AC 2009-1148: INTRODUCING A "WAYS OF THINKING" FRAMEWORK FOR STUDENT ENGINEERS LEARNING TO DO DESIGN

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Introducing a "Ways of Thinking" Framework for Student Engineers Learning to Do Design

Abstract

Designers and Engineers view things differently. A *Ways of Thinking* framework relating Future Thinking, Design Thinking, Engineering Thinking and Production Thinking is introduced and explained using design documentation generated by recent student design projects from the ME310 graduate engineering design product-based-learning course sequence at Stanford University. Example student team project work and their design steps through their process is compared to a general model for the design process, a pedagogical learning model for the ME310 course and the *Ways of Thinking* framework.

Introduction

In observing students in ME310 Design Project Experience with Corporate Partners,[1,2] a year-long mechanical engineering design product-based-learning course at Stanford University, a curious transformation how graduate mechanical engineering students begin the class as engineers and end up thinking about themselves as designers. Almost all students come into their first year of the Master's program in Mechanical Engineering having received their requisite undergraduate education from another institution in mechanical engineering or a related field. For most, their exposure to design, design thinking, and the design process has been limited to a discrete capstone engineering course or exposure to design in industry during internships, if at all. How these engineering students experience and learn a design process is the motivation of this exploratory work.

Engineers and designers are different and the lenses through which they view the world differ. Similar distinctions among other academic fields have been described or attributed as being of different cultures[3] or of wearing different hats.[4]

Here is a point of illustration of a perceived difference between designers and engineers, in the form of the "how many people does it take to change a light bulb?" joke:

Q1. How many designers does it take to change a light bulb?
A1. Well, does it have to be a light bulb?

Q2. How many engineers does it take to change a light bulb?
A2. Well that depends. How high off the ground is the light? What is the wattage of the bulb?

In this pair of parables the designer is focused on the functionality of the light bulb whereas the engineer is focused on the physical aspects of the artifacts. They may have the same intent (to change the light bulb) but view the problem and solution set differently.

"Ways of Thinking" Framework

The framework being introduced here is a model of *Ways of Thinking* that engineering design students access during their engineering design course activities. As shown in Figure 1, it is visually represented as a matrix showing relative position of Design Thinking, Engineering Thinking, Production Thinking, and Future Thinking.

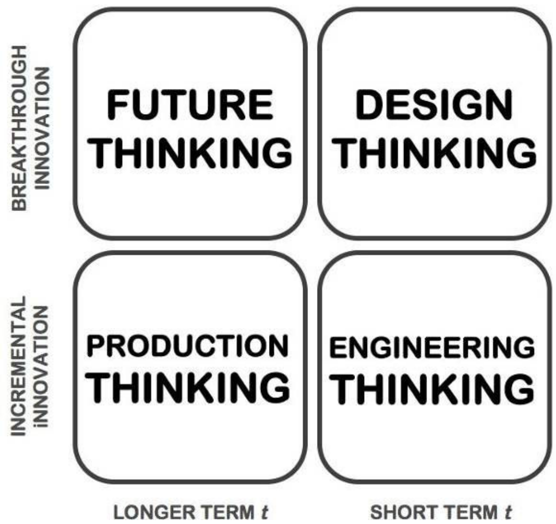

Figure 1. *Ways of Thinking* Framework

Along the Y-axis is a spectrum of incremental innovation to *breakthrough innovation*.[5] Time is measured along the X-axis, short-term to long-term. The activity of Design Thinking[6] can be to *solve a problem* with the end result being an *idea* created. For Engineering Thinking[7,8] *making a solution* results in an *artifact* or *stuff*. Production Thinking[9] allows for the *remaking of a solution* with the results being *facsimiles of stuff* or plans by which to make copies. Future Thinking[10] allows one to *reset the problem* with the outcome being a *question*. This visual representation can be considered circular with the elements being successive Future Thinking can occur before Design Thinking or after Production Thinking.

The Design Process

With a focus on design engineering and a research test bed in ME310 being available with engineering students right in the midst of the design process it seems congruent to overlay the traditional design process model on top of the *Ways of Thinking* framework. Figure 2 shows the visual design process encompassing the Design Thinking space and Engineering Thinking space. Much engineering education and design research focuses on what happens in the Design Thinking space. Atman and Bursic[11] looked at seven design textbooks and came up with a consensus list of steps in the design process. It is interesting to note that while Design Thinking in this context is described well enough (problem definition, identified need, gather info, modeling, feasibility, evaluation, decision) the Engineering Thinking space is described only by one term (implementation). Crawly also uses *implement* to describe the Engineering Thinking space in his Conceive-Design-Implement-Operate model.[12] Problem re-setting can also be added to the list.[13,14]

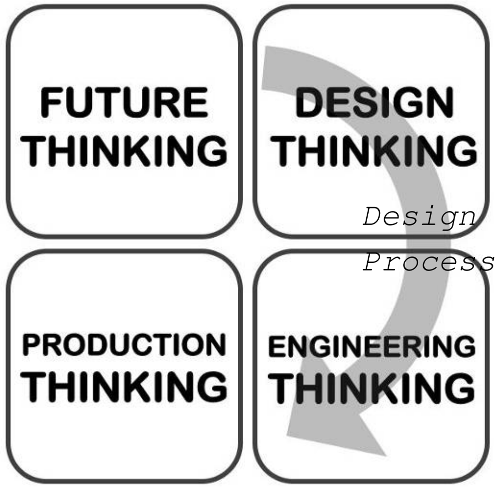

Figure 2. Design Process within Ways of Thinking Framework

Implications for Course Content

The core programs and courses of mechanical engineering, design and mechanical engineering design experienced by design and engineering students at Stanford University can be overlaid onto the *Ways of Thinking* framework, as shown in Figure 3. Courses in designing the future and foresight methodology such as ME410[15] serve to cover the Future Thinking space. The Joint Program in Design and Product Design programs[16] as well as classes under the auspices of the Hasso Plattner Institute of Design (d.school) [17] include projects and classes that focus on the functionality of the design or artifacts. Of note, the Future Thinking and Design Thinking (as the light bulb jokes illustrate) tend to focus on functional aspects over physical aspects. There are courses that do emphasize the physical aspects of design and engineering. In the engineering space ME218 Smart Product Design[18] is skills-based electro-mechanical core course. In the Production Thinking space, ME317 Design for Manufacturability[19] exists as an historic outgrowth of ME310 that deals with issues of manufacturing and production. Interestingly enough ME310 lives in the middle of the array, covering aspects of Design Thinking and Engineering Thinking but also touching on Future Thinking and Production Thinking.

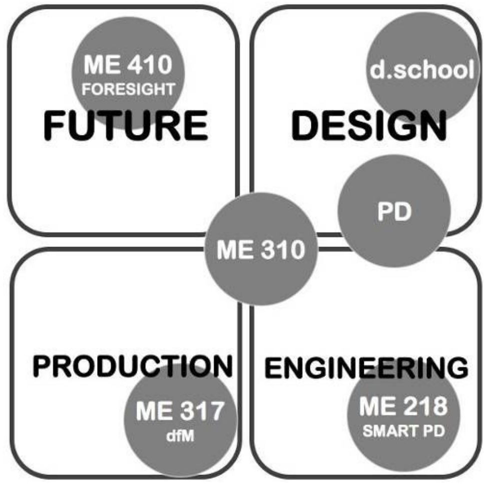

Figure 3. Ways of Thinking Framework Applied to Core ME Design Courses at Stanford

Map to Past ME310 Course Content Focus

ME310 has been a course that has shifted its focus over the years from Engineering Thinking to Design Thinking to Future Thinking.[1] Year-long problem-, project- and product-based engineering design courses with various names have existed at Stanford University for the past 50 years. Using class records from the Stanford University Bulletin[20] the course existed as Engineering Design for the better part of 25 years, Automation and Machine Design in 1985, Mechatronic Systems Design and Methodology in 1993 and Cross Functional Systems Design to 1995. Here, a transition from Engineering Thinking-focused project content to Design Thinking-focused project content was made and a distinction made when people started to become part of the systems students were meant to design (a human-centered design approach).[1]

In 1996 the course was renamed Experience in Team-Based Design for the first quarter and Team-Based Design Development with Corporate Partners for the second and third quarters. In 1998 ME310 was titled Tools for Team-Based Design for the fall quarter and Design Project Experience with Corporate Partners for the winter and spring terms.

Specific examples of project titles from different eras of the course will serve to support the contention that there is a trend from Production Thinking to Engineering Thinking to Design Thinking to projects that have a more futures-oriented bent, as shown in Table 1.

Table 1. Selected ME310 Project Content (1979, 1999, 2006)

Projects from 1979	*Projects from 1999*	*Projects from 2006*
Design steam leak measurement system	Driver scanning automatic car door	Artificial car co-pilot
High-speed Kevlar wrapper	Innovative composite crutch	Spherical image display
Arm ergometer	Key fob	Enhancing passenger communication
Low-cost facsimile printer	Smart bed	Intuitive remote control
Universal gas seal	Parallel parking assistive system	Reinventing rear seat entertainment
Robotic arm controller	Shift simulator	Future blood glucose meters
	Power expendable towing mirror	Making air conditioning personal
	Inspection device for detection of contaminated blades	Tactile touch screen
		Car shifting system
		Wireless power steering

Projects from 1979 represent the Production Thinking space orientation having such terms and project titles as “low cost”, “high speed” as well as measurement projects like Arm Ergometer and Design Steam Leak Measurement. Projects selected from 1999 still have some that are in the Engineering Thinking space but most fall into Design Thinking oriented projects. As examples there are systems that have people in the system like Smart Bed and Car Door projects. More recently projects from 2006 show a continuation in the trend from Engineering Thinking to Design Thinking to Future Thinking. There still are a small number of engineering projects like a car shifting system or pulling power wirelessly from a steering wheel, but most are in the Design Thinking space, considering a human-centered design approach. Some additional projects that year that bleed over into the Future Thinking space include the role of the artificial co-pilot of 2020, an example that will be revisited, future blood glucose meter and an example of a future display spherical surface.

To better classify projects in the spaces it is also useful to divide up each quadrant among a quotient of specificity, from amorphous[21] to specific. A measure or quotient can be assigned to each project according to its project content focus at the beginning or end of the project or at any point within the project. The coding schema used for determining the project content focus was represented along the following distinctions:

- Amorphous Future Quotient
- Specific Future Quotient
- Amorphous Design Quotient
- Specific Design Quotient
- Engineering Technology Quotient
- Engineering Optimizing Quotient
- Production Technology Quotient
- Production Optimizing Quotient

The array of these can be seen in Figure 4. The dispersal of Project Content Focus in projects from 1979, 1999 and 2006 can be seen in Figure 5.

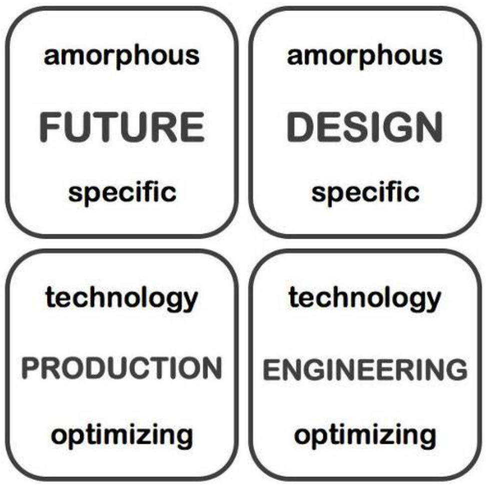

Figure 4. Array of Project Content Categories

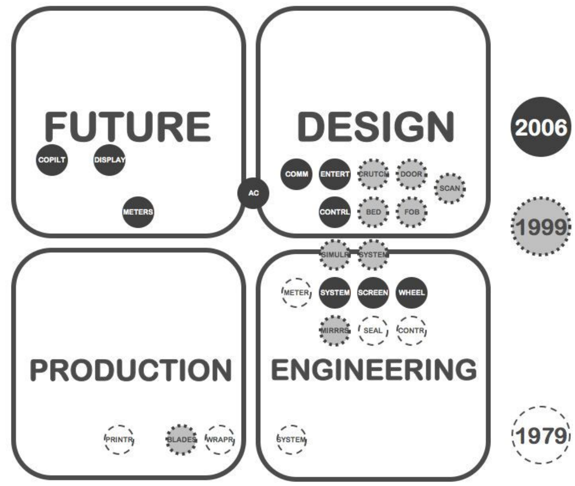

Figure 5. Dispersal of Project Content Focus in Selected ME310 Projects (1979, 1999, 2006)

Map to Current ME310 Course Content Focus

Mechanical Engineering 310 is a master's level course at Stanford University in mechanical engineering and design. Students are set up in teams and spend the school year, over three quarters, attacking a problem supplied by industry, having the freedom of time, money ($15K) and plenty of self-efficacy. Many students have had design classes their senior year but ME310 serves as a *Capstone Plus* course wherein rather than learning through a problem-based learning environment, the students are in a *product*-based learning environment. The literature[22,23,24,25] paints the distinction as small but for the students ME310 is not the Capstone or culmination of their undergraduate education, attempting to synthesize their undergraduate curriculum, but rather an opportunity for students to succeed or fail and apply their own judgment in a low risk environment. Faculty and teaching assistants are engaged along with experts from industry both as consulting faculty and as professionals coaching student teams. The focus for the students is not just on the engineered product outcome but also on practical and industry-applicable skills developed throughout. The course serves as an introduction to the design process for engineering students, but the learning objectives also include not only the project outcome and developed engineering requirements, but personal skill development, teamwork and project management skills as well.

The ME310 Pedagogical Model has limited pre-defined milestones and assignments for the student teams but scaffolds in a way to encourage student team self-efficacy and independence. Assignments decrease from quarter to quarter both in number and frequency. Rather than a linear design process model the assignments and milestones in ME310 serve to model for the students a more expert design approach.

Figure 6 uses the milestones and assignments in the course and overlays the pedagogical model of ME310 over the *Ways of Thinking* framework. In Figure 6 one can see both how the class supports iterations in the design process as well as opportunities to redefine or re-set the project or problem statement. With the pre-production prototypes deliverable at the end of the term students are encouraged to outsource elements of the project whether it be plastic part fabrication or electromechanical control design, adding that additional experience in communicating their work to professionals.

Using student team design documentation for the course as the basis for data, it is illustrative to classify student team activities according to a coding scheme. Table 2 and Figure 6 show examples of milestones and activities and types of prototypes to be expected throughout the course.

Table 2. Coding Scheme

FUTURE ACTIVITIES:	RE-SETTING
DESIGN ACTIVITIES:	PROJECT BRIEF BENCHMARKING NEEDFINDING IDEATE CONCEPTUAL PROTOTYPE EXPERIENCE PROTOTYPE TEST DECISION
ENGINEERING ACTIVITIES:	CRITICAL FUNCTION PROTOTYPE FUNKY SYSTEM PROTOTYPE FUNCTIONAL SYSTEM PROTOTYPE PRE-PRODUCTION PROTOTYPE
PRODUCTION ACTIVITIES:	SEND OUT

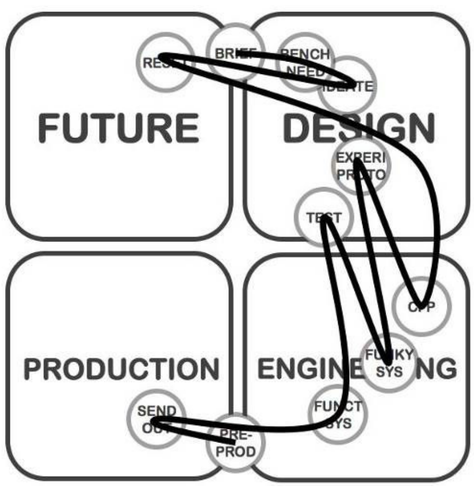

Figure 6. ME310 Pedagogical Model Within the Ways of Thinking Framework

In their design documentation, student teams have described their design process in a subsection titled design development. This documentation is self-reported, collated at the end of each term as a deliverable. The order of activities may very well have been post-rationalized and rectified by the students while doing their documentation. It is an area for future work to closely observe student teams or ask students to record steps more frequently in a diary or logbook more discretely captures day to day reflections rather than recollections at the end of each quarter.

Example Student Projects

A pair of student projects has been selected to compare and contrast their design processes. Both projects begin as Amorphous Future projects and end up as Specific Design projects. Students in Project "A," done for an Automobile Company, were tasked with designing *the Car Co-pilot of 2020*. As can be seen in Table 3 and Figure 7, applying the coding scheme using the codes as nodes and connecting those with lines chronologically, from a more qualitative and gross perspective, the activities of this project team are loosely aligned with a pedagogical model class.

Table 3. Activities of Student Teams Working of Projects "A" and "B"

Project "A"	Project "B"
Project Brief	Project Brief
Benchmarking	Needfinding
Experience Prototype	Ideate
Ideate	Experience Prototype
Funky System Prototype	Experience Prototype
Re-Setting	Experience Prototype
Funky System Prototype	Conceptual Prototype
Experience Prototype	Conceptual Prototype
Test	Benchmarking
Funky System Prototype	Benchmarking
Funky System Prototype	Funky System Prototype
Funky System Prototype	Experience Prototype
Test	Functional System
Functional System	
Send Out	
Pre-Production Prototype	

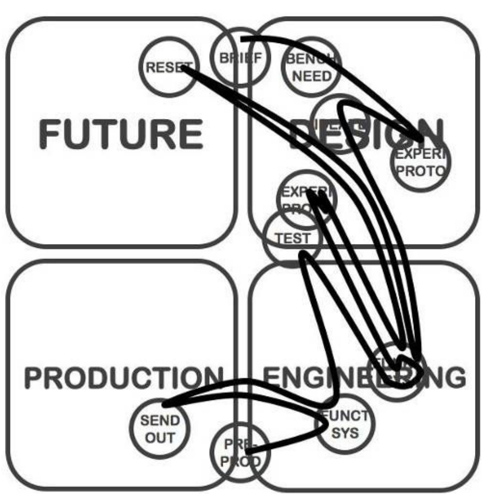

Figure 7. Project "A" Design Process

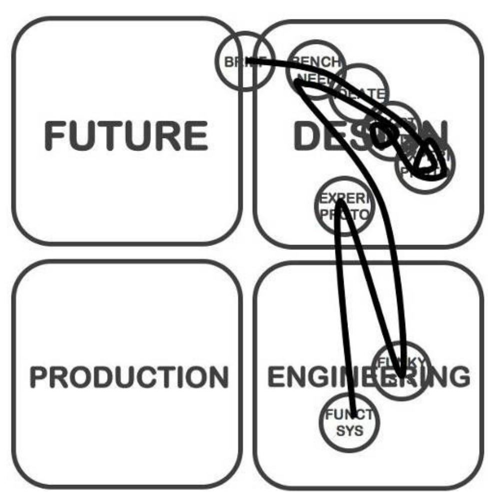

Figure 8. Project "B" Design Process

The students have iterated a number of times between Design Thinking activities and Engineering Thinking activities; early on they redefine the scope of the project from a car co-pilot of 2020 towards something dealing more acutely with information processing. Towards the goal of having a pre-production prototype at the end of the course the students outsourced some fabrication of parts.

Another example of student work, again with an amorphous future project becoming a specific design project, is seen in Project “B” for a consumer product company. The students were given the beginning design prompt to do something with “very human technology.” With Table 3 and Figure 8, taking the same approach of coding the team’s activities according to their self-reported design and development, by coding those nodes connecting the lines the gross representation of the design process is much different than Project “A.” The student team for Project “B” spent a lot of time benchmarking existing technology as well as drawing upon storyboards of possible experiences. Over the course of the year, while students considered what very human technology meant, they struggled to make headway in redefining the project direction. Towards the end of course students chose a route that allowed them take their ideas and their design experiences out of the realm of just Design Thinking into Engineering Thinking and resulting in actual physical tangible artifacts. However, their work stopped short though of having a pre-production prototype. Their end result was a wayfinding and tagging system that used a handheld computer to mimic the functionality of their imagined device, as well as a form model of what it could look like. They ended up with an functional “works-like” as well as an aesthetics “looks-like” for a pair of final prototypes.

Summary

This paper establishes a framework to visualize the relationships among Future Thinking, Design Thinking, Engineering Thinking and Production Thinking in the space of engineering design, by characterizing student design projects from a year-long product-based learning class along this *Ways of Thinking* framework. In summary, ME310 projects differ from one another. Projects have different beginning and ending points and unique paths in between. Even project with similar starting prompts can go in different directions and have different pathways of development. It seems apparent that students following along a more expert model of the design process rather than a more linear and arguably more novice model have a better project outcome and learning experience.

For the benefit of the students’ learning as well as the project outcome in the course it seems that from this initial investigation, benefit comes from repeated iterations between Design Thinking and Engineering Thinking as well as forays into Future Thinking (by means of resetting the design prompt). The time spent designing and engineering are also helped not only by the depth explored within a certain quadrant of the *Ways of Thinking* framework for engineering design but also time spent crossing over into other spaces and pushing outwards the bounds of the possible solution space. For the example of the co-pilot project the students benefited from iterating between Design Thinking activities and Engineering Thinking activities as well as reconsidering the project direction and scope in a Future Thinking manner at the start, and outsourcing some of the manufacture of their final pre-production prototype.

Next Steps

More work can be done in characterizing design projects. The pair of projects represented above follows the amorphous future projects turning into specific design projects. There is a history of projects done in past years in this same pedagogical model that touch on different starting points and ending points. It is an interesting next step to take a look at different combinations of starting and ending points (as again shown in Figure 9) to investigate further characterization or paths of high performing projects or low performing projects based on the student learning outcome and the project outcome.

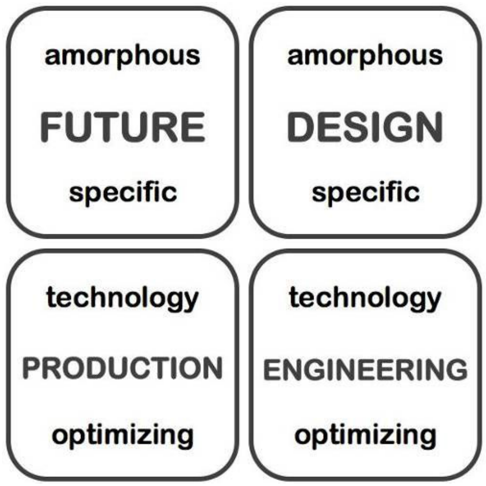

Figure 9. Array of Project Content Starting and Ending Points

A functional-physical distinction was noted between quadrants within the *Ways of Thinking* framework, but ambiguity and uncertainty would be other areas to investigate. Initial forays suggest that in the Design Thinking space ambiguity is appreciated, whereas in the Engineering Thinking space uncertainty is a thing to be minimized. At what point ambiguity goes from being a positive to negative thing as well as the inflection point from being ambiguous to uncertain is also of interest.

The design process model overlaying this framework is another area that could benefit from further investigation. It is the author's intention that this model of the design process in undergraduate and graduate education scaffolds the mental models and could support a transition from a simple novice model to more intermediate to an expert model. Hopefully the student's representation of the design process either reported individually, or in their design documentation as a team, could be one means to assess student learning in engineering design courses. It is imagined that individuals models of the design process fall along a spectrum and considering individual's process models would be another factor of diversity to consider in team formation in engineering design.

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