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Joshua D. Summers
Clemson University, jsummer@clemson.edu

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Joshua D. Summers
Clemson University, Clemson, SC

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Abstract
Engineering design is a generally nascent area of research within the engineering disciplines, spanning only a few decades of critical investigation. Clemson University has been at the forefront of the development of this field and continues this with a living experiment in how to integrate education, practice, and research through the CEDAR group. This essay introduces the reader to design research and the areas of study within CEDAR. Following this, an analysis of the research trends exposes three pillars of CEDAR philosophy: helping others, seeking variety, and learning from others. The goal of this essay is to introduce the wider scientific and engineering research and education community in South Carolina to this field and the possible opportunities for collaboration.

Engineering Design Research: Successful Integration of Education, Practice, and Study in the CEDAR Group

Joshua D. Summers*[a]

Engineering design is a generally nascent area of research within the engineering disciplines, spanning only a few decades of critical investigation. Clemson University has been at the forefront of the development of this field and continues this with a living experiment in how to integrate education, practice, and research through the CEDAR group. This essay introduces the reader to design research and the areas of study within CEDAR. Following this, an analysis of the research trends exposes three pillars of CEDAR philosophy: helping others, seeking variety, and learning from others. The goal of this essay is to introduce the wider scientific and engineering research and education community in South Carolina to this field and the possible opportunities for collaboration.

What is Engineering Design Research?

Engineering design research has been a field under study for only the past several decades. Within mechanical engineering, the first technical committee at ASME (http://www.asme.org) to specifically address design theory study was established 25 years ago with precursors in the area including design automation and optimization study dating to only 15 years earlier. It is with this backdrop that one recognizes that only newly minted engineering design faculty within the past couple of decades were specifically trained in the study of how engineers design products.

In studying engineering design, efforts have been focused on defining the *product*, typically ranging from abstract representations of requirements through geometric and parametric models through manufacturing and lifecycle views; on understanding the *process*, examining information exchange, the transformation of this information, or synthesis of new information; or on studying the *people*, such as in the role that individual personalities play in design or in how teams interact. The objectives of the researchers are typically to (1) understand how engineering is done, (2) develop new tools or methods to improve the process of design, or (3) use systematic design processes to develop new technologies or products. Typically, researchers develop a deep expertise in one of these areas, using one research tool from a suite such as case study, protocol study, user study, or simulation study. Within the Clemson Engineering Design Applications and Research (CEDAR) group at Clemson University, we have taken a holistic approach to engineering design research. Instead of choosing one dimension of design to study, we explore topics of how to represent information in design, study how the individual designer develops and explores ideas, and investigate group ideation and decision making. Rather than having a single objective, we have a three-pronged approach of understanding design, improving design, and practicing design. To achieve these objectives in these different dimensions, we employ a wide spectrum of design research tools.

What is Studied in Design Research?

While there are many different possible categorizations of the topics of study in design research (Finger and Dixon 1989a, 1989b, Eder 1998, Horvath 2004), we onsider product, process, and people as a simplified and useful delineation.

First, the product is at the center of engineering design as it is the desired artifact that is needed to meet the needs. A product representation includes both the requirements elicited from the customers, users, and stakeholders, and the final representations that describe the solution at different levels of abstractions. These representations may be useful for human based activities or for computational archiving and analysis.

Second, the challenge of eliciting the requirements, using these to synthesize solutions, and analyzing how these solutions satisfy the requirements is explored by studying the process of engineering design. Studying, defining, and characterizing the design process can help in developing new tools and in more effectively educating engineering students.

Researchers have identified differences in how experts and novices approach engineering design problems (Ahmed *et al.* 2003, Cross 2004, Atman *et al.* 2005), such as how experts tend to intuitively leap to solutions while novices employing a more systematic process generate better solutions than those without a process. This leads to the third dimension of studying the people involved in engineering design. There are numerous individuals and groups that are involved in engineering design, starting with the customer, including the marketing and technologists in the early stages, continuing with the engineers, managers, and analysts, and concluding with the manufacturers, users, and end-of-life stakeholders.

Why Study Engineering Design?

In studying engineering design, the goal is typically centered on one of three different objectives. First, researchers may focus on developing a fundamental understanding of how engineers design, such as in understanding the cognitive implications that different types of representation have on ideation (McKoy *et al.* 2001, Hannah *et al.* 2012). Further, they may create new design tools to support various design activities, such as in developing a CAD query language or refining existing idea exploration tools (Summers *et al.* 2006, Tiwari *et al.* 2009). Finally, researchers may focus on developing new technologies by practicing design, such as in developing new meso-structures for non-pneumatic tire shear bands or LED headlights for automotive applications (Morkos *et al.* 2009, Berglind *et al.* 2012).

In the first case, the researchers are concerned with uncovering the behaviors of the designers as they relate to different factors, both controlled and uncontrolled. This understanding is sought to align and compare with research from other disciplines, such as psychology or sociology. As an example, psychologists have studied group decision making and found that in experiments where a group was tasked with making a decision on the release of a drug given different information, those teams where the information was not shared with all members before the review meeting had improved decision making over those teams where all team members had the same information (Kelly and Karau 1999). This was experimentally compared to a typical engineering activity of conducting a design review to identify potential errors and flaws in a design product (Wetmore III *et al.* 2010). The engineering experiment showed that sharing inforamtion with all team members improved the performance of the team. Therefore, a fundamental difference in group decision making is identified, requiring further definition and clarification. This fundamental understanding may lead to developing new theories or in testing existing theories. These theories can be used to inform and guide the development of new tools, an alternative objective for some design researchers.

A second goal for engineering design research is to create new tools and methods for engineers to improve the efficiency of the design process, in terms of resource commitment, or to improve the effectiveness of the process, in terms of achieving higher quality and performing solutions. These tools are typically based on the theories that are developed based on the fundamental understanding. Rather than seeking to uncover new truth, tool developers are focused on improving design. As an example, a new idea generation tool, C-Sketch (Shah *et al.* 2001), was developed to support designers based on the understanding that provocative stimuli and sketching can have positive impacts on ideation (De Bono *et al.* 1984, Goldschmidt 1991, Masaki Suwa 1996). These tools may be experimentally tested within a controlled exercise in academia (Caldwell *et al.* 2012, Sen and Summers 2012) or may be deployed and evaluated in an industrial setting (Namouz *et al.* 2010, Kayyar *et al.* 2012). These approaches are discussed in the next section.

While understanding design and developing tools to aid designers are goals of design researchers, a third goal is also recognized in which the design researchers actually practice design by developing new technology. This third goal serves to help motivate the need for deeper understanding or the need for new tools while providing evaluation of the tools. More importantly, this objective also provides students, graduate and undergraduate, experiences in practicing design. This, in turn, prepares them for a professional career outside of traditional research. Some examples of this might include the work on developing new meta-materials or meso-structures to replace polymeric material in the non-pneumatic tire shear band (Ju *et al.* 2009, Berglind *et al.* 2010, Kolla, Ju, *et al.* 2010), developing a new integrated trash and recycling truck (Johnston 2007, Smith *et al.* 2007, Smith 2010), or developing new traction concepts for soft-soil (Orr *et al.* 2009, Kolla, Summers, *et al.* 2010, Mathieson, Thompson, *et al.* 2011).

Within CEDAR, each of these research goals and objectives is embodied in different efforts. This provides for a wide variety of opportunities for students to explore the complex discipline of engineering design as a practitioner or as a researcher. This is important as a philosophical foundation for the lab and is discussed in later sections.

How to Study Engineering Design?

Four different approaches to conducting engineering design research are illustrated here: case study, protocol study, user study, and simulation study. These are not formally classified, but this grouping and these definitions are useful when instructing students in how to conduct engineering design research. This structure has been used in both the graduate class on engineering design research newly introduced at Clemson University and at a research methods class taught collaboratively at Grenoble University (2012-2013).

Case studies are used to study complex, contemporary, uncontrolled phenomena where the context is critical in drawing conclusions (Yin 2003). This research method can be used for both theory building and theory testing, but is not based on replicative logic (Teegavarapu *et al.* 2008). In engineering design, case studies are often used to understand how practice is done in industry to discover patterns of behaviors and influencing factors, such as uncovering how information is lost in the product development process or change propagation initiation factors (Joshi and Summers 2010, Shankar *et al.* 2012). Identifying these factors is critical to understanding the root cause before addressing them in corrective tools. Case study research requires significant time resources, as the phenomena under investigation are on the order of weeks to years. Thus, a related challenge is the sensitivity of the findings to the specific case under study which might limit the ability of the researcher to extrapolate the findings to other contexts.

While case studies investigate uncontrolled phenomena in real-world situations, protocol studies look at understanding smaller scale activities and behaviors in a controlled setting. These behaviors are often uncontrolled as the “natural” behaviors and responses are studied. Protocol studies have been used to compare the design activities of freshmen and senior students (Atman *et al.* 2005), to understand how engineers create fucntion models (Sen and Summers 2012), to explore how engineers interact with physical objects during idea generation (Hess 2012), or how designers move between information domains such as requirements to functions to structure (Dinar *et al.* 2011). An advantage to the protocol studies is the ability to control the situation and environment, replicating it whith multiple subjects. However, the transcription, coding, and analysis of the protocol sessions can be intensive; roughly 40 hours of analysis for each hour of data collected. Therefore, researchers are challenged to ensure that the protocol is robust before executing the study. In protocol studies, the object of study is the behavior or cognitive activities of the engineer or team. Often, the end product or results of the design activity is not evaluated.

A third type of empirical research that is used in engineering design is the user study. In this instance, a small slice of a design activity is controlled and manipulated to study the influence that different variables have on the outcome. This type of study is most similar to the commonly understood scientific method, though it is complicated by the use of human subjects. User studies typically focus on a testing a few variables while using replicative logic to draw statistically significant conclusions. Some examples of user studies in engineering design include studying the modes of communication and their influence on design review effectiveness (Ostergaard *et al.* 2005), studying the influence that abstraction level and physicality has on reviewing design solutions (Hannah *et al.* 2012), or studying the impact that different techonologies have on errors in CAD modeling (Summers *et al.* 2009). The experimental design of a user study is of critical importance, so much so that, many times, the design problem might be reused for multiple different user studies with different participant pools (Ramachandran *et al.* 2011, Richardson III *et al.* 2011, Smith *et al.* 2012).

While these three methods have focused on human centric activities, a fourth type of study centers on the simulation of design and reasoning activities to develop new understanding or introduce new tools. These simulation studies are more challenging in engineering design to validate against the human agents that they are modeling, but are useful in transitioning between theoretical mathematical models and engineering practice. One example of this might be the simulation studies conducted to examine potential sequencing of discrete decision making in engineering design (Sen, Ameri, *et al.* 2010) simulations conducted to determine whether a popular design tool in industry, Quality Functional Deployment (QFD), is anything more than a random number generator based on a game theoretic understanding of decision making (Olewnik and Lewis 2008), or agent based modeling of fixture design (Pehlivan *et al.* 2009).

With each of these research methods, there are challenges in terms of validation of the results and verification of the research process. With engineering design research still in a nascent stage (Eder 1998, Cantamessa 2003, Blessing and Chakrabarti 2009), with some considering it pre-paradigm, these challenges of qualification of the research is critical and is under study (Dain *et al.* 2013). It is our objective to use the research tools and methods as objectively, neutrally, and repeatably as possible. Understanding the limitations of the research methods is as central to our research philosophy as conducting the research itself.

CEDAR Research Themes

Using these research methods, the CEDAR lab studies the product, process, and people involved in design in order to achieve all three research goals. Specific research themes within the lab range from studying representation and reasoning, to complexity and collaboration. Additionally, the idea of practicing design is a strong theme, with students reporting on new technologies developed within the lab for specific sponsors. Each of these are briefly discussed.

Representation

Engineering design representations (Summers and Shah 2004) include the fuzzy front end of engineering design with textual descriptions of requirements (Shankar, Morkos, *et al.* 2010) and qualitative models of a desired functionality (Sen *et al.* 2011) through to the detailed geometric description of the product (Summers *et al.* 2006) and the associated necessary manufacturing systems (Ameri and Summers 2008). The CEDAR lab is interested in both the virtual, information-intensive representations used in engineering design (Anandan and Summers 2006a, Sen, Summers, *et al.* 2010) and the physical representations of prototypes (Stowe *et al.* 2010, Mathieson, Thompson, *et al.* 2011, Hannah *et al.* 2012, Hess 2012). These representations allow designers to communicate, archive, analyze, externalize, and evaluate their decisions in exploration and refinement of the problem and the solution space. Studying these reasoning activities is a theme of the CEDAR lab.

Reasoning

Engineering design reasoning is a second core theme within the CEDAR lab as we study how designers think (Sen and Summers 2012), use tools (Miller and Summers 2012), and process information (Sen, Ameri, *et al.* 2010, Hannah *et al.* 2012, Smith *et al.* 2012). The design process is realized through the reasoning activities of the designers and the automation of the computers, such as in morphological analysis supported by genetic algorithms (Tiwari *et al.* 2009). The reasoning is supported by the representations that are studied. The representations are only useful if they can explicitly support design reasoning activities. Therefore, we are interested in understanding what aspects of the representations support what types of reasoning activities (Namouz *et al.* 2012, Rosen and Summers 2012, Prudhomme *et al.* 2013, Summers *et al.* 2013).

Complexity

A third theme within the CEDAR lab is the study of complexity in engineering design (Summers and Shah 2010). Within this theme, we have explored how different views of complexity expose different aspects of products (Ameri *et al.* 2008), how structural complexity can be used to predict the end cost of a product based on abstract functional descriptions (Mathieson, Shanthakumar, *et al.* 2011), how the graph properties of a communication network can predict design progress (Mathieson *et al.* 2009, Mathieson, Miller, *et al.* 2011), and most recently how we can use the assembly and liaison graphs to predict assembly times (Mathieson *et al.* n.d., Miller, Mathieson, *et al.* 2012, Owensby *et al.* 2012, Namouz and Summers 2013). This research into complexity has focused on trying to understand why different structural connectivity metrics contribute to the ability to predict seemingly distant properties in products while at the same time trying to develop computational tools to support engineers in the development process. We are continuing to investigate the possibility of using the structural connective complexity metrics for such things as evaluating effort required to address engineering analysis problems and test questions.

Collaboration

The fourth theme within the CEDAR research centers on understanding collaboration, specifically how engineers interact and communicate. In studying collaboration, we have investigated communication and information sharing in design reviews (Ostergaard *et al.* 2005, Wetmore III *et al.* 2010), leadership properties within teams (Palmer and Summers 2011), and the evolution of information generation through design projects (Mathieson *et al.* 2009, Joshi and Summers 2010, Mathieson, Miller, *et al.* 2011). To study collaboration, we turn to an incredible resource, the numerous student design teams that we supervise and our collaborators and colleagues in industry. These two sources provide us with opportunities to explore collaboration in different settings and with different levels of control.

Technology Development

Finally, within the CEDAR lab we place significant effort on the development of new technologies, through the application and practice of design. This includes developing testing equipment (Orr *et al.* 2009, Morkos *et al.* 2010), developing traction concepts (Kolla, Summers, *et al.* 2010, Mathieson, Thompson, *et al.* 2011), or developing meso-structures for non-pneumatic tire shear band replacement of polymerics (Kolla, Ju, *et al.* 2010, Shankar, Ju, *et al.* 2010, Berglind *et al.* 2012, Ju *et al.* 2012). In exploring the practice of design, we are able identify new challenges and opportunities for research and study. For instance, in working with a local company in developing a combined trash/recycling truck (Smith *et al.* 2007, Miller and Summers 2012), the issue of requirements came to the forefront. This motivated new research in studying engineering requirements, their definition, evolution, and role in engineering design. Further, the development of numerous prototypes of lunar tire systems (Stowe *et al.* 2010) has led to research into the areas of physical representations in engineering design. Thus, this cross-generational discovery of challenges from past student design projects to serve as motivation for new research is a key strategy within CEDAR.

Analysis of CEDAR Research

In this reflection on research within the CEDAR Group, we can examine the research of the graduate students advised by Dr. Summers in the past decade. Table 1 illustrates the research based on the students, examining what is being studied (product, process, people), why it is studied (understanding, improvement, practice), how it is studied (case, protocol, user, and simulation study and practice), and the theme investigated (representation, reasoning, complexity, collaboration, and technology development). If there is a strong, explicit link, a "1" is placed in the corresponding cell. If there is a weaker, implicit relationships, then a "0.5" is placed in the cell. This is done to illustrate the priorities within the student research. Based on this, some comparitive analysis can be done to explore research in CEDAR.

First, we can consider what is studied within CEDAR (Figure 1). In this figure, we see that most of what is being studied is the design process itself, with the design product

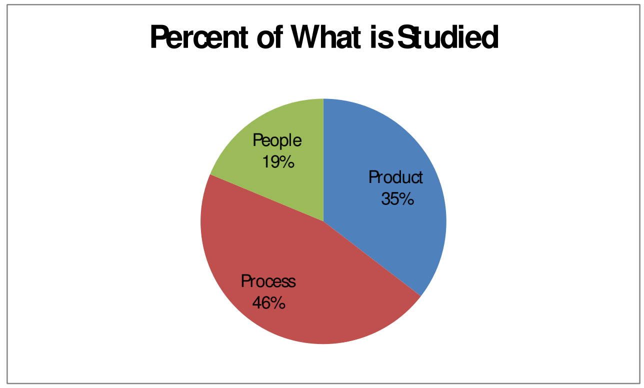

Figure 1: What are CEDAR Students Studying

being the next largest contributor. However, is it clear that what is being studied is fairly balanced within CEDAR. We have a strong interest in studying the people involved in design, but this can be an extremely resource intensive aspect of design to study. A balanced approach is definitely sought, though.

Next, we can examine the research objectives for the different projects and graduate student research theses (Figure 2). It is clear that half of the effort spent in the lab is dedicated to improving engineering design practice. This is not accidental, but indicative of our background as engineers rather than scientists. Where science is about understanding what is, engineering is about trying to create what can be. This is codified in our attempts to actively influence and impact engineering design practice by developing new actionable tools for students and industrial practitioners. Ironically, this does not translate into actual practice of engineering, as it is the smallest percentage of the theses within CEDAR. Thus, while we seek to provide students with opportunities to design and produce new technologies, the emphasis within the lab is to improve practice. The practice that is reported in the thesis work is typically relegated to motivations for developing new tools. This emphasis on helping others by improving design, is an altruistic characteristic of the CEDAR lab.

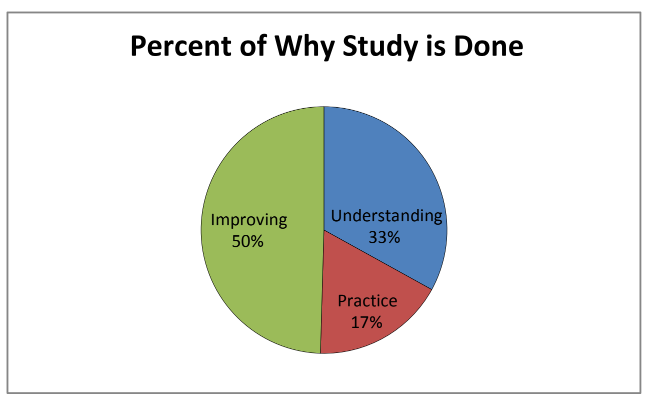

Figure 2: Why are CEDAR Students Studying

Third, we can examine how the students conduct research within the CEDAR lab (Figure 3). This figure suggests that simulation studies and case studies are the two preferred approaches to conducting research within the lab. Simulation is more comfortable for traditional engineers and physical scientists, possibly explaining why so many students are comfortable with this approach to research. Case study, however, allows students to interact, integrate, and investigate live, industrial situations. Thus, those students that are pursuing industry-oriented careers are provided with unique opportunities to learn about industry through their research. User studies, as the third most popular approach, have been used since early in the history of CEDAR, and its precursor the Automation in Design (AID) Lab. Typically, because of the challenge of conducting only a few studies a year in order to not innundate the population of students that serve as the fodder, there is limited capacity for conducting user studies with the classroom setting. Finally, protocol studies have only recently been introduced into the research toolbox at CEDAR, but there is a growing interest in understanding how this research approach can be used to augment both case and user study. Interestingly, there are several students that triangulate their research with more than one approach. This balanced approach and willingness to adapt new research approaches is another hallmark of the CEDAR lab.

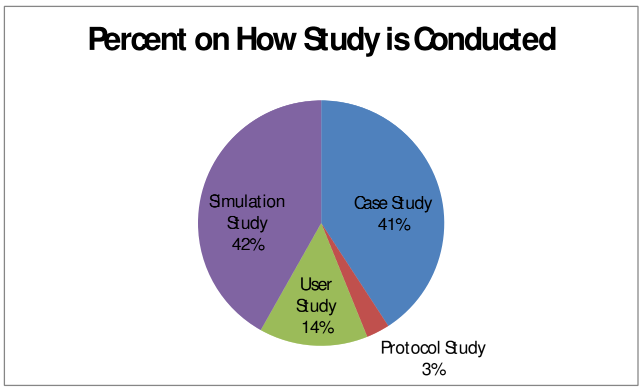

Figure 3: How are CEDAR Students Conducting Research

Finally, we consider the research themes within the CEDAR lab (Figure 4). Design representation and reasoning are two of the largest themes for the student research, which is not surprising when one recognizes that representation without reasoning is of no value and that reasoning cannot be done without a representation on which to reason. While collaboration and complexity are the two smallest of the research themes, these are interests of current students and this trend should become even more balanced in the future. The theme of developing new technologies is well represented, again demonstrating that exercising design process is critical to research within CEDAR. In the future, an additional research theme that might be introduced is the study of design education. While many education oriented papers have come from CEDAR, these have not yet resulted in theses or dissertations. This coarse analysis of the research that is being conducted at Clemson University within the CEDAR group, suggests a balanced approach in many dimensions. This sense of balance is a guiding principle within the lab and is found in the philosophies that have developed within it. These philosophies, general priniciples

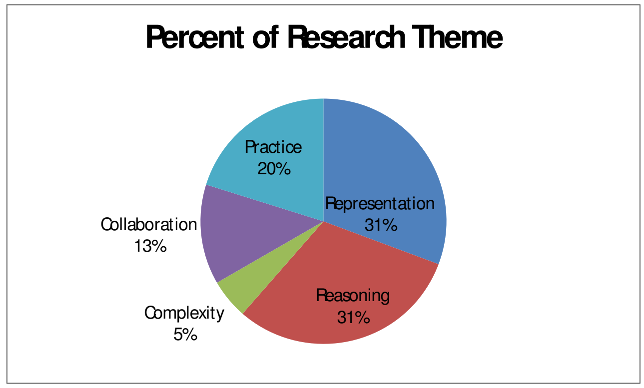

Figure 4: What are the CEDAR Student Research Themes

that guide life within the lab, include research, service, education, and advising. It should be noted that these have not been formally codified, voted upon, or accepted by all lab members, faculty or students, but are what this researcher has learned from his time in the lab.

CEDAR: The Experiment

Over the past decade, the CEDAR group has evolved a philosophy and resulting guiding principles that center around how we approach research, service, education, and advising. The students and the faculty of CEDAR have collaboratively developed these philosophies. This collaboration is a key foundation and is augmented by a principle of intentionality. The three hats of an engineering faculty, scientist, engineer, and teacher, are all central, but each has a slightly different priority for each faculty member. For me, the sorting starts with first being a teacher, second an engineer, and third a scientist or researcher. This prioritization creates a framework in which the roles and objectives of the students in the CEDAR group operate and develop the respective philosophies.

Research Philosophy

We will first start with the research philosophy as that is the common focal point for many faculty at research institutions. While this is an important component, it is not the sole purpose for the lab. Our research philosophy has evolved to recognize that our fundamental objective is to help engineers do their job better, as evidenced in the emphasis on the objective to improve design in Figure 2. We continually seek opportunities to collaborate with industrial partners as both motivation and as validation of our work. Further, we rely heavily on the students' own past experiences in industry to help define the motivation for their studies. In this way, the students are taking a keen ownership in their research studies and have a clear goal of improving the process. Thus, our first research philosophy pillar is to seek to improve design practice.

A second critical aspect of our research philosophy is the decoupling of the work done by the students on industry or federally-funded projects and their thesis research. This decoupling allows for more flexibility in aligning students on projects, permitting short duration projects to be brought into the lab without the concern that the student's thesis research might outlive the project duration. Thus, during a student's career in the lab, they might work on several different funded projects. This variety has helped to provide students with a broader experience than many of their peers, while helping to challenge the students into becoming adept engineers and researchers. Thus, variety is a second pillar in our research philosophy.

Next, we believe that engineering and research are not individualistic activities and are truly social activities (Dym *et al.* 2006). Each student will work on several collaborative projects. This ranges from students partnering on writing papers to student teams for the industry projects. In fact, no student within the CEDAR lab should graduate without having worked with others in the lab. This sense of collaboration extends beyond the lab as we seek new relationships and research opportunities with other faculty, other departments, and other schools. This extensive collaboration provides students with exposure to more ideas and views as they continually learn from each other. Thus, a final pillar of our research philosophy is to learn from each other.

The three pillars of our research philosophy are that we should seek to aid others by improving design practice, that we should seek variety and balance of opportunities, and that we should be open to learn from our colleagues and teammates. These pillars are replicated in our service, education, and advising philosophies also.

Service Philosophy

Public service within the CEDAR lab is recognized as critical and important to both the development of the individual students and as an alturistic contribution to society itself. This service has been realized through many student driven activities, such as volunteer efforts at local elementary schools, providing engineering services to local inventors through undergraduate research, introducing the general public to engineering practices with Cub Scouts and Girl Scouts activities, and through design projects for schools and small companies. One recent example of this is the design and build of wind tunnels for three schools in Six Mile, Anderson, and Greenville through an undergraduate design course (Summers 2012). We feel that it is our duty to share and dissiminate new knowledge both through passive approaches of publication, but also through active approaches by reaching out to the community. This service philosophy is realized through at least two activities a semester organized by the CEDAR students, welcoming project requests from inventors for student teams to address, and by using project assignments in our design courses to address the needs of real customers, such as elementary schools.

The pillars of helping others is clearly realized in the service component of the lab. The fact that several service opportunities are sought reinforces the commitment to variety and balance. Finally, in all of the service activities, the CEDAR lab acts as a team, helping, encouraging, and supporting each other.

Education Philosophy

In terms of educating, we believe that design education is best realized through collaborative experience and active reflection. This means that we seek opportunities for students, graduate and undergraduate, to work on design projects, while challenging them to continually reflect on what works or not. We believe that teaching is not simply about lecturing about design tools, but guiding the students in exploring these tools to understand their strengths and weaknesses. We have continually sought to introduce new educational opportunities for the students, graduate and undergraduate, through new courses and novel structures of existing courses. Most importantly, we have sought to integrate the graduate students and their research in the undergraduate experiences as advisors and coaches on design teams, as guest lecturers, or as researchers conducting experiements in the classroom. This active involvement and exposure of students to research through education is critical. We believe that education of our student engineers is found not just in the classroom, but in all other interactions that we have with the students, both graduate and undergraduate. Therefore, we seek to involve the CEDAR lab as much as possible in the development, delivery, and dissemination of the design education at Clemson University.

Again, helping others by volunteering in the classroom or as a design coach aligns with the first pillar. The second pillar of seeking variety and balance is seen in the continual introduction of new courses and design opportunities for both the undergraduate and graduate students. Finally, the collaborative learning is recognized through the team based approach that is predominate in the educational philosophy of CEDAR.

Advising Philosophy

A final dimension of CEDAR philosophy is a more personal one. This dimension of advising is one that relates to the faculty exclusively as the students are being advised. In essense, this is the heart and genesis of the CEDAR philosophy, as perceived by Dr. Summers. First, the goal of the advisor is to help students grow as engineers, researchers, and individuals. This growth will be different for each student and will require different approaches and techniques in nurturing the student. However, if this is the primary goal of the researcher, then challenging or weaker students become opportunities, not burdens. Moreover, this shifts the focus from generating new knowledge through research to teaching students how to generate new knowledge through research. This subtle shift is simultaenously seismic as it transforms the faculty member from a researcher who has a set of tools (students) to execute their research plan to a faculty member who is a teacher challenged with guiding students in their evolution into capable researchers.

One result of this shift from researcher to teacher is that it frees the faculty member to ask the student a seemingly dangerous question "what do you want to know?". This question can lead to many new avenues and areas of study that are new to both the student and the faculty advisor. However, this simple question allows the student to take ownership of their own study. It provides a personal incentive to the student. It places the student at the center of the equation, with research as the platform on which to teach.

This shift from researcher to teacher also fundamentally transforms the underlying motivation for publication. Rather than being focused on writing papers to top journals to achieve the prestige due great researchers, the teacher uses the act of writing and presenting the student's work to help the student learn to articulate and crystallize their ideas. Instead of waiting to write conference and journal papers from the completed theses of the students, students are encouraged to write about their research in progress. This helps them put to paper their ideas before the daunting task of writing a thesis. Moreover, it allows the advisor-student team to gain quicker feedback from the research community so that they can adapt and modify their research directions.

However, a challenge with getting students to write about their research is their fear that their work is not "good enough". Thus, we discuss the morality of publication and dissemination of knowledge. As we are a research lab within a public institution, it is our moral duty to share new findings, both significant and small, with the community at large. It is not our goal or objective to make financial gains from our research. Thus, while students might have a challenging time accepting writing for the sake of improving their thinking, they can accept the moral obligation of sharing new ideas with others.

Implications of these Philosophies

The CEDAR group is still a relatively new entity and will continue to evolve. We have welcomed and said goodbye to different faculty and students through the years, but we believe that we have something inherently good about our philosophies that guide how we teach and do research within the lab. As we look at CEDAR as a living experiment, we can continue to explore new ideas and test whether current practices are truly best. That said, we believe that the three pillars of helping others, seeking variety of experiences, and learning from others will continue to guide the CEDAR lab.

Notes

[a] *250 Fluor Daniel Building, Mail Stop: 0921, Department of Mechanical Engineering, Clemson University, Clemson, SC 29634-0921, Fax: 864.656.4435; Tel.: 864.656.3295; E-mail: jsummer@clemson.edu*

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Table 1: Comparison of CEDAR Student Research (What, Why, How, and Theme)

	What is Studied			**Why Study**			**How Study**				**Research Theme**					
Graduate Student Researcher	Product	Process	People	Understanding	Practice	Improving	Case Study	Protocol Study	User Study	Simulation Study	Representation	Reasoning	Complexity	Collaboration	Practice	**Reference**
Morkos	1	0.5		0.5		1	1			0.5	1	0.5				(Morkos *et al.* 2012)
Shankar	0.5	1		0.5		1	1			0.5	0.5	1				(Shankar *et al.* 2012)
Sen	1	0.5		1		0.5		0.5		1	1	0.5				(Sen *et al.* 2011)
Teegavarapu		1	0.5	1		0.5	1					0.5		0.5	0.5	(Teegavarapu *et al.* 2008)
Anandan	0.5	1		0.5		1			0.5	1	0.5	1				(Anandan and Summers 2006b)
Pehlivan	1	0.5		0.5		1				1	0.5	0.5				(Pehlivan and Summers 2008)
Shanthakumar		1				1				1	0.5	1				submitted
Hess		1	0.5	1			1	1			0.5	0.5				Submitted
Owensby		1				1			0.5	1	0.5	1	0.5			(Owensby *et al.* 2012)
Griese	1			0.5		1				1	0.5				1	Submitted
Rayate	0.5	1				1				1	0.5	0.5				(Rayate and Summers 2012)
Miller, M.	0.5	1		0.5		1	0.5			1	0.5	0.5	0.5			(Miller, Griese, *et al.* 2012)
Schultz	0.5			0.5		1				1	0.5				1	(Schultz *et al.* 2012)
Mathieson	0.5	0.5	0.5	1		0.5	1			1	0.5	0.5	1	0.5		(Mathieson *et al.* n.d.)
Berglind	0.5	0.5			0.5	0.5	0.5			1	0.5	1			0.5	(Berglind *et al.* 2010)
Richardson	0.5	0.5		0.5		1			1		0.5	0.5				(Richardson III *et al.* 2011)
Namouz		0.5	1	0.5	0.5		1					0.5		0.5	0.5	(Namouz *et al.* 2010)
Joshi	0.5		0.5	0.5		0.5	1				0.5					(Joshi *et al.* 2011)
Kolla		0.5		0.5	0.5	0.5	1			0.5	0.5	0.5			0.5	(Kolla, Summers, *et al.* 2010)
Palmer			1	0.5			1							1		(Palmer and Summers 2011)
Smith, E.		1		0.5	0.5	0.5	1					0.5		0.5	1	(Smith *et al.* 2007)
Hannah	0.5	0.5	0.5	0.5		0.5			1		1	0.5				(Hannah *et al.* 2012)
Osborn			1			1	0.5							1		(Osborn *et al.* 2011)
Sen (Masters)	1			1						1	0.5	0.5	1			(Sen, Summers, *et al.* 2010)
Stowe		1		0.5	1		1				0.5	0.5				(Stowe *et al.* 2010)
Michaelraj	1					1	1			0.5	0.5					(Hannah *et al.* 2008)
Miller, W.		1	0.5	1			1				0.5	0.5		1		(Miller and Summers 2012)
Kanda	1					1				0.5	0.5					(Kanda and others 2008)
Johnson		1			0.5		1					0.5			1	NA
Smith, G.	0.5	0.5		0.5		1			1		0.5					(Smith *et al.* 2012)
Kayyar		1				1	1					0.5			1	(Kayyar *et al.* 2012)
Srirangam	1	0.5			1	0.5	1			0.5	0.5	0.5			0.5	(Anandan *et al.* 2008)
Chavali		1			1	0.5	1					0.5			1	(Chavali *et al.* 2008)
Putti	0.5	0.5				1				1	1	0.5				(Putti and Summers 2006)
Snider	0.5	0.5			0.5	1	0.5				0.5	0.5				(Snider M. 2008)
Wetmore		0.5	0.5	0.5		0.5			1					1		(Wetmore III *et al.* 2010)
Bayanker		0.5	0.5	0.5					1			0.5				(Summers *et al.* 2009)
Divekar	0.5					1				1	1	0.5				(Summers *et al.* 2006)
Ostergaard			1	1					1	0.5				1		(Ostergaard and Summers 2009)
Veisz		0.5	1	1			1				1			0.5		(Veisz *et al.* 2012)
Morkos (Masters)	0.5				1					1					1	(Morkos *et al.* 2009)
Nowlay	0.5				1					1					1	NA
Troy	0.5					0.5				0.5					0.5	submitted
Gunturi	0.5				1	0.5				0.5		0.5			0.5	NA