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Unpacking an Engineering Practicum: Building Engineers, One Participant Structure at a Time

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Building Engineers, One Participant Structure at a Time

Gina Navoa Svarovsky

World War II brought extraordinary technological advances to U.S. society. In an effort to help students grasp the complex theories and principles behind these advances, engineering educators began to emphasize science and mathematics courses in the core undergraduate engineering curriculum more heavily. However, this reprioritization was often at the expense of courses that focused on manufacturing and design, rendering engineering students noticeably unprepared for the transition to the workforce (Dutson, Todd, Magleby, & Sorensen, 1997). Calls from industry for more qualified engineering graduates soon followed, and the golden era of the capstone engineering experience began.

Today, 1- to 2-semester capstone design courses are expected and anticipated during the senior year of most undergraduate engineering programs. Moreover, cornerstone courses—design-based courses that are more introductory in nature and generally encountered during the early years of the undergraduate curriculum—are on the rise. Engineering professors and professionals realize that these experiences are critical to the complete development of new engineers. In order for students to understand the nuances of engineering—and be able to think, act, and indeed *be* engineers—undergraduates must engage in the essential activity of the profession, engineering design, within a meaningful context. In an effort to provide students with an authentic "real world" experience, capstone and cornerstone courses often attempt to recreate aspects of industry design. However, do these adapted professional activities serve a more important pedagogical role than just increasing authenticity?

In this paper, I investigate this question by describing an ethnographic study of Biomedical Engineering (BME) 201, an engineering design course for sophomores at a large Midwestern university. The goal of the study was to uncover the learning processes that students experience in the course. In particular, I examined two activities—or *participant structures* (Shaffer, 2005)—for their pedagogical significance during BME 201: the weekly design meeting and the student design notebook. Understanding how these participant structures facilitated student learning can influence the future design of capstone and cornerstone experiences as well as the broader landscape of engineering education.

Theoretical Framework

In an attempt to standardize and improve undergraduate engineering education, the Accreditation Board for Engineering and Technology (ABET) recently released Criterion 3, a set of 11 outcomes the board believes all undergraduate engineering students should possess upon graduation (Gorman, 2002; Shuman, Besterfield-Sacre, & McGourty, 2005). Among engineering

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educators, Criterion 3 is generally divided into two informal categories: the "hard skills" and the "professional skills." Table 1 lists the outcomes that comprise these two categories.

Table 1
ABET Criterion 3 Categories

Hard skills	Professional skills
• An ability to apply knowledge of mathematics, science, and engineering (3.a) • An ability to design and conduct experiments, as well as to analyze and interpret data (3.b) • An ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability (3.c) • An ability to identify, formulate, and solve engineering problems (3.e) • An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice (3.k)	• An ability to function on multi-disciplinary teams (3.d) • An understanding of professional and ethical responsibility (3.f) • An ability to communicate effectively (3.g) • The broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context (3.h) • A recognition of the need for and the ability to engage in life-long learning (3.i) • A knowledge of contemporary issues (3.j)

Although it is not unanimous throughout the engineering education community that these are the right set of outcomes, ABET's Criterion 3 outlines a set of capabilities that undergraduate engineering programs are required to address. ABET was motivated to create Criterion 3 based on research by the government, industry, and academia that identified the glaring gaps between engineering education and the needs of professional engineers in practice. Even at first glance, it is clear that many of these outcomes—particularly the professional skills—cannot be addressed adequately in an engineering program oversaturated with science and mathematics content courses.

Engineering Pedagogy

In an effort to address Criterion 3, engineering educators at most universities have made several changes to the undergraduate curriculum, including streamlining core course offerings and material (for example, collapsing a 2-semester sequence in thermodynamics into a more focused 1-semester course), providing more options for program electives (for example, courses in engineering ethics and green, eco-friendly design), and incorporating current issues and technologies into coursework (for example, discussing potential ways to improve the safety of mining equipment and conditions). Although these modifications have contributed to the more complete development of today's engineering students, it is the continual and rapid development of capstone and cornerstone courses over the past 20 years that appears to have had the most influential impact on engineering education (Dym, Agogino, Eris, Frey, & Leifer, 2005).

Real world design-based courses. Real world design-based courses are intended to provide students with a realistic engineering experience and thus address many components of Criterion 3. Generally, students in these courses work in teams to solve realistic design problems specific to their engineering discipline under the guidance of a professor (Dym & Little, 2000; Miller & Olds, 1994; Todd, 1993; Tompkins et al., 2002). Students brainstorm ideas, identify constraints, research products, build prototypes, and evaluate their designs in order to understand the nuances of the engineering design process. They write reports, give oral presentations, and participate in formal design reviews to develop the communication skills essential to success within industry. They keep a detailed design notebook to become familiar with the rigorous demands of engineering documentation for legal and patent purposes (Burghardt, 1999; Dym & Little, 2000). These activities are commonly included within design courses in order to provide undergraduate engineers with an *authentic*, real world experience as a way to develop the skill set required to be a successful practicing engineer.

The reflective practicum. Design-based courses rely on the authenticity of the activities and course components to help prepare undergraduate engineering students for industry. By participating in realistic adaptations of actual engineering practice, the students in these classes engage in a controlled environment that removes at least some of the commercial, physical, and social constraints of industry. In other words, the students engage in an authentic *simulation* of professional engineering practice.

Practicum is another term used to describe professional learning environments that simulate authentic practice. Practica are generally "off-line" situations that recreate and approximate the real world professional context (Waks, 2001). Particularly relevant to the domain of design education is the work of Donald Schön (1983, 1987), which examines a particular type of practicum: *a reflective practicum,* where novice professionals engage in authentic, messy, and ill-structured problems under the supervision of more experienced, often expert, mentors—or as Schön calls them, "coaches." As a result of undergoing the reflective practicum experience, novice professionals generally mature in their ways of thinking, doing, and acting, making significant progress towards becoming *reflective practitioners* who exhibit artistry within their field.

The artistry exhibited by an expert reflective practitioner is seen in the ability to shift from standard, skilled performance to a more analytical and experimental mode when an unexpected complication arises during practice, which Schön identifies as *reflection-in-action* (Schön, 1983, 1987). For example, when a reflective designer encounters an unexpected wrinkle while working on a project, that individual can shift into reflection-in-action: engaging in on-the-spot thought and action experiments, often consisting of considering an action, asking "what if?," and thinking about the consequences—both intended and unintended—that the move will have on the design, and how those consequences will affect future moves. By listening to the situation's *back-talk* in this way, expert designers engage in a *conversation with the materials*, which is the way Schön identifies and defines good design practice.

The aim of the reflective practicum, then, is to help novice professionals learn how to reflect-in-action. Within the reflective practicum, novices work on authentic problems from the field, which almost never have a simple, single, or straightforward answer. After the student grapples with these problems singly, a coach consults with the student on the progress made, often *reflecting on* the student's actions, helping to reframe the situation to point out misalignments with the norms of the profession. This *reflection-on-action* provides the student with insights into artistic professional practice. The coach can not only reflect on the student's past actions and help that student understand why they might not have been the best choices; the coach can also reflect-in-action and discuss with the student ways of making forward progress on solving the problem, such as positing a set of potential moves, playing them out by considering their repercussions, or presenting different ways to reframe the problem so that the student may become "unstuck." Later, the student might reflect on past interactions with the coach, thinking about how those conversations may have influenced development as a professional, or perhaps providing insights to the coach (typically through solicited feedback) on how the tone or content of those conversations could be improved for future students. This ongoing dialogue between coach and student is essential for making the ways of thinking and knowing of a profession visible, understandable, and accessible to new members.

It is important to note that the distinction between reflection-on-action and reflection-in-action is quite subtle. Schön (1983, 1987) and Shaffer (2005) both highlight this issue and determine that the primary difference between these two forms of thought is the temporal relationship of the reflection to the action. Reflection-on-action involves reflection in the present and action in the past. Reflection-in-action involves reflection in the present coincident with action in the present. In this paper, I define reflection-on-action and reflection-in-action along these boundaries while acknowledging that they are not completely and clearly delineated.

The ideas of *reflection* and *coaching* are not completely foreign to engineering education. Gorman, Richards, Scherer, and Kagiwada (1995) described reflection as understanding problem-solving strategies at the metacognitive level, which in turn enables practitioners to apply these strategies in novel contexts. Adams, Turns, and Atman (2003) analyzed data from four studies to investigate how engineering students exhibited reflective practice when engaging in certain design tasks, such as iterating through ideas during the design process and problem setting. Khisty and Khisty (1992) described a "laundry list" of teaching practices employed within a particular capstone course in an effort to promote reflection-on-action and reflection-in-action, though no analysis was conducted on student learning outcomes or processes. Marin, Armstrong, and Kays (1999) addressed the issue of coaching by providing three criteria for coaching and mentoring students successfully within a capstone course. However, none of these studies addressed how students can develop reflection-in-action within the design practicum. In my study of BME 201, a practicum in its own right, I sought to discover and understand the underlying opportunities for reflection embedded within the design meeting (as a form of design review) and the design notebook.

Reflection and the epistemic frame. Learning to reflect-in-action is more complex than mastering a list of abilities such as ABET's Criterion 3. Certainly, outlining a set of competencies is a valid and widely accepted way of characterizing the members of a particular profession. However, it is not the only way to do so. Another view—arguably a more complete one—of how to describe a profession's particular manner of acting and thinking is to use the idea of an *epistemic frame* (Shaffer, 2005, 2006; Shaffer, Squire, Halverson, & Gee, 2005). An epistemic frame consists of the set of skills, knowledge, identities, values, and epistemology of a particular profession. For example, scientists act like scientists, know what scientists know, see themselves as scientists, are interested in scientific discoveries, and perhaps most important, *think and reason* like scientists. Likewise, other professionals—such as lawyers, doctors, and urban planners—each have their own ways of doing, seeing, caring, and being, and thus each have a different epistemic frame.

Shaffer (2005) has argued that learning to reflect-in-action means developing the epistemic frame of a particular profession. In other words, as students work under the supervision of a coach in the practicum, they begin to learn the skills and knowledge required to practice as professionals. They begin to identify themselves as capable practitioners who understand the value system of the profession as they learn to see and act on the world in a new way. Here, I explore how BME 201 helps sophomore engineering students begin to develop the epistemic frame of engineering, focusing on the components of skill, knowledge, value, and epistemology. The identity component of the epistemic frame is beyond the scope of this paper and has been discussed elsewhere (Svarovsky & Shaffer, 2006).

Participant structures: Occasions for reflection. Within a reflective practicum, the epistemic frame is developed through specific activities, or *participant structures,* in which reflective conversation occurs. Investigating these participant structures and understanding the types of reflection that occur—as well as the content of those reflections relative to the epistemic frame—is done through a type of ethnographic study called an *epistemography* (Shaffer, 2005). For example, an epistemography conducted on a reflective journalism practicum revealed three participant structures (news meetings, war stories, and copy editing) as key contributors to the development of a journalistic epistemic frame (Shaffer, 2005). News meetings were occasions for students to discuss the stories they were working on in front of a veteran journalist and their peers. War stories were occasions for veteran journalists to share their professional experience with the entire class. Copyediting sessions were occasions where the professor or students commented on another student's story. Although these participant structures may have been included in the course by the professor for other reasons, such as to create an authentic context for journalistic practice, it was their capacity for fostering reflection that made them pedagogically powerful.

The salient and reflective participant structures identified within the journalism practicum were all rooted in interactions between people, such as the student-student, student-professor, and student-veteran conversations. Here, I propose to extend the concept of a participant structure to include interactions between person and tool by applying the theory of *distributed mind* (Shaffer & Clinton, 2006), which argues that person-tool interactions can be analyzed with the same lens as person-person interactions. In other words, in the analysis of the journalism practicum, person-person interactions cultivated reflection and thus helped students develop the epistemic frame of the profession. In my analysis of BME 201, I will analyze not only a person-person interaction (the design meeting) as a potential catalyst for reflection, but also a person-tool interaction (the student design notebook).

Context of the Study

BME 201 is a cornerstone course in the BME department at a large Midwestern state university. At this university, the 4-year undergraduate engineering curriculum is built around a 6-semester design-course sequence (Tompkins et al., 2002). Beginning with the first semester of the sophomore year (when most of the students are admitted to the department), students engage in biomedical engineering design projects posed by local clients, such as doctors, physical therapists, and professors of kinesiology. The first three courses—BME 200, 201, and 300—involve semester-long projects, while the last three—BME 301, 400, and 402—focus on the extended design and development of a single device over a 3-semester time frame.

I learned about the course through a series of formative interviews with several professors affiliated with the BME department. Initially I had intended to observe the BME 301 course, which was populated by juniors. However, these students were already quite advanced in their engineering development, and within the context of BME 301, they would be embarking on a 3-semester design project. Because I was interested in studying the earlier stages of engineering training as well as investigating a project from beginning to end over the course of 1 semester, I ultimately decided to study the sophomore-level course.

BME 201 was a one-credit course that met for 2 hours once a week, 14 times during the semester. The first day of class was reserved for assigning projects and teams, and one additional class during the semester was reserved for a lecture on engineering ethics. Finally, one class was set aside for mid-semester presentations, and the last class was spent doing final poster presentations in a public area within an engineering building. Students were required to generate slides and reports for each of these external reviews.

During the formal class time, student teams had design meetings with their design advisors. According to one of the course professors, the design meeting was meant to function as a "mini design review" in which the students reported their progress and any problems to their design advisor and the design advisor provided insights, guidance, and at times, encouragement. These design meetings typically lasted approximately 15 minutes per team and occurred regularly in the first half of the semester, when the students were in the conceptual design stage and generating design alternatives. After the mid-semester presentation, the students transitioned to building a prototype or model, so the design meetings were often shorter and more focused on the mechanics of the prototype instead of conceptual design. Outside the scheduled course meeting, students met with clients, met with each other in their teams, and worked individually on various aspects of the project. Teams were required to write weekly progress reports which were e-mailed to their client and design advisor.

Students were also required to keep design notebooks to document their design work. The design notebook used throughout the BME design sequence is modeled after the professional documentation generated by practicing engineers. The course syllabus outlines several reasons for students to keep such a record of their work, indicating that the notebook could be useful as evidence for patents and a resource for preparing reports. In addition, by outlining the steps taken and lessons learned during the design process, the design notebook could be particularly helpful for projects that are passed to other design teams or span several semesters of work.

Certainly, both the design meetings and the design notebooks served pedagogical and pragmatic purposes throughout BME 201, exposing students to authentic engineering practices while also allowing professors to check in regularly with students to monitor progress and effort during the course. However, the purpose of this study is to explore how these specific participant structures functioned in the learning environment. Thus, the research questions guiding this work are:

- Do design meetings and design notebooks function as reflective participant structures in the design course?
- If so, do students develop elements of the engineering epistemic frame while engaged in these activities?

Methods

Data Collection

In order to address the research questions stated above, I collected different types of qualitative data throughout the semester. I was present at 11 of the 14 classes as an observer. I attended the first session where the students chose their projects as well as both presentation days. The eight remaining classes I observed consisted of the regular sessions involving design meetings between the student teams and design advisors. Five of these occurred before the mid-semester presentations, and three were after. During these observations, I generated field notes that provided a detailed description of the events, including direct quotations whenever possible. In the Results section, I use quotation marks to identify the actual utterances.

After the 3rd week of the semester, I began to follow one of the student teams closely. I obtained electronic copies of their weekly written progress reports, their mid-semester and final papers, and copies of their slides for presentation. I also asked the students for their design notebooks at the end of the semester. The week before the final presentations, three student teams—including the one I observed closely—participated in focus groups. In addition, I conducted individual interviews with the two professors who acted as design advisors in BME 201, as well as six other students who did not participate in the focus groups. All interviews and focus groups were tape-recorded.

Data Analysis

All field notes and audio recordings were transcribed. Field notes from the design meetings of the team I observed more closely were segmented initially by date, and then by turn of speaker. Due to the change in focus of the course after the mid-semester presentations, only the data from the first five design meetings were included for analysis. The turn-by-turn segments were coded for instances of reflection-on-action and reflection-in-action, as well as the *skill, knowledge, values,* and *epistemology* components of the epistemic frame. I also took the design notebook of one student from the team, Erik,[1] and segmented it first by date, then by entry. Here, I define a notebook "entry" at the level of a bulleted list, a sketch or design drawing with description, or a block of text such as a paragraph. These entry segments were also coded for instances of reflection-on-action and reflection-in-action, as well as the skill, knowledge, values, and epistemology components of the epistemic frame. For an example of these analytic codes, see Table 2.

[1] All names are pseudonyms.

After initially coding the data, I analyzed (a) the relationship between the two participant structures (the design meeting and the design notebook), (b) the types of reflection that may have occurred within them, and (c) the elements of the epistemic frame included in the reflective moments. I used a grounded theory framework (Glaser & Strauss, 1967; Strauss & Corbin, 1998) for my analysis. I also conducted nonparametric statistical analyses to further support the qualitative findings.

Table 2
Analytic Codes Used in Qualitative Data Analysis

Code	Description	Examples of coded comments or excerpts
Reflection-on-action	Comments regarding past action; consequences of past action; ways to improve past action in the future	"Good work! It's always good to get information not only from the client, but from the people who work with the client and around the client." Notes on earlier advisor suggestions (notebook)
Reflection-in-action	Comments regarding current and/or potential action; consequences of current and/or potential action	"[You need to] figure out what the client wants, in the priority that he wants it. What is most important? What is non-negotiable?" List of questions and potential answers (notebook)
Skills	Abilities students need to develop to become engineers	"We're doing more research, trying to decide which company to go with. We are looking at different aspects of the software now." Design diagrams (notebook)
Knowledge	Aspects of engineering domain knowledge	"We're working on a PDS [product design specification] report." Details of client setup (notebook)
Values	Things that are important to engineering practice	"You have a hands-on client . . . you might want to set up a weekly meeting to get regular feedback." List of client needs (notebook)
Epistemology	Ways of thinking about or justifying activity within the engineering community	"You don't want to sit around waiting for information to come to you. You want to pick up the momentum of the design . . . keep the information coming in so you don't stall." Written justification for design choice (notebook)

Results

The results from this study are presented in three sections. The first describes the design meeting and the design notebook as reflective participant structures within the course. The second section describes how these occasions for reflections were focused on the skill, knowledge, and value components of the engineering epistemic frame. The last section describes the relationship of these three components to the epistemology of engineering. In each section, I present examples from my data in anecdotal form, then analyze the examples.

Reflective Participant Structures in BME 201

The analysis of the design meetings and design notebook indicated that both of these participant structures were occasions for reflection in BME 201. Both of these structures involved reflection-on-action and reflection-in-action, though in different amounts.

Design meetings. During the second class meeting of the semester, the members of the student design team —Erik, Ken, Nicholas, and Jack—were working individually on Internet research when their design advisor, Mark, came along to check on their progress. After greeting the students, Mark asked Erik what they had been working on over the past week. Erik replied that they were trying to "figure out the problem statement" and that the team had been doing a lot of "research online" while trying to think about a "list of questions for the client." Ken, the team communicator, chimed in, mentioning that they had not yet been able to meet with the client due to scheduling conflicts.

Mark indicated that this was normal and to just keep trying to coordinate with the client, mentioning that perhaps a phone call might be more effective than e-mail for on-the-spot scheduling. Mark suggested the team "should draw out" what they thought the system looked like based on the client description in order to "get an initial idea of what's really happening." Mark then asked if the students understood how "the main component of the system works—the mass flow controller?" Nicholas, the most mechanically savvy member of the team and the team leader, said that he thought he knew how the mass flow controller—or MFC—worked, though he did not provide any further information to demonstrate his understanding.

Mark then steered the conversation in a new direction by asking about the team's progress in researching the problem. Erik said they had "been looking up different parts of the system online" and that each of them was "looking at different types of MFCs for sure." He added that other members of the team were also "looking at the software for MFCs." Mark agreed with the students' actions but also advised the team to "check out how MFCs work and look for information on the condition itself, on hypoxia." Mark then told the students that they "need to know about what the client works on," so they could more clearly understand the client's needs. The students nodded and a few jotted notes down in their design notebook. Mark opened the floor for any questions, and after pausing for a short while with no replies, he told the team that they were doing well and that he would see them the following week.

In this design meeting, the design advisor, Mark, engaged in both reflection-on-action and reflection-in-action. For example, he reflected-on-action when he commented on how common it was to have difficulty scheduling meetings with the client during the design process and provided the students with a suggestion on how to deal with this problem in the future (by placing a phone call to the client instead of e-mailing him). Mark also reflected-in-action when he told the team to also "look for information on the condition itself."

Figure 1 shows significantly more occasions of reflection-on-action than reflection-in-action during the design meetings (paired *t*-test, controlled for date of meeting, $p < 0.05$). These reflections were made by both the design advisor and the students, with each making 14 reflective comments for a total of 28 reflective comments over the five meetings observed. The design advisor's comments were split evenly between reflection-on-action (50%, 7/7) and reflection-in-action (50%, 7/7). Of the 14 student comments, 86% (12/14) were reflection-on-action, and 14% (2/14) were reflection-in-action.

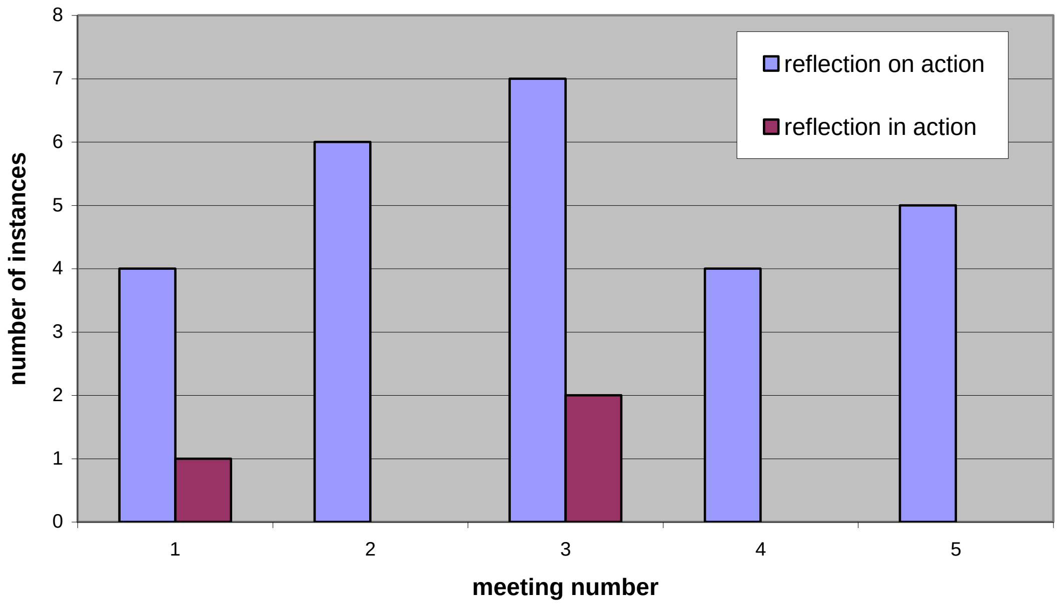

Figure 1. **Types of reflection found in the design meetings.**

Design notebook. Focus groups conducted with three teams at the end of the semester revealed that attitudes towards the design notebook were highly variable, with one student claiming to "love the design notebook," another stating "it was worthless," and others being unsure about their views. Regardless of their thoughts on its usefulness, students were required to record notes from brainstorming sessions, background research and literature searching, and all project meetings, as well as all sketches and calculations in their design notebooks. For example, following the design meeting described above, Erik sketched out his understanding of a mass flow controller, as seen in Figure 2.

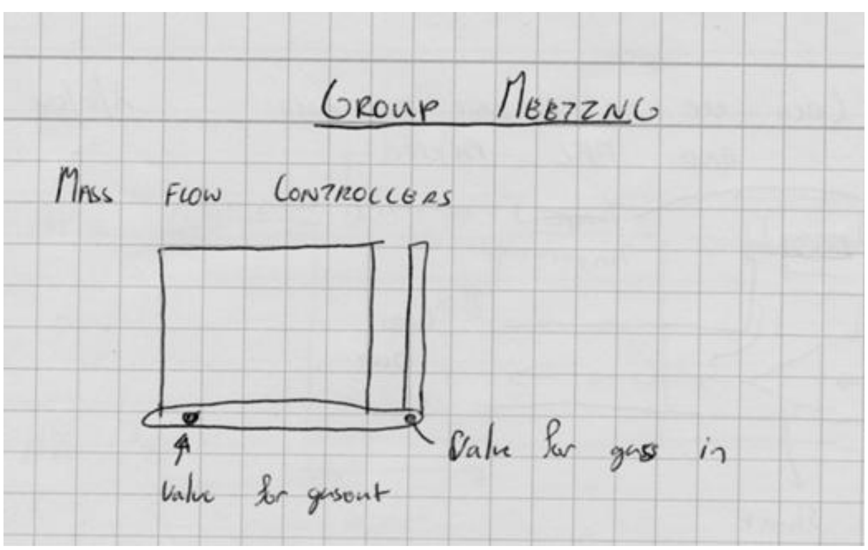

Figure 2. **Design sketch of device.**

Erik identified only two points on his MFC diagram: the "valve for gas out" on the lower left of the image, and the "valve for gas in" on the lower right. This was Erik's first diagram of the MFC, indicating his initial understanding of how the component functioned.

Below this sketch, Erik used the client's lengthy description to create a design drawing of the system, as suggested by Mark, the design advisor (Figure 3).

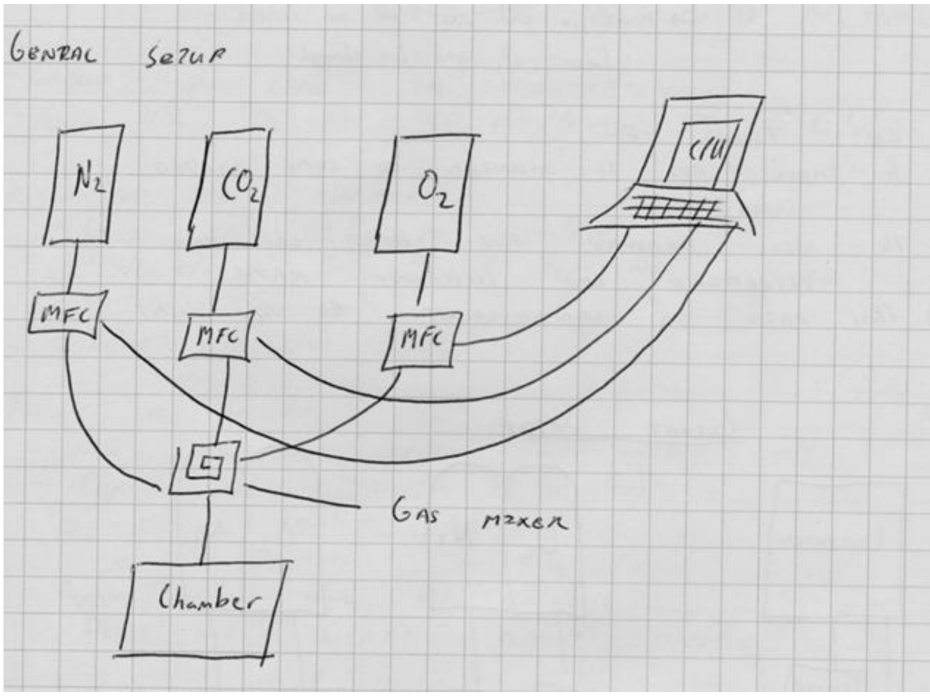

Figure 3. **Design drawing of existing client system.**

In Figure 3, Erik had each of the gas tanks (N_2, CO_2, and O_2) connected to an MFC that is controlled by a computer, thus allowing for the regulation of gas into the gas mixer and the experimental chamber. This diagram was followed by a written description of the system, as seen in Figure 4.

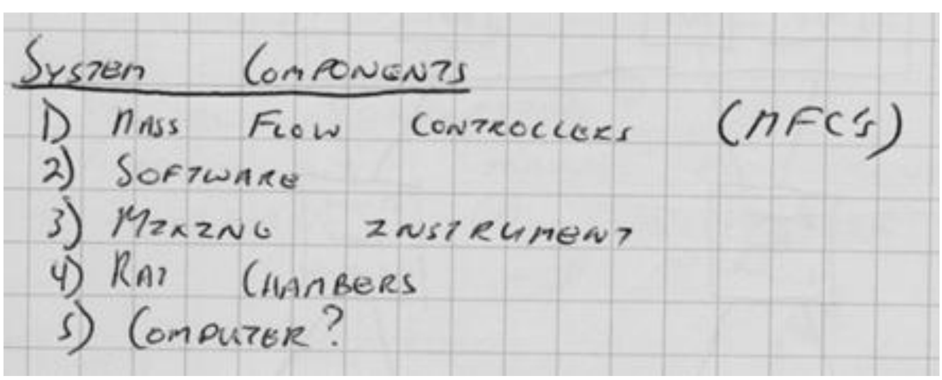

Figure 4. **List of system components.**

Here, the actual gas tanks were not included, while the software and computer were listed as separate elements. In Figure 3, these two elements were integrated into the image labeled *CPU*.

At the bottom of the page, Erik listed questions to be asked at the team's first meeting with the client, as seen in Figure 5. These questions stemmed from a desire to understand the parameters of the design problem, including the client's needs ("priority of components for project") and the physical and material constraints ("data acquisition card").

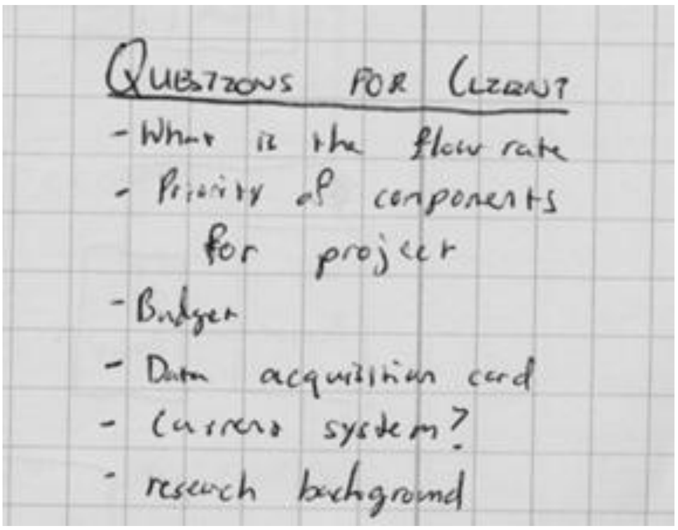

***Figure 5.* List of questions for the client before first meeting.**

After a few additional scheduling problems, the team was finally able to meet with their client during the 3rd week of the semester. Two days passed, and then the team gathered again to continue working on the project. The team discussed the client meeting, the information the client was able to share with them, and everyone's current understanding of the client's needs. In his notebook, Erik recorded these suggestions by the team, as seen in Figure 6.

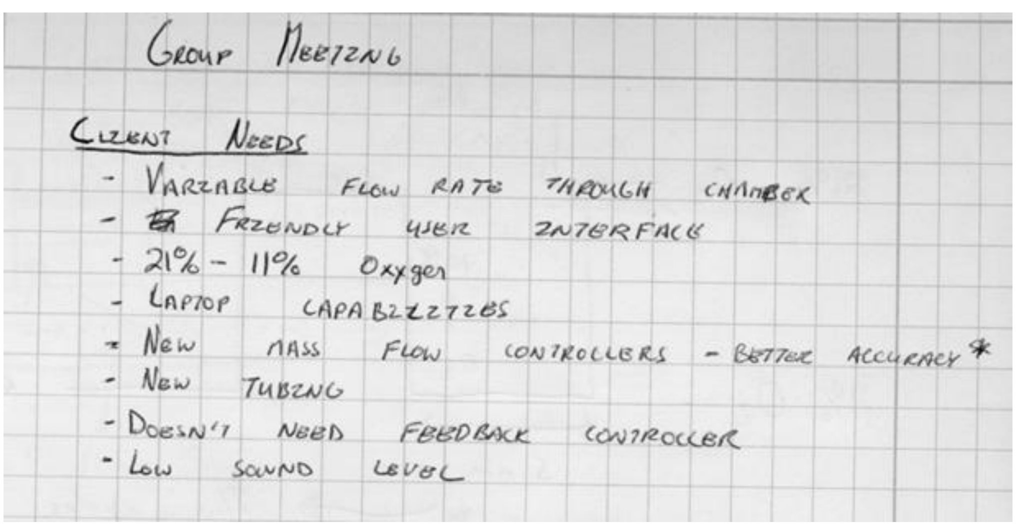

***Figure 6.* Summary of client needs after first meeting.**

The list of client needs includes design objectives ("better accuracy"), constraints ("21%–11% oxygen"), and functions ("variable flow rate through chamber").

These excerpts from Erik's notebook demonstrate the effectiveness of the design notebook as a tool for reflection. For example, he reflected-in-action when he listed the system components (Figure 4), wondering if the software and computer should be two separate components. If so, the implication would be that his team would have to research and identify both the software to control the MFCs and the computer to run the software. Erik again reflected-in-action when he generated the list of questions for the client (Figure 5). Here, he was thinking about what information he needed from the client, as well as some potential components of the system to discuss with the client. In Figure 6, Erik reflected-on-action when he—with his teammates—discussed the initial client meeting and identified an initial list of client needs.

Erik's design notebook contained significantly more occasions of reflection-in-action than reflection-on-action, as seen in Figure 7 (paired *t*-test, controlled for date of notebook entry, $p < 0.01$). Of the 33 reflective entries, 85% (28/33) were reflections-in-action, while the remaining 15% (5/33) were reflections-on-action. This distribution differs greatly from the distribution of reflective comments in the design meetings, where most student comments (86%) were reflections-on-action.

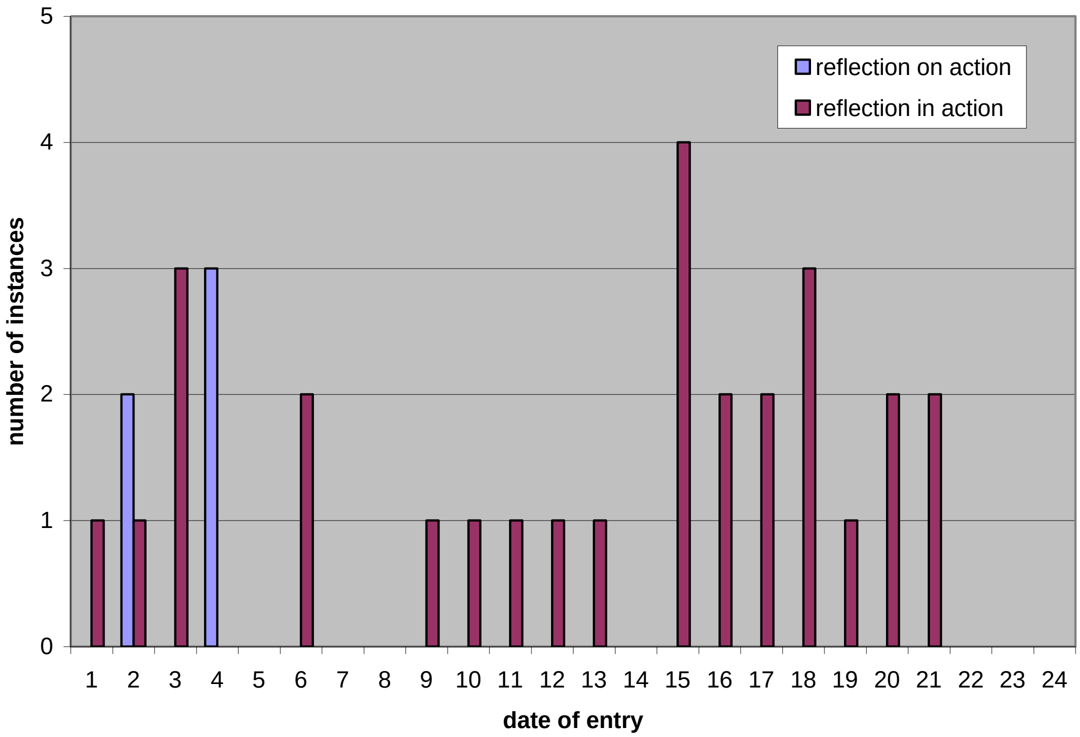

***Figure 7.* Types of reflection found in Erik's design notebook.**

Reflection and Engineering Skills, Knowledge, and Values

The design meeting and design notebook excerpts described in the previous section demonstrate both kinds of reflection within BME 201, *on-action* and *in-action*. Naturally, given the context of the course, these reflections were about getting the team of sophomore engineers to solve the design problem set before them at the beginning of the semester by the client. However, a closer look at Erik's conversations—both with the design advisor and with the design notebook—reveals that these participant structures were about developing engineering skills, knowledge, and values.

Design meetings. In a design meeting 2 weeks before the mid-semester presentations, Ken and Jack were talking with Mark about how the latest client meeting was "really very informative," and therefore the team had "a much better idea of what he really wants."

Mark replied enthusiastically, "That's good! Now you can restate the problem statement." This process allowed the students to reframe the problem and significantly trim the lengthy problem statement initially provided by the client at the beginning of the semester. Mark acknowledged that the students could now "zero in" on what they needed to do.

Mark then turned to another issue, asking the team, "Who else are you talking to besides the client?" Nicholas replied that he was talking to a software engineer on campus to "figure out more about MFC control networks." Mark nodded and said that this was a good idea, because "getting the perspectives of other people" who have other experience with the devices involved could provide the team with "another plan of attack." After a brief pause, Mark asked the team members what they thought some of the main differences between their design alternatives might be, perhaps "different MFCs . . . or different software . . . or different hardware?"

Erik looked up from his notebook and indicated the team wasn't "sure yet" because they still had "to learn a little more about the system." Mark said that was fine, but he suggested the team should "get moving" on their other design ideas. "Remember," he cautioned, "you want to have at least three alternatives to present to the client."

During the reflective conversation in this design meeting, Mark referred to engineering *skill* by telling the students to "restate the problem statement." He addressed engineering *knowledge* by advising the students to get different "perspectives of other people" who might have additional and complementary experiences with the devices involved in the design. Finally, he touched on engineering *values*, noting the importance of having "at least three alternatives" to present to the client.

Design notebook. The design notebook also demonstrated Erik's development of engineering skills, knowledge, and values. For example, an excerpt from his notebook (Figure 8) shows a graph of the different concentrations of oxygen and nitrogen gas required for the experimental conditions. Here, Erik demonstrated the engineering *skill* of design drawing. Instead of describing the necessary gas concentrations in words, he sketched out the pattern in his notebook, also including a partial time dimension by noting that the 11% oxygen gas concentration must last 5 minutes. Figure 8 also demonstrates Erik's engineering *knowledge*—he understood the chemical symbols and axial dimensions of the diagram.

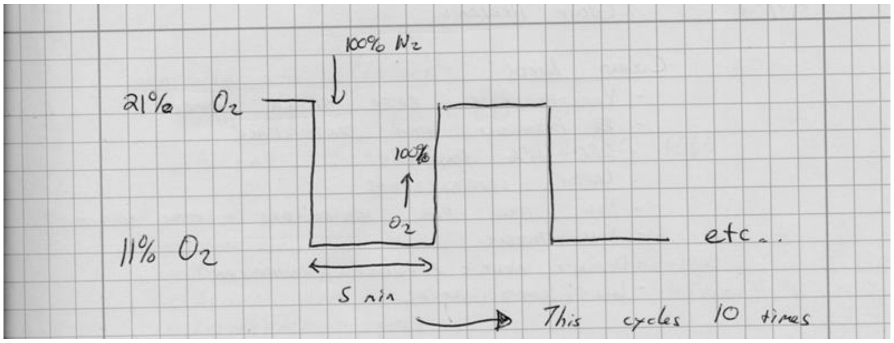

Figure 8. **Design sketch of oscillating gas concentrations required by the system.**

In another excerpt from the notebook (Figure 9), Erik identified the required "specs" for the chambers of the machine—meaning the required features that must be included in the design. This list was generated during a client meeting. By identifying the required specs of the chambers, Erik enacted the engineering *value* of interpreting client needs based on client description.

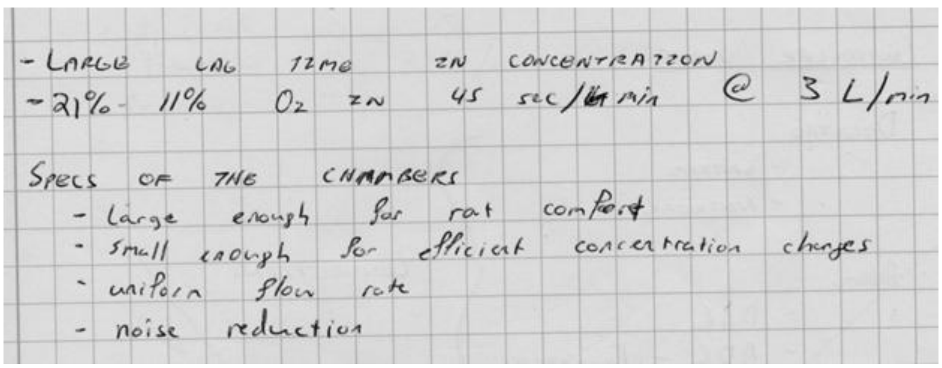

Figure 9. **List of required specifications for the chambers in the system.**

The design meeting and design notebook excerpts presented here involved reflection and also demonstrated how these reflections were about engineering skills, knowledge, and values. Figure 10 (next page) shows the distribution of these frame elements within each reflective participant structure. Approximately 40% of the reflections in both the design meeting and design notebook were focused on engineering skills. The design meetings focused slightly more on engineering values (31%) than engineering knowledge (29%), while the design notebook focused more on engineering knowledge (42%) than engineering values (18%).

Engineering Epistemology

Not surprisingly, references to engineering skills, knowledge, and values were abundant throughout the semester. However, it is interesting to note the ways in which these references were bound together throughout the design meetings and design notebook, especially when tied to epistemic statements about engineering.

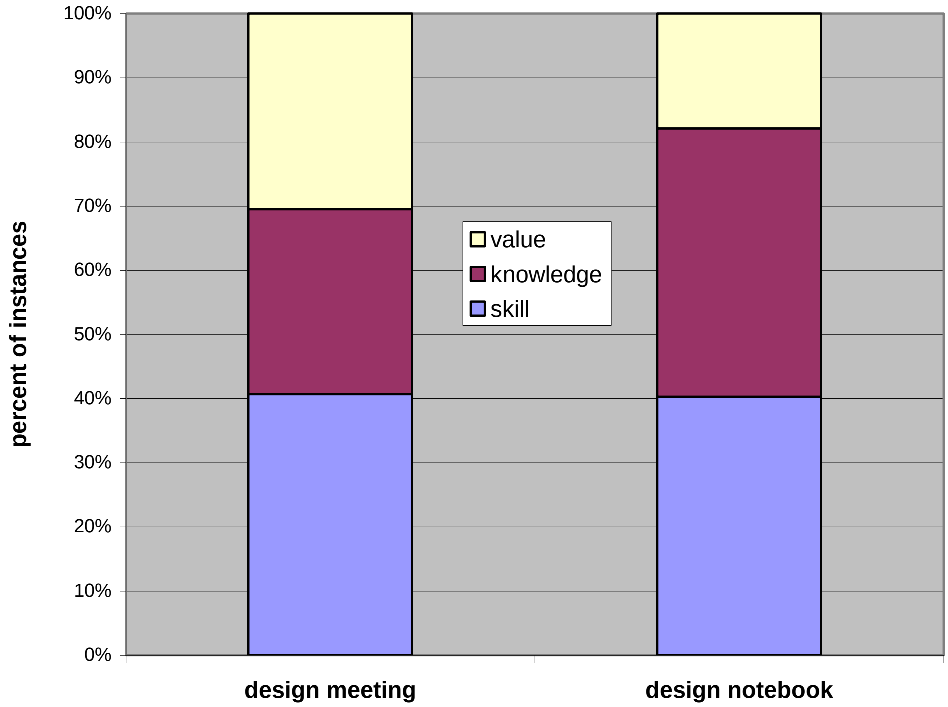

Figure 10. **Percentages of references to engineering skill, knowledge, and value within the design meetings and design notebook.**

Design meetings. As seen in Table 2 above, epistemic statements are utterances that include justification for some professional action. For example, at the end of the design meeting Mark reminded the students that they should have three design alternatives to present to the client at the mid-semester meeting. To these cautionary words, Erik answered, "We think we have a good basic idea for the parts we're going to need," as well as what the system "will look like when it gets set up."

However, Mark directed the conversation back to his previous point, saying "That's fine, but just be sure to really think about other design alternatives." He recognized that the team might "really like [the] first idea," but there are always other products or configurations that might "make a better design—less money, more efficient, that sort of thing."

In this brief excerpt at the conclusion of the design meeting, we see that Mark made an epistemic statement by justifying why a design or product might be better than another—"less money, more efficient, that sort of thing"—from the engineering worldview. This explanation bound together his earlier comment about understanding other products and configurations (engineering knowledge) in order to create additional design alternatives (engineering skill) so as not to commit to a favorite or first design idea (engineering value).

Design notebook. Epistemic statements in the design notebook also bound the skill, knowledge, and value components of the engineering epistemic frame together. For example, in one excerpt from his design notebook, Erik justified why he needed to replace the mass flow controller (Figure 11).

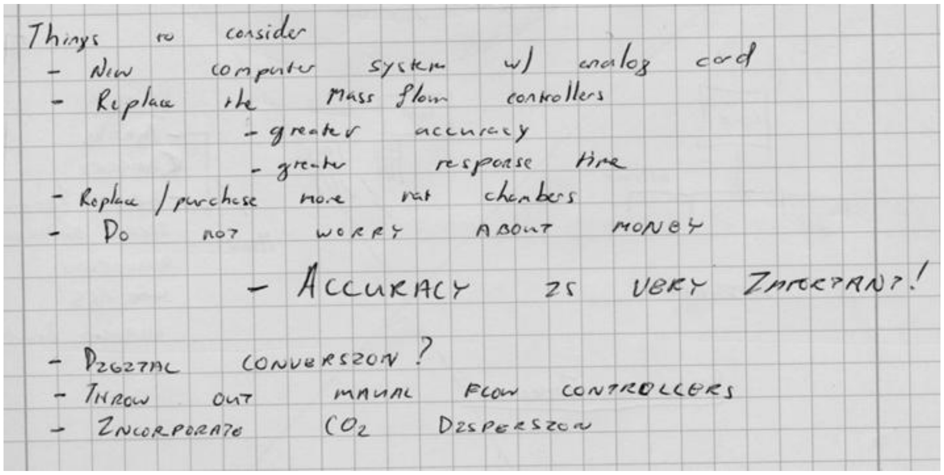

***Figure 11.* List of considerations during the design process.**

With the second bullet point, Erik identified the need to replace the existing mass flow controllers, and he justified that decision by listing two reasons: the greater accuracy and greater response time that the new controllers would offer in the design. With particular attention to accuracy, Erik was identifying the needs of the client (an engineering skill), while understanding components of the design (engineering knowledge) and simultaneously satisfying the client's needs (an engineering value). Moreover, it was important for Erik to explicitly note these justifications of his design choices, so that when he presented the design alternatives to the client he could explicitly warrant the ways in which the new design was an improvement over the extant system.

By looking at the total number of epistemic statements across both the design meetings and the design notebook—and the co-occurrence of these statements with engineering skills, knowledge, and values—we see that epistemic statements bound together skills, knowledge, and values of the profession (Figure 12, next page). In both the design meetings and the design notebooks, the occurrences of skills, knowledge, values, and epistemic statements were highly correlated: $R = .774$ ($p < 0.01$) for design meetings, and $R = .749$ ($p < 0.01$) for design notebooks.

Discussion

The analysis of BME 201 suggests that the design meetings and design notebook were in fact reflective participant structures. Moreover, these participant structures were occasions for the students and the design advisor to engage in conversation regarding engineering skills, values, and knowledge. References to these elements of the epistemic frame also tended to be bound together with a fourth component, epistemology, as represented in epistemic statements about the engineering profession.

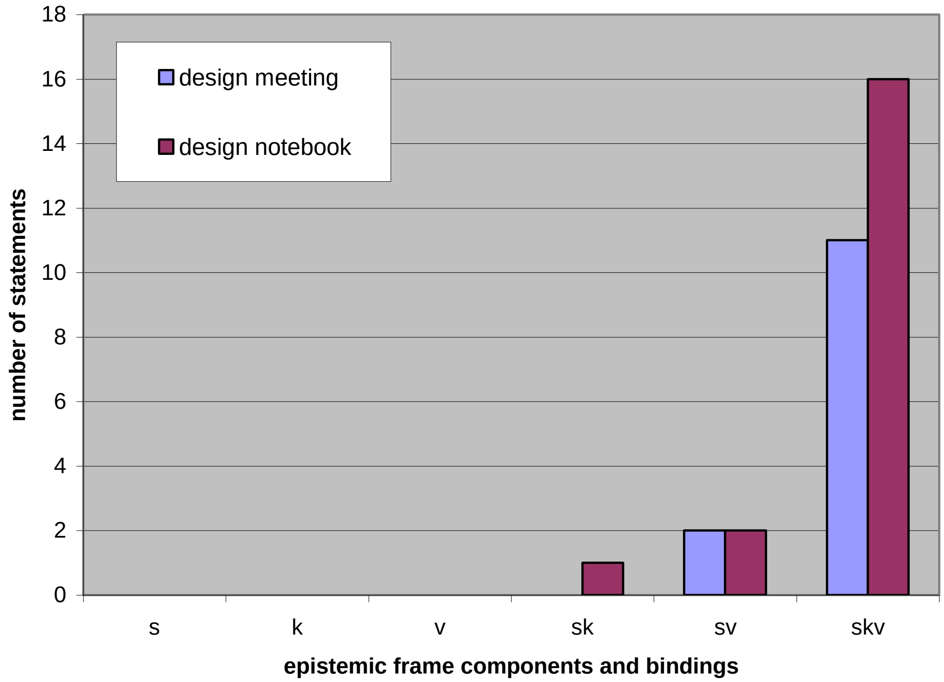

***Figure 12.* Binding of skill, knowledge, and value in epistemic statements about engineering.** S = skills; K = knowledge; V = values.

Given Schön's work (1983, 1987) and Shaffer's (2005) investigation of a journalism practicum, one might expect the design meetings in BME 201 to be a reflective participant structure. Similar to the architectural *desk crit*, the musician's lesson, and the journalistic news meeting, the BME 201 design meeting is a thoughtful interaction between student and coach organized around, and in, professional activity. Here, the design advisor and students engaged in more reflection-on-action than reflection-in-action. This might be explained by the original intent for the meetings to function as quick check-ins to make sure the student teams were moving forward with their work and to provide suggestions if their progress had stalled. Also, the relatively short contact time between student and coach (as superficially compared to the contact time between student and coach in other accounts of reflective practica) may have prevented the conversation from moving more towards the types of interactions Schön (1983, 1987) reported in the architecture studio, where the coach spins "a web of moves," asks "what if?," and considers the consequences. Nonetheless, the design meetings in BME 201 did in fact promote and support reflection within the practicum, thus serving in a powerful—and not necessarily intended—pedagogical role.

By applying the theory of *distributed mind* (Shaffer & Clinton, 2006), we can extend the construct of reflective participant structures within a practicum to include not only person-person, but also person-tool, interactions. Thus, I was able to explore a student's engineering design notebook as a tool for reflection by using the same lens I had applied to the design meetings. Documenting the design process from his own perspective in the design notebook required Erik to externalize his ideas, understanding, and justifications on paper. Although these representations were written and not spoken, they commonly demonstrated Erik's reflection-in-action and thus a gradual progression towards a more mature engineering practice. As stated within the course materials, the design notebook is intended to be a document that can be used for patenting and legal purposes, serve as a resource for report writing, and potentially be a guide for future teams taking on the project. Certainly, the design notebook functioned in some of these authentic ways during BME 201. Perhaps more significant, however, was the fact that the design notebook also helped Erik engage in reflection-in-action, which is a key facet of the undergraduate's professional development. Thus, the design notebook fulfilled an instrumental—and once again, not necessarily intended—pedagogical role as part of engineering practicum.

Though much of the focus of this paper has been on reflection and reflective participant structures, the content of these reflective moments should not be overlooked. Naturally, the reflections in the course were about "doing" engineering. For example, some of the reflections in BME 201 addressed (a) how to find information, (b) what that information means, (c) how to use that information to solve the design problem, (d) why engineers need certain types of information, and (e) what counts as useful information. More generally, the reflections were about elements of the engineering epistemic frame, particularly the skills, knowledge, values, and epistemology of the profession. However, it is the binding of skills, knowledge, and values by epistemic statements that is most interesting. In this study, epistemic statements tended to use a particular value to justify a particular skill that required particular knowledge, such as when Erik bound together the requirement to satisfy the client with identification of client's needs and the understanding of different design components. This finding suggests an underlying model for the epistemic frame of engineering and its development: in order for students to develop the engineering epistemology and begin to "think like engineers," they must be engaged in meaningful activity that involves the development of these three other frame components.

Of course, the study presented here has several limitations that should be considered. First, the scope of the analysis is quite narrow, consisting of the design meetings of a single student team and the design notebook of a single student. Second, this small cross-section of data was confined to one design course in a 6-semester sequence, thus resulting in a detailed yet discrete snapshot of undergraduate engineering development. However, this study does shed light on the reflective capabilities of two common participant structures within engineering practica, the ways in which these participant structures address elements of the engineering epistemic frame, and the nature of the engineering epistemic frame itself. These findings—and future studies investigating reflective engineering design practica and the development of the engineering epistemic frame—can illuminate how to better prepare undergraduates to transition smoothly and successfully from the classroom to the workplace.

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