Makers as Adaptive Experts-in-Training: How Maker Design Practices Could Lead to the Engineers of the Future

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Introduction

A large and growing population of inventors, builders, and tinkerers have to started to self-identify as Makers. Makers create technical artifacts, often in order to solve problems that they have personally identified. Design thinking and iterative prototyping are key Maker activities [1], as is community collaboration, which often takes place at Maker Faires. In these fail-safe environments, Makers as young as eight years old feel comfortable pitching their ideas and receiving constructive criticism on them from other Makers and the general public. Even outside of these fairs, Makers rely on a strong learning ecology [2] with similar characteristics. In spaces such as TechShop [3], Makers work on their projects alongside other Makers, providing a platform for sharing skills, knowledge, and experience. Within these patterns of activity, Makers exhibit the ability to design solutions that require a dynamic, adaptive mindset, where patterns of both innovation and efficiency appear in the design process taken.

This study seeks to understand how Makers exhibit design expertise, through observing their procedures, and level of understanding of their successes and failures. Makers do impressive design work, and demonstrate engineering design skills, such as troubleshooting, iterating, and problem solving. The *Engineer of 2020* [4] requires the fluid and dynamic mindset of the adaptive expert, and this attribute is discussed, claiming, "…it will not be this or that particular knowledge that engineers will need but rather the ability to learn new things quickly and the ability to apply knowledge to new problems and new contexts" [4]. The ability to learn and adapt to innovate solutions to new problems will be essential to the engineers of tomorrow, more so than knowledge of existing, efficient solutions and procedures.

Makers do not generally identify themselves as engineers, and engineers are reluctant to identify Makers' projects as artifacts of engineering [5]; yet, there is significant overlap in their practices, skills, and knowledge. Like engineers, Makers must find technically-complex solutions to multi-faceted problems. Using the lens of adaptive expertise to understand engineering-related practices, such as Making, we can gain insights to better inform our educational pedagogy in formal settings.

Background

Adaptive Expertise

Hatano and Inagaki were the first to characterize adaptive expertise in *Two Courses of Expertise* [6], where the adaptive expert is juxtaposed to the routine expert, a master of efficiency and skills necessary to develop solutions on preconceived ideas. Other thinkers on adaptive expertise [7] define those that design with both efficiency and innovation. Figure 1 below maps the adaptive expert against other design thinkers:

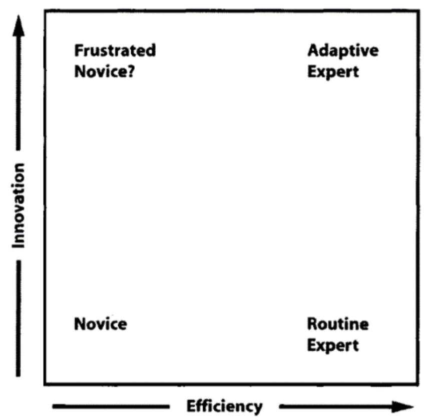

Figure 1: Schwarz, Bransford and Sears' Two dimensions of learning in design [7]

The core characteristics of an expert in the context of design thinking are based in their successfulness in generating effective, long-lasting solutions in each of the design dimensions. Learning and design thinking is performed in both dimensions by the adaptive expert, enabling holistic solutions. Razzouk and Schute [8] agree that experts generate the best solutions, because they are able to perceive the root of the problem and work to solve it in its entirety. Experts are also able to use what they have learned through past experiences, implementing past solutions that have proven themselves effective, or exhibiting more opportunism in using resources.

Design Thinking: Building Design Expertise

Design thinking is an ongoing process that can happen through many unique procedures [9], necessarily tailored to specific problems. Design experts employ these processes iteratively and adjust them as they encounter problems. Neeley [10], in his dissertation *Adaptive Design Expertise* identifies the fundamental difference between routine and adaptive experts as their understanding of the skills they perform. His definitions of the different dimensions of design thinking are below:

1. The active dimension, built on theories of intellectual development, characterizes the designer's ability to think actively and independently
2. The abstractive dimension characterizes the ability of the designer to engage in reflective, complex and abstract thought
3. The adaptive dimension characterizes the designer's ability, to strategically shift between the thinking skills and levels represented in the active and abstractive dimensions as a function of external stimuli and internal direction

Neeley associates the abstractive dimension with innovation, and the active dimension with efficiency. The abstractive thinker might easily think of a new, innovative way to solve a problem, but often face problems when trying to build a working prototype of their solution. Whereas an active dimension thinker, or routine expert, would work to replicate an existing solution, improving the method through which it is made. While innovation and efficiency are valuable skills, it is their intersection that results in successful engineering. Here, adaptive experts apply conceptual knowledge of what is necessary to generate a working solution, and past experience to improve their own design thinking and processes, and ultimately solutions.

The Design Process as a Lens

Specifically identifying the knowledge and skills developed by prototyping and other stages of the design process will show the value of project based learning in training adaptive engineers and design experts. Prototyping requires the abstractive skills to conceptualize how a solution will work, and the active ability to bring the design to a physical, working solution. Cross [9] recognizes the modern designer as diametrically opposite the maker, or fabricator of the solution. He identifies the most essential modern design activity as the production of a final description of the artifact [9]. There is however a different, physical type of design, which he explains as the potter whose first iteration is in clay. Iterative prototyping is hardly a part of modern design, as it is not the most efficient use of resources, but experts are still generally expected to be able to produce physical, functional, solutions [8]. This 'making design' Cross identifies happens with modern technology within the Maker movement, and through studying Maker design activities, the connection between using a design process rooted in prototyping and the development of adaptive expertise will be clear.

The Maker Design Process

Engineering in industry generally requires adherence to a specific design procedure, as that process has been determined to be the most efficient. Makers structure their design processes themselves, and are only constrained by the resources available. When designing their solutions, there is the freedom to design with the process that uses the stages that they are most comfortable with, most notably prototyping. By studying unique Maker design processes through the artifacts brought to Maker Faires, this work aims to understand the relationships between the dimensions of design, and which ones are most useful for those with engineering dispositions. Knowledge of the processes designers find intuitive will enable design teachers by indicating where to start, and how to help students grow into design experts and ultimately successful engineers.

The learning ecology of this movement and the spaces it lives in, is worth emulating in the classroom [2]. Makers exhibit adaptive expertise, and Young Makers (9-17 yrs old), show progress towards this expertise by indulging their engineering dispositions through adaptive design thinking. The working prototypes that are demonstrated at Maker Faires are the result of multiple dimensions of design thinking. By attending the Maker Faire, where they can exhibit anything from a functional prototype to a start-up's minimum viable product, Makers are able to receive feedback from the Maker Community, and expand their learning ecology or learn from vicarious experience. Doing this repeatedly, even outside of the context of a Maker Faire, is what develops the characteristics of a Lifelong Maker that are shared with the *Engineer of 2020* [4].

Research Design

The purpose of this research is to better understand the design processes used by Makers, and is guided by the primary question of, *What dimensions of design expertise do Young Makers demonstrate through their engineering and making activities?* Answering this question will show how and in what dimensions the rapid prototyping of the Maker design process builds expertise.

While this knowledge is useful, attempting to form expertise in the same way requires a more complete understanding of the Maker Community. The need to understand how Makers are supported leads to the secondary question of, *How does a Maker learning ecology foster adaptive design expertise in Young Makers?* With a more complete understanding of how the Maker Movement enables Makers to become experts in realms of design thinking, it becomes easier to recreate their learning ecology, and to train others in the knowledge, skills, and dispositions of a prototyping expert.

Crotty's [11] four elements of a research study (epistemology, theoretical perspective, methodology, and methods) informed the research design. Table 1 describes the four elements, specific theories and methods selected for this study and the rationale for each element.

Table 1: *Elements of a Research Study (Crotty 1998)*

	Definition	Selected	Rationale
Epistemology *Informs:*	Theory of knowledge	*Constructivism* Knowledge is constructed through human-world interaction (Piaget, 1967)	To understand how and what Young Makers learn through their creations
Theoretical Perspective *Informs:*	Philosophy that informs methodology	Constructionism Meaning is created through constructing and sharing artifacts (Papert, 1991)	To understand how Young Makers create meaning through the design and sharing of their creations
Methodology *Informs:*	Design connecting methods to outcomes	Constructivist Grounded Theory Researcher is the author of participant's voice and meaning (Charmaz, 2000, 2006)	Little is known (Corbin & Strauss, 2008) about what Young Makers know and their pathways. Methods must be sensitive to study objectives: to understand what Young Makers learn and how their pathways intersect w/engineering.
Methods	Implementation of methodology	D1. Screening questionnaire D2. Artifact elicitation interviews	D1. To screen potential participants D2. To understand Young Makers' creations and knowledge and skills learned by creating them

Data Collection

To answer the research questions about Makers, a stratified purposeful sampling strategy [12] will be how participants are selected from the pool of exhibitors at flagship Maker Faires. By selecting participants for maximum variation across the strata described in the Table 2, underrepresented groups will be part of the dataset. Whereas representative sampling may not show all relevant educational pathways that Makers take [13].

Table 2: Stratifications for purposeful sampling

Primary Strata	**Secondary Strata**
• Self-identified Young Maker • Range of ages (grade levels) • With/without informal engineering education experience (e.g., robotics team, hacker space) • Member of an underrepresented group based on ethnicity and gender	• With/without vision of an engineering-related degree and/or career • With/without an engineering-related hobby • Years of experience as a Young Maker

The data used in this study is in the form of semi-structured Artifact Elicitation interviews [14] conducted at the Flagship Maker Faires in New York and the Bay Area over the course of three years. The dataset consists interviews from Makers of all ages (24 Young Makers ranging from 8-17, 12 Adult Makers) that attended the New York or Bay Area Maker Faire in 2013, 2014, or 2015. By asking Makers about what they brought to the faire, it is easy to learn about the skills used, concepts learned, and general approach to the design of their solution, as the reason they came to the fair is to showcase and explain their projects. Sample artifact elicitation questions are shown in Table 3.

Table 3: Sample Artifact Elicitation Questions

Can you tell me about what you brought to the Maker Faire? (probe) What technology does it use? (probe) Can you show me how it works?	Knowledge and skills
What knowledge and skills did you have to learn to make this [insert name of artifact]?	Knowledge and skills
Where did you learn these things?	Learning ecology
How did you come up with the idea for this [insert name of artifact]? (probe) What could you improve in your [insert name of artifact]?	Attitudes, Abstractive thinking

Data Analysis

The theoretical framework for this study is largely based on Neeley's work that asserts that the adaptive expert most often creates long-lasting, effective solutions. Their ability to move their design process fluidly between the active and abstractive dimensions results in solutions that take a holistic view of the problem into consideration, take previous solutions of similar problems into consideration, and ultimately succeed in satisfying the users' needs. A deductive analysis of the data was conducted using thematic analysis based on frameworks from both Neeley [10] and Schwarz, Bransford, and Sears [7]. Utilizing these dimensions will make it easier to identify the affordances of Making activities and behaviors. The codebook listed in Table 4 (and examples shared in the Results section in Table 5) also includes an inductive analysis of the design work that Makers do, to juxtapose the stages of the design process they identify and their mindset in overcoming design challenges with the dimensions of design thinking. These actions and the order they are performed are what is discussed in the interviews, and will shed light on the role Maker spaces have on the development of a design process.

Table 4: Example Coding Scheme

Node	Sub-nodes
Neeley Design Thinking	Abstractive Dimension, Active Dimension, Adaptive Dimension, Expertise
Schwarz, Bransford, Sears Design Thinking	Efficiency, Innovation
Design Process	Prototyping, Problem Identification, Brainstorming, Sketching/Modeling, User-Centered Design
Obstacles	Fail Safe Environment, Experience Gained, Apply Past Experience, Learning Ecology Help

Results

RQ1: What dimensions of design expertise do Young Makers demonstrate through their engineering and making activities?

For design thinking, Tables 5 and 6 summarize the coding scheme, and provide a short definition as used in the code book with an example passage from the participant interviews.

Table 5: Neeley Design Thinking code examples

SubNode	**Explanation**	**Coded Example**
Active Dimension	Solving using theories, where designer thinks actively and independently.	*I found this guy named [name] who previously built this. He had a bill of materials. I contacted him and asked him if he could be my mentor. He agreed. Then I've been emailed him problems I had.*
Abstractive Dimension	Designer engaging in reflective, complex, and abstract thought.	*we really wanted to focus on localization as a crucial aspect and also wanted to focus on an algorithm design so this was the best project that combined those two.*
Adaptive Dimension	Designer shifted between the thinking skills and levels represented in the active and abstractive dimensions as a function of external stimuli and internal direction.	*I like how we can adapt it, kind of thing? Maker Faire isn't about competing or anything, it's just working together, so I can just work on it, and it can go in any direction I want it to. Like, we're seeing that our application has a very young demographic. They can't read the buttons that say [words]. So my sister and I, this year we were like, "Let's just make it an arrow instead of words." And that makes it a lot easier for them. So the free form of the whole project is what I like best about it.*

Table 6: Schwarz, Bransford, Sears Design Thinking code examples

SubNode	**Explanation**	**Coded Example**
Innovation	Are any parts of their design process or solution unique? Why did they think to do it that way?	*I found that, after doing a bit of research online, that even though there's so many other advances in technology, there didn't seem to be a single solution for something at this level, at a very basic level. I figured that other people probably had a similar problem that we had with our garden, so we wanted to bring it and share it with other people.*
Efficiency	Is any part of their design or solution routine or common practice?	*We were brainstorming at the very beginning of the semester, in January, and we were thinking of a lot of things. Out of all of our ideas that one seemed the most in reach with the technology available.*

The inductive analysis for design process, shows the design activities Makers use most often. Table 7 summarizes the coding scheme, and provides a short definition as used in the code book and an example passage from the participant interviews.

Table 7: Design Process code examples

SubNode	Explanation	Coded Example
Prototyping	Most artifacts brought to Faire are prototypes.	*At the beginning we prototyped and then we CADed everything up and we eventually started to fabricate, and make parts machine and laser cut everything.*
Problem Identification	Problems are generally chosen by Makers, not given.	*Basically my invention that I created with my parents is a yard monitoring system. We use Raspberry Pi because we usually have an issue with deer going and coming every year and eating our vegetables and plants.*
Brainstorming	Is this done with other in the Maker Space?	*Well, usually we spend time, like a creative time, me and my family. We're brainstorming a bunch of ideas, and some random ideas would come up. We would make a list and choose the best.*
Sketching/ Modeling	How much design is done before prototyping starts?	*I like the drawing part, I like the designing part, and then bringing it to something more than just a drawing. That's what I enjoy about it.*
User-Centered Design	Who is the target user for the device? Self-selected problems inherently user-centered.	*we kind of figured out how to, how to do the manufacturing from that and we just did a lot of testing with kids and we were basically like free babysitters, we just go in and bring in our toys and just make it. We did a ton of redesign for a number of months last year for us to get to this product.*

Through thematic analysis of participant interviews, the deductive category for design thinking was further broken into subnodes for the active dimension, abstractive dimension and adaptive dimension, innovation, efficiency, and expertise as defined by Neeley [4] and Schwarz, Bransford, and Sears [7]. The overlap between these two frameworks was complete, with examples of innovation appearing in the abstractive dimension, and efficiency in the active dimension. The data suggests that adaptive design thinking is a significant feature of the Maker Mindset, and is developed through the generation of functional physical prototypes. Their own method of design, coupled with the learning ecology of their space, suggests that Maker community is and adaptive expert incubators. Adaptive design experts think abstractly to apply past experience to their active design work, and generate the best process for designing a holistic solution in doing so. As the self-directed Maker continually designs solutions, they demonstrate the dispositions of lifelong learners and adaptive experts, both of which are faces of *The Engineer of 2020* [4].

RQ2: How does a Maker learning ecology foster adaptive design expertise in Young Makers?

For obstacles, Table 8, summarizes the inductive coding scheme, and provides a short definition as used in the code book with an example passage from the participant interviews.

Table 8: Obstacles code examples

SubNode	**Explanation**	**Coded Example**
Fail Safe Environment	Reflection and abstractive design thinking inherent in troubleshooting failures.	*I think the main idea is just trial and error, and constantly persevering. Constantly persevering, and continuing to improve and improve. Those are the main skills.*
Experience Gained	Knowledge brokering in a Maker space in addition to iterative prototyping builds experience.	*another thing I had to learn was how to work in a team because ... It was nice that we were able to split up the work so that I was able to sort of focus on the theoretical abstract aspect but I still had to communicate with my partner*
Apply Past Experience	Application of personal and vicarious experience is a trait of an adaptive design expert.	*First of all just basically thinking logically, understanding how it would work. For instance, last year we came to Maker Fair with a similar invention, except a slightly more simplified version of it. We used a touch sensor instead of the cameras, and the issue with that is we realized then that touch sensor's not a very great solution, because you have to have tons and tons of those.*
Learning Ecology Help	Where do Makers look to for just-in-time learning while designing.	*Well I came to Maker Fair to exhibit my idea and to meet other makers and get some new perspectives on my idea too, on how to improve my algorithm.*

These nodes seek to understand how Makers are interacting with the space they work within. The resources made available by the space itself and the people within it are an integral part to the Maker design process. Additive innovation, inherent in Maker spaces and design thinking [15], enables knowledge brokering and reflection on experience, and practical ingenuity resulting from available resources being the only real constraint, stimulates design thinking in the adaptive dimension. This learning ecology fosters adaptive design thinking, and as Makers take on new projects and design with this breadth of experience, they become adaptive design experts.

Discussion

Adaptive Design Thinking

Rapid prototyping, and making mock-ups is familiar to Makers, and often the first stage in their design process. Makers have a more natural design process, defined by their mindset as opposed to procedures. The dimensions of design thinking and skills that are necessary for iterative prototyping show that Makers are building themselves the necessary foundation of an adaptive expert. Changing their design process each time they create a solution ensures that they will never be stuck in the routines of an active expert, and the craving to build something physical ensures that they are never stuck in the abstractive dimension. Makers practice design thinking in all dimensions, and this free form design process essentially guarantees that Lifelong Makers end up adaptive experts, as they constantly present themselves with new problems to solve, gaining experience, and building design expertise.

Design Expertise of Engineering

Engineering work is necessarily different from design, and the public and private systems developed by engineers must be done rigorously, to ensure the safety of users over the life of the solution. The active dimension of design is more relevant to modern engineering, as innovative projects mean nothing if they cannot be successfully implemented and sustained. *The Engineer of 2020* [4] will however, need to have some traits of the adaptive expert.

McKenna [16] characterizes the adaptive expert with engineering design in mind, and Figure 2 below shows how she defines the dimensions of design thinking in relation to these experts, and the characteristics of design processes used by experts of those dimensions.

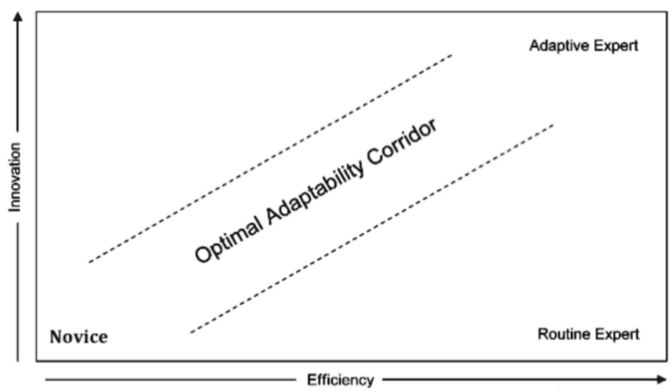

Figure 2: Adaptive expertise as a balance between two dimensions for learning and assessment: Efficiency and innovation. [16]

Within this optimal adaptability corridor, or adaptive dimension, innovation and efficiency develop together [16], as the designer uses skills and knowledge associated with those other dimensions. Skills such as reflection, sketching, and brainstorming are useful, but when they are not balanced by the technical skills and benchmarking that happens in the active dimension, the fruit of this narrow design process is less likely to be a sustainable solution. Many do not consider Making activities to be professional engineering [5], and they are not wrong. But in educating engineers of the future, educators should aim for adaptive experts over routine, and consider emulating Maker practices when teaching design.

Obstacles

The dimensions of the Maker design process were made apparent when looking at what they do when they get stuck in their design process. Obstacles for these Makers are generally frequent, but rarely insurmountable, since many are used to facing them and have a preferred method of learning how to get around the obstacle. This is one place where the active dimension is used, as troubleshooting requires testing to see what is going wrong. Then finding the necessary information to solve the problem requires more active thinking. Even when a Maker is relying on their learning ecology of their home or Makerspace, the active dimension comes into play when explaining the project and problem, and effectively communicating the issue that they face.

The abstractive dimension was observed with this dataset, often mentioned most explicitly when Makers talked about brainstorming, or thinking their way through problems, but there is an amount of abstractive design thinking inherent to iteration that often went unmentioned in the interviews. One surprising observation was that the abstractive dimension was often used in the problem identification stage of the design process. Many Makers are just interested in building something, and are more inclined to identify problems that will allow them to use a specific skillset or tool in the construction of their prototype. Operating in the abstractive dimension in this way requires active dimension design, showing that these Makers can fluidly move between the skills of the abstractive and active dimensions for their design process.

Conclusions

The emphasis on prototyping, and creating functional models of a solution is the only constraint on a Maker's design process. Work is done across the active and abstractive dimensions, and a successful solution is generated by the adaptive expert navigating between these axes. Prototyping as an early stage of the design process, and rapid prototyping as a design skill have Makers gaining experience and expertise in the adaptive dimension in a way and at a rate that traditional classroom learning cannot hope to match. Neeley specifically identifies agility as part of the adaptive dimension, and writes, "it is this agility and fluidity of mind that compels and innervates business, excites students, motivates practitioners and defines the field" [10]. Using the skills and methods of both the active and abstractive dimensions is necessary, and an engineer must be capable of applying both in their design process. As the technological landscape changes at an increasing rate, only those who are experts at redefining their design process to match the resources and skills available to them will be able to generate working solutions and apply new technology effectively, meaning the engineer of the future will be an adaptive expert.

Makers are able to take this approach, and generate working prototypes often because of the expansive learning ecology that surrounds them. The luxury of having the resources to answer a question on a whim enable the designer to design without constraint, confident that they can find an answer or technique once needed. The Maker community provides a much more extensive learning ecology than is generally available to a designer. Whether it is through presenting to other Makers at a Maker Faire, or asking someone at a local Makerspace, Makers have the collective experience of other Makers available to them while designing. This open-sourced mindset, and the breadth of experience that comes with it, allows the Maker to perform in the adaptive dimension more easily. The active consideration of other's problems and solutions, can stir the question of how to do something differently, an abstractive approach to a problem. Through these reference points, an inexperienced designer has the means to work as an adaptive expert, and through the ethos of sharing, retain those experiences for use in future solution generation.

Implications and Future Work

For the first author, a current undergraduate student studying electrical engineering, there is a struggle faced when creating a prototype, testing it, debugging it, and eventually reiterating the design until it is functional. With my prior experience as a researcher of the Maker Movement

[2], I can clearly see what the students of this project-based class are learning, and am frankly surprised with how complex and functional my peers' and even my own solutions are. Physical engineering skills like soldering, PCB manufacturing and testing, and wiring are all gained, but almost secondary to the design expertise developed. Thorough documentation and reflection throughout the course of the semester and the design process, student makers think about what they are doing, and how they could be doing things differently. Students are generally more engaged in this class than others too, as in many cases they are working alongside friends to create unique solutions within a larger, shared focus or theme of a class such as devices in a smart home.

The curiosity about making, makers as lifelong learning, and adaptive design thinking will be further explored in the academic year 2017-2018. This preliminary work with then be extended to provide framing and a procedure to further students in a junior-level embedded systems class. It will be interesting to see how our current understanding of makers out in the wild may translate to engineering students in the classroom.

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