyping, show don't tell, bias toward action and radical collaboration" [3].

Making encompasses tinkering with technology. A Maker is an emerging colloquial term used to describe a group of do-it-yourself-minded individuals participating in informal communities (doing-

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it-with-others) that support and celebrate building and prototyping technical proof-of-concept exploration and ad-hoc product development. A Maker is a modern-day tinkerer and hands-on doer and fashioner of stuff. Makers create their inventions wholly out of their imaginations, with the support of a rich collaborative community both online and in person. By defining terms, participants collectively defined "making" (as an example) as "making something" [22]. The act of Making is to make real ideas, but often with the aid of rapid prototyping tools or other technology. It matters less what the creation actually is but more so the act of creating and building an artifact. The product is more important than the process, differentiating Makers from design thinkers. Professional engineers, artists, and hobbyists alike participate in the Maker movement. However, even though the artifacts created by many Makers involve significant engineering, many Makers have no formal engineering education background even though their own vocational advancement could readily benefit. Dougherty [23] also has aligned a "Maker Mindset" with Dweck's growth mindset [24] concept, "summarized as 'what can you do with what you know?'"

3. Methodology

This study used a thematic analysis [31] based in a constructivist grounded theory [32] framework to explore the research question, how does the Maker community approach innovation? Forty-two adult Makers were recruited and interviewed at flagship Maker Faires in New York City and the San Francisco Bay Area over the last 3 years. Participants were purposefully stratified across descriptors such as self-identification as a Maker, age, demographic, and years as a Maker, formal or informal engineering education experience, and engineering-related careers or hobbies. Makers participated in artifact elicitation interviews, based on the method of photo elicitation [25] on site, and critical incident technique interviews [26] via Skype in the weeks following. Each interview lasted approximately 60 minutes. Example artifact elicitation interview questions included: *What skills did you have to learn to build [project]?* and *How does your passion for [project] relate to job or major in school?* Example critical incident interview questions included: *Tell me about a time when you decided what to study in college* and *Tell me about a time when you decided not to pursue a career in engineering*.

A portion of each interview focused questions on the boundaries among "designing," "engineering" and "making." Several times throughout the study (in iterative cycles), individual members of the research team conducted an inductive thematic analysis on the transcribed interviews (generating theory from the data), which fed back to inform questions asked in the interview protocol. The results from individual inductive analysis were triangulated with a deductive coding of the data to generate a theory of Maker design communities. This triangulated theory, inductively grounded in data and deductively connected to literature, describes the Maker community's philosophies of design and helps inform improvements for formal engineering education.

4. Findings—additive innovation mindset

Findings from our qualitative artifact elicitation and critical incident interviews showed that Makers demonstrate the characteristics of an *Additive Innovation* mindset that describes the open community of sharing and learning that is in the Maker community. Introduced in this paper as an umbrella concept, *Additive Innovation* is a mode of collaboration where participants in a community are:

(a) inspired by shared artifacts/ideas,
(b) openly share (and learn about) technology and processes used to create these, artifacts/ideas,
(c) design and prototype own modified version of the shared artifact/idea, and
(d) share their modified artifact/idea back with the community.

The community design process in Fig. 1 and examples below from the Maker community further illustrate the mindset of additive innovation. Selected passages from these qualitative interviews are used to illustrate aspects of the Additive Innovation mindset in the following sections.

4.1 Inspiring a community of innovators

At Maker Faires, there are a large range of projects on display. Categories include toys and Tesla coils,

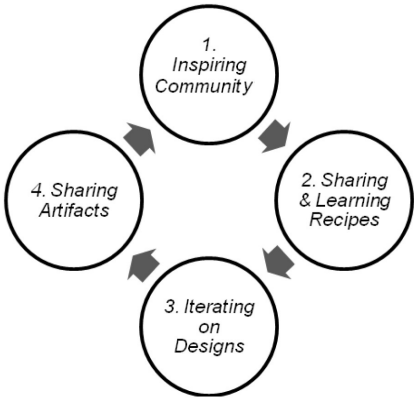

Fig. 1. Additive Innovation Mindset Community Design Principles.

alternative energy and Arduino projects. Absurd practicality is a hallmark of many projects in the Maker community. Makers exhibit projects with elements of creativity, whimsy, and novelty beyond the norms of highly optimized engineered products. This spirit of playful invention is evident in projects that inspire excitement in both participants and visitors at Maker Faires, and provide a foundation for future innovations. Ideas can be shared either by individuals or the community, but individuals or small groups of Makers generally have ownership of these physical manifestations of ideas. In addition to sharing ideas and know-how, there is also, inherent to this attitude, the notion of failure. Failures serve as both badges of admission and honor in the Maker community. Even in public, failures are celebrated rather than judged, and Maker community members rally to provide suggestions and resources. Makers attend Maker Faires to both inspire and be inspired.

Some Makers attend Maker Faires to inspire others to become Makers and engineers. For example, Matt (pseudonyms used for all participants) believes that "part of what I would like to do is encourage kids. I think that you have to hit them at age 10 or so with the basic concept to get them enthralled before they'll go on and do technical stuff." Mark mentors his daughter's FIRST Robotics team, which showcases robots at Maker Faires. Yin uses 3-D printed jewelry of molecules as a hook to initiate conversations. She believes that her jewelry says "Come ask me about my earrings," and the resultant conversations can increase public awareness of science. Aside from conversations, she "really wanted to learn CAD modeling, so that's part of the inspiration of why I wanted to do them 3-D printed."

Other Makers attend Maker Faires to be inspired by others, perhaps influencing their own future work or play. For example, Samantha said "you just see stuff and you're like whoa. I want to make something else." She finds the experience inspiring, and it is a direct part of her creative process "for next year's Burning Man." Similarly, Aaron "had a ton of fun making [project] and I think it's super cool, but bringing it to Maker Faire and seeing other people think it's super cool, and having people interact with it is also really awesome." The exposure provides "perspectives other than your own, in terms of use and design and functionality" which influences Aaron's design process. Roberto also looks at others' projects for inspiration on his own work. He says, "I realized that designers a lot of the times use more or less the same materials. So sometimes you can fix, mix different things from one design with stuff from another design" to make something new.

4.2 Sharing and learning recipes of how "it" was made

The Maker community exhibits an ethos of sharing [27], where Makers openly share knowledge, artifacts, and processes used to create artifacts. These behaviors create a community of self-directed learners who actively engage by asking questions and freely teaching others for the overall growth of the community. Makers want to learn, share what they have learned, and help others learn and grow.

Nearly all Makers interviewed talked about learning something in order to build their projects. For example, Samantha (again, pseudonyms were used for participants) "wanted to learn how to weld. Then I wanted [to] take a welded project" as an expression of the "complete creative burning inside me that doesn't ever go away." Matt had to learn 3-D CAD software in order to publish his designs on the Thingiverse website. Yin's experience learning how to 3-D print jewelry resulted in making her designs "available online for free so anyone can go download and print it themselves." This increases the potential impact of her work to increase science literacy in society. Other Makers bring their projects to Maker Faire with the intent of fielding questions about how it works, and sometimes taking them apart. Aaron found that "people have been very willing to use it and engage with it and ask questions about it" which allows him to engage more deeply with the community. Such feedback has also caused iterations in his design, as he reports: "we definitely screwed up a whole bunch of things. But then we did them again and figured out how to do them a little better."

Some Makers rely on the web to spread knowledge within their community. For example, Roberto shares his work at Maker Faire and is an artist-in-residence for a Maker website that crowdsources project ideas. Matt also publishes his work on both the Instructables and Thingiverse websites, so that people have "all of the print and design files so anybody can totally duplicate it." Part of Matt's interest in sharing is to create a modular extensible platform so that "clubs or groups or whatever could build their own units here" and add on to his design. Still other business-minded Makers provide visitors to Maker Faire with a small experience with the hope of making a sale for a longer experience.

4.3 Iterating to create new designs

Most Makers actively engage in more making when away from Maker Faire events. They are inspired by Maker Faires, magazines, or simply their own imaginations. They actively iterate on ideas, sometimes exhibiting fearless creative confidence that drives them to make the seemingly impossible or

difficult realizable and actualized. Both creativity and innovation define citizenship in the Maker community, through additively building on the work of others and freely sharing knowledge and processes back with the community.

Some Makers are inspired by what they have seen at Maker Faires, but want to make their own versions with a unique twist. For example, Samantha was inspired by the large number of robots present at the Maker Faire, but wanted to "add a blinky heart inside of the robot. There could be other things happening, like. . . maybe I'll put some EL [electroluminescent] wire in there, maybe I'll start putting in organs. I don't actually know where this could go, but the concept is that they will be robots." Other Makers like Aaron took basic machines and changed the way that they function. "We've taken a basic vending machine and added a lot of electronics to it that allow it to not only look great and have sound and lights to it but it also has RFID chips in every toy" allowing the display of additional information about the toys on a display, according to Aaron. This new spin on a vending machine is both creative and engages visitors, taking "a normal everyday experience and make it new again" according to Aaron.

Other Makers draw heavily upon the open source hardware and software movement to provide a platform for their innovations. For example, Eric came to Maker Faire as a result of his participation in the open source 3-D printer community. He took an open source 3-D printer design from the community that had "a boxy frame. . . [that] doesn't allow for the removal of a printer cartridge easily" and created his own design that "addresses all of that. We made an open frame for ease of removal." He also used an "Arduino Uno. . . which is open source with an open source shield on top that controls all the motors within this [3-D] printer," and is sharing his designs back with the community.

Samantha also uses Maker Faires to find collaborators for her next projects. Her projects have continued to improve because she has "learned how to probably get people, other people to be project partners with me on things that are very complicated. . . I publicly announced I'm looking for project partners on a new project and the kind of person I would be looking for." This search for creative collaborators resembles the way faculty and researchers search for research collaborators. These interactions could be an interesting opportunity for further research.

4.4 Sharing improved artifacts back with the community

Following the successful (or not so successful) creation of an artifact by a Maker, the cycle repeats by sharing the modified artifacts back with the Maker community. Sharing can take many forms, including exhibiting at Maker Faire, creating Instructables project recipes, writing articles for Make Magazine, etc. This iteration and sharing is an integral part of the Maker community design process to push the collective understanding.

Mark continuously improves his adjustable mannequin exhibit every year for Maker Faire, both by adding additional features to the mannequins and adding interactive aspects. For example, he "made all the joints of the robot to be anatomically correct, so there are three degrees of freedom in the hips. The hips move around; the shoulders move around; the back can rotate; to get the hands we had to go to wires." He also added a "bouncing machine which is a real hit with the kids," along with "a fountain, so we have buttons being pressed to shoot stream of water which really keeps the kids occupied." For Aaron, success for Makers is getting "recognition from people they admire, you know, actually improving and adding to a field. Now let's say you do something completely new with 3-D printing and you really advance the industry, that's also success. So doing something new and novel can be success in its own way."

5. Implications

We can learn much from adult Makers in the Making community. On many fronts, what they do and how they do it out *in the wild* can be useful to better understand the limitations and opportunities within the engineering classroom at the undergraduate teaching level. Consider descriptions of prototypical engineers from recent reports and how Makers readily embody some of these expressed characteristics. Makers possess creative confidence, a penchant for absurdly yet practical solutions, and are self-directed learners. They embody the *Engineer of 2020* characteristics [1] of *creativity, practical ingenuity*, and *life-long learning*. These characteristics also align with the ABET outcomes [28] for students to have the ability to identify, formulate, and solve engineering problems and adopt an attitude of life-long learning (although noteworthy is that explicit creativity is suspiciously absent from ABET student outcomes). The 21st century skills for learners [29] also align with the characteristics of Makers in the Maker community, specifically with regard to creativity and innovation, critical thinking and problem solving, and initiative and self-direction. A comparison of the characteristics of the Maker community, *Engineer of 2020*, ABET student outcomes, and 21st century skills is summarized in Table 1.

With the community and sharing aspects of

Table 1. Comparison of Characteristics of Makers and Engineers

Maker Community	Engineer of 2020 [1]	ABET Student Outcomes a–k	21st Century Skills
Creative Confidence [13]	Creativity	*No direct connection*	Creativity and Innovation
Playful Invention	Practical Ingenuity	Identify, Formulate, and Solve Engineering Problems	Critical Thinking and Problem Solving
Self-Directed Learning	Lifelong Learning	Lifelong Learning	Initiative and Self-Direction

Additive Innovation mindset, it can be constructive and illustrative to consider how such focus can be implemented into the engineering classroom. How might we reverse engineer an adult Maker to realize a vision of the engineer of the future? For many experiences in the classroom, arising out of a reasonable concern of how to fairly evaluate students, students are asked to do the same parallel activities. Dougherty [23] compares the ''pain of education'' to the ''pleasure for real learning.'' With the heightened expectations of technical competencies that traditionally accompany engineering learning in the classroom, there is less and less room to consider, let alone practice, practical and professional skills identified by most of the other ABET student learning outcomes. The same could be claimed about allowing students to pursue their own motivations and interests throughout their education. In contrast to the supportive learning ecosystem demonstrated in the Maker community, the limits of how we teach engineering could be expanded. In contrast to formal engineering education, sharing intellectual property is considered cheating. In contrast to industry, keeping intellectual property private provides a competitive advantage. What if intellectual property issues were negated by the rules of participating in an engineering classroom of *Additive Innovation*? The learning and innovation aims for some classroom topics then could be better realized and our engineering students could practice to be better future coworkers and collaborators.

Making is a progressive approach to being student or learner centered. Because of the factory-like nature of higher education, there is not much opportunity to appreciate the interests and experiences of the individual learner. Design thinking, like *Additive Innovation* through a making experience, allows for the subjectivity and accumulated judgment of the individual student, and small teams of students, to guide the process evolution and project evolution. It can then be more resonant with the individual of what they may want to learn or experience and the structure of open-ended project-based learning may actually allow for in the classroom. Additional skills and attitudes can also be picked up that are part not just of design thinking, making, or even engineering—but parts of an entrepreneurship mindset to be able to more rapidly build, share, and get feedback for one's ideas and innovations.

Additionally, including habits of design thinking and Making within a context of the fields of engineering could broaden the spate of potential future innovators. A world of possibilities might open up to those who want to solve real world problems through design thinking and Making—beyond the enthusiasm of only building. A more inclusive vision of engineering crossed with making could build future engineering capacity as well as raise awareness to the general public of the work and impact such work offers. Our ambition is to change the conversation to highlight the efficacy and possibilities for this second group. We do not equate engineering students, practicing engineers and Makers completely but find the possible overlaps and stories of pathways within to be possible for transformational change in our field. Consider the benefits to STEM (science, technology, engineering and math) education and resulting societal benefits for those who have influence over student decisions like teachers, school counselors, and parents to have an appreciation of the multiplicity of pathways into such careers or the value of technical literacy, both based in problem solving or making activities. This is especially true for underrepresented groups to make the case that they are evident in the population of people already doing. Figuring out how best to bring in what we can learn from the Maker community into the engineering classroom, through an appreciation of an *Additive Innovation* approach could help the entire innovation engine.

6. Conclusions and future work

Making is quite a unique experience. Like design thinking, it offers yet another lens to creative problem solving activity. There is a particular flavor of radical collaboration within the Maker community, as expressed by a concept of *Additive Innovation*. The Maker community is also an *Additive Innovation Network*, both as a social and intellectual community that encapsulates aspects of community, sharing, and an appreciation of learning with each other.

Elements of a shared philosophy of design think-

ing and in the Maker community can be leveraged to improve formal engineering education. In particular, project-based learning environments could be constructed to embrace design thinking and Making. To extend an understanding of the range of pedagogy in active learning, students or professionals could pursue solutions that are personally motivating or rewarding in a product-based learning exploration. Additionally, students could operate with a framing of trying to understand how solutions fit into a larger context in a way that benefits learning and generates creative and novel solutions. Makers' work is done inside and outside the confines of established engineering education curricular activities. But their commitment and engagement is something that can be better understood to advantage our teaching in the classroom. This approach also aligns with project-based learning as a teaching method in the classroom, a call made in Sheppard's *Educating Engineers: Designing for the Future of the Field* [30]. Engaging future engineering students may mean developing curriculum and pedagogy that allows students to apply their knowledge, explore solution spaces that they are personally motivated by, and design and make solutions.

Additional exploration of the Maker community is necessary. So far, our work has looked at Adult Makers and understanding that experience. As an extension, we are starting to interview Young Makers to expand a Maker Theory and better understand their ambitions and how Making, design thinking, and even engineering are a means to explore their curiosity and creativity writ large or the ends themselves.

Aspects of leadership and innovation management are also fodder for further exploration. There are examples and models of innovation described by the Creative Commons and Open Source Software and Open Hardware communities that are worth exploring further. Also extending the *Additive Innovation* notion to describe the novelty and success of collaborative and communal businesses like KickStarter and Quirky are of additional interest.

When we discuss Making and design thinking, we mean a different approach to addressing a large, complex problem than a traditional engineering or engineering design approach has tended to afford. There is unrealized potential in each approach but more so, in realizing the benefits of each and an ability to contribute to more than the sum of its parts. Design thinking makes empathy and the user so important. Making takes some idea and helps realize it in some form. One without the other is lesser than taking advantage of each — this could be a strong basis for the engineering student or engineer for the future.

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Shawn Jordan, Ph.D. is an Assistant Professor of engineering and a Fulton Exemplar Faculty Member in the Ira A. Fulton Schools of Engineering at Arizona State University. He teaches context-centered electrical engineering and embedded systems design courses, and studies the use of context in both K-12 and undergraduate engineering design education. He received his Ph.D. in Engineering Education (2010) and M.S./B.S. in Electrical and Computer Engineering from Purdue University. Dr. Jordan is PI on several NSF-funded projects related to design, including an NSF Early CAREER Award entitled ''Engineering Design Across Navajo Culture, Community, and Society'' and ''Might Young Makers be the Engineers of the Future?,'' and is a Co-PI on the NSF Revolutionizing Engineering Departments grant ''Additive Innovation: An Educational Ecosystem of Making and Risk Taking.'' He has also been part of the teaching team for NSF's Innovation Corps for Learning, and was named one of ASEE PRISM's ''20 Faculty Under 40'' in 2014.

Micah Lande, Ph.D. is an Assistant Professor in the Engineering and Manufacturing Engineering programs at the Polytechnic School in the Ira A. Fulton Schools of Engineering at Arizona State University. He teaches human-centered engineering design, design thinking, and design innovation courses. Dr. Lande researches how technical and non-technical people learn and apply a design process to their work. He is interested in the intersection of designerly epistemic identities and vocational pathways. Dr. Lande received his B.S in Engineering (Product Design), M.A. in Education (Learning, Design and Technology) and Ph.D. in Mechanical Engineering (Design Education) from Stanford University. Dr. Lande is the PI on the NSF-funded project ''Should Makers Be the Engineers of the Future?'' and a co-PI on the NSF-funded project ''Might Young Makers Be the Engineers of the Future?'' Dr. Lande is a Co-PI and engineering education researcher lead on the NSF Revolutionizing Engineering Departments grant ''Additive Innovation: An Educational Ecosystem of Making and Risk Taking.'' He also is a participant in the NSF Innovation Corps for Learning 2015 cohort (''Leveraging Maker Pathways to Scale Steam + Making Outreach Programs) and served as senior personnel / instructional team on the 2014 pilot for NSF's Innovation Corps for Learning (I-Corps-L). Dr. Lande founded the first Maker Corps site in Arizona, a program of the Maker Education Initiative.