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Abstract

Recently, K-12 engineering education has received increased attention as a pathway to building stronger foundations in math and science and introducing young people to the profession. However, the National Academy of Engineering found that many K-12 engineering programs focus heavily on engineering design and science and math learning while minimizing the development of engineering habits of mind. This narrowly-focused engineering activity can leave young people – and in particular, girls – with a limited view of the profession. This study describes Digital Zoo, an engineering learning environment that engaged girls in authentic engineering activity in order to link the development of engineering skills and knowledge to engineering ways of thinking. Specific activities from an engineering practicum were recreated in the learning environment, where ten middle school girls from diverse backgrounds role-played as engineers designing solutions to a client-based project. Responses on pre, post, and follow up interviews suggest the participants were able to develop each of the five epistemic frame elements – engineering skills, knowledge, identity, values, and epistemology – as a result of Digital Zoo. In situ data from the intervention was analyzed with a sophisticated mixed methods approach that integrated qualitative methods with a new quantification technique, Epistemic Network Analysis. These techniques allowed for the exploration of complex thinking and learning throughout the different activities of Digital Zoo. The results of this analysis identified client-focused activity and notebook-based reflection as two activities within Digital Zoo that fostered key linkages to engineering values and epistemology.

Keywords: authentic engineering learning environments, learning processes, assessment, informal learning, women in engineering

Introduction

In contrast to the rising number of engineering professionals being produced internationally, the United States is currently undergoing a period of negative growth in the development of talented engineering candidates (Friedman, 2005). After reaching a peak in 2002, the number of first year college students choosing to enter engineering programs has steadily declined in recent years, and women and minorities continue to be under-represented in engineering majors (Hewlitt *et al*., 2008; NSF, 2009; Sonnert, Fox, & Adkins, 2007; Thom, 2001), Given the various unfavorable consequences of falling behind international peers in engineering and technological capacity, several agencies and organizations are have issued an urgent challenge to the engineering education community, advocating for intensified efforts in the recruitment, retention, and training of innovative engineering and technology professionals in our nation (National Academy of Engineering (NAE), 2005).

While many efforts are being undertaken to improve engineering education at the undergraduate level (NAE, 2005; Sheppard *et al.*, 2008), there is a growing focus on developing effective K-12 engineering programs. Providing pre-college students with meaningful and engaging engineering programs can contribute in several ways to our domestic efforts to build technological capacity. Specifically, these experiences have been shown to help young people become more interested in engineering as a career path (Eccles, Barber, & Josefowicz, 1999) and develop a stronger foundation in both math and science courses (Brophy *et al.,* 2008; Klein, Portsmore, & Rogers, 2008; Douglas, Iversen, & Kalyandurg, 2004; Kolodner *et al.*, 1998; Kolodner, Gray, & Fasse, 2003). However, many of these programs can focus too heavily on the design and construction of one product (American Association of University Women Educational Foundation, 2004), and as such, deliver an "uneven" treatment of ideas from the engineering profession to young people that overemphasizes basic design skills and scientific and mathematical content knowledge without addressing other key concepts such as optimization, modeling, and analysis (NAE, 2009). This lack of context can make engineering seem quite unappealing to girls, who typically dislike "narrow and technically focused" classes and activities that "lack social relevance" (Denner *et al.*, 2005). Moreover, the limited view of engineering presented in these programs can inadvertently reinforce the unfavorable stereotypes (Ambady *et al.*, 2004, Eccles *et al*., 1999; Knight & Cunningham, 2004).

One potential way to reduce negative stereotypes and misconceptions about engineering may be to engage young people, and girls in particular, in meaningful, contextualized engineering activity that not only cultivates the skills and knowledge associated with engineering design but also links these concepts to other facets of the profession. Outside of the K-12 arena and in the realm of professional education, these types of connections between different elements of professional practice are often forged in the *practicum* setting, where novices work on authentic real-world problems within a simulated professional environment (Schon, 1987). For engineers, practicum experiences are commonly found in the senior-level capstone design course, where college students typically work on realistic design problems under the guidance of a professor or mentor. Unlike abstract content courses encountered early on in engineering degree programs, capstone courses immerse undergraduates in an authentic professional setting, where they work on authentic problems from the field and face authentic constraints. Several engineering programs have recognized the pedagogical effectiveness of capstone courses in helping students make key connections between different components of the profession and, as such, have begun to incorporate authentic design activities further "upstream" in the curriculum in order to help first and second year undergraduates develop a more meaningful and accurate foundation for engineering (Cox, Diefes-Dux, & Lee, 2006; Montgomery, Follman, & Diefes-Dux, 2003; Sheppard et al., 2008).

In a similar manner, introducing authentic and situated engineering activities like those seen in the practicum at the K-12 level may help young people not only develop engineering skills and knowledge, but also help them connect those concepts to engineering habits, views, and ways of thinking. This paper focuses on the study such a learning environment, *Digital Zoo*, a four-week summer program in which a group of middle school girls engaged in authentic engineering activity modeled after an undergraduate design course. Specifically, this work investigates whether the participants in Digital Zoo were able to develop a well-rounded understanding of the engineering profession and its different, interconnected facets. More importantly, however, this study also begins to explore how, and during which activities, participants were developing this understanding through the use of *Epistemic Network Analysis* (Shaffer et al., 2009), a novel assessment technique that examines the formation of linkages between different concepts over time. By studying both the learning outcomes and learning processes involved in an authentic pre-college engineering environment for young women and identifying salient activities promote sophisticated types of learning, this work can potentially and substantially impact the design of more effective and inclusive engineering experiences at the K-12 level.

Theoretical Framework

Over the past two decades, researchers have investigated the use of the design, the fundamental activity of engineering, as a pathway for studying concepts and mechanisms in middle and high school science and math classrooms. Several studies (Middleton & Corbett, 1998; Penner *et al.*, 1997; Sadler, Coyle, & Schwartz, 2000) examined how students in middle and elementary school were able to explore concepts in statics, kinematics, and biomechanics by building and testing models in the context of a science class. A comprehensive approach is taken by the Learning By Design (Kolodner *et al.,* 1998; Kolodner *et al.,* 2003) curriculum, which consists of several units that explore different scientific concepts including force and motion through the use of design. Within each of these units, students engage in a series of "rituals", or activities, that constitute design and inquiry cycles in order to explore and develop different ideas throughout the project. After participating in a Learning By Design unit, students show significant learning gains in the emphasized science content as well as in collaborative and metacognitive skills (Kolodner *et al.,* 1998; Kolodner *et al*., 2003).

While these programs use general design practices primarily as a means to fostering science learning, others seek to engage young people in more authentic forms of engineering design to facilitate students' STEM learning as well as generate interest in engineering as a potential career path. Notable examples of these types of programs include Project Lead the Way and the Infinity Project, both of which offer full engineering curriculum packages for middle and high school students. Project Lead the Way is implemented in over 1,300 schools across the nation, while the Infinity project has been used by over 285 schools (Brophy *et al.,* 2008). In these programs, students engage in a series of introductory engineering courses, which in some cases can be counted for college credit. Although recent studies have challenged the actual STEM content learning that occurs in these learning environments (Tran & Nathan, 2010), students do report increased interest in pursuing engineering careers as a result of participating in these courses (Brophy *et al*., 2008; Douglas *et al.,* 2004; Klein & Geist, 2006).

While programs like Project Lead the Way and the Infinity Project can play a role in addressing the potential shortage of engineering talent in our nation, the National Academy of Engineering (NAE) (2009) argues that many of the extant K-12 engineering programs tend to focus too heavily on product design and construction. Concentrating on these aspects of engineering can potentially leave young people with a limited view of the profession and also disenfranchise particular underrepresented groups such as women and minorities from pursuing engineering careers (Eccles *et al*., 1999). Based on these findings, the NAE outlined three principles that should be included in pre-college engineering experiences: a) an emphasis on engineering design; b) the development of appropriate math, science, and technology skills; and c) the development of engineering habits of mind and ways of thinking. In light of the overemphasis of the first two principles and the lack of attention on the third principle, the NAE went on to strongly recommended continued and ongoing research into the learning goals and learning processes of pre-college engineering environments, with a particular focus on understanding the integration and interconnection of the three principles in a given learning context.

The NAE's three principles provide one possible framework for the structure of the engineering profession, which is multi-faceted and complex. Like other *communities of practice* (Wenger, 1998), the engineering profession has created and defined a particular and complex culture all to its own. Engineers act like engineers, engage in design like an engineer, understand what is important to an engineer, and know about engineering. These ways of knowing, doing, and acting are made possible by a looking at the world in a particular way – by thinking like an engineer. Engineers would approach problems differently than members of other professions, such as architects, lawyers, and doctors. Another way to describe the structure of a particular community of practice is an *epistemic frame* (Shaffer, 2004a, 2006a), which includes the five primary elements:

- *Skills*: the abilities and competencies that community members are able to perform and demonstrate
- *Knowledge*: the facts and information shared by community members
- *Identity*: the social and cultural roles that community members view themselves as having
- *Values*: the opinions and beliefs held by community members that define what is important (and conversely, not important)
- *Epistemology*: the justifications and methods of proof that legitimize actions and claims within the community

These frame elements, bound together in particular ways and patterns, comprise the grammar of a particular professional culture and organize the ways in which the profession is practiced in the world. As professionals become more expert in the practices and norms of their work, these individual frame elements are increasingly connected and bound together into a more coherent epistemic frame incrementally over time.

In contrast to isolated design activities that focus too heavily on skills and knowledge, pre-college engineering experiences that engage young people in activities that lead to the development of a more complete engineering epistemic frame may be potentially more inclusive and widely attractive to a broader audience. One approach to this end would be to design an *epistemic game* (Shaffer, 2006a) based on engineering, which is an immersive, technology-supported learning environment in which young people role-play as new professionals in training. Epistemic games are specifically modeled after practicum settings, where new members of a professional community often begin their epistemic frame development by engaging in authentic activity under the guidance of a mentor (Shaffer, 2005; Schon, 1987) Examples of common practicum experiences include moot court for lawyers, clinical rotations for nurses, or supervised practice for psychologists. Epistemic game designers carefully study practicum settings in order to identify and examine salient features of the learning environment that appear to contribute to epistemic frame development (Shaffer, 2005; Shaffer *et al*., 2009) and then recreate these activities and participant structures within the game. Over the past decade, several epistemic games have been developed in this manner, including games based on the professions of science journalism and urban planning (Bagley & Shaffer, 2009; Hatfield & Shaffer, 2006; Shaffer, 2006b).

In order to develop an engineering epistemic game, an earlier study (Svarovsky & Shaffer, 2006a, 2006b) investigated a common engineering practicum setting: the undergraduate engineering design course, where students typically work in teams to solve real-world design problems specific to their engineering discipline under the guidance of a professor (Dym & Little, 2000; Miller & Olds, 1994). This prior work highlighted the importance of reflection (Svarovsky & Shaffer, 2006a) and working with a client (Svarovsky & Shaffer, 2006b) in developing elements of the engineering epistemic frame during the practicum experience. In particular, these participant structures (Shaffer, 2005) appeared to foster connections between the different frame elements, linking skills and knowledge to values and epistemology (Svarovsky & Shaffer, 2006a). Based on these results, *Digital Zoo*, an engineering epistemic game that incorporated and recreated these activities and practices for the target audience of middle school girls, was developed and implemented. Specifically, this work was driven by two research questions that sought to test the theory of epistemic games (Shaffer, 2006b). First, do middle school girls develop their understanding of engineering epistemic frame elements as a result of playing Digital Zoo? And if so, are there specific participant structures within the game that evoke reflection about, and connections to, the specific epistemic frame elements of values and epistemology?

Methodology

In order to answer these questions, an educational design experiment (Brown, 1992; Collins, 1992) was conducted. Digital Zoo was a 60-hour program in which ten middle school girls from diverse backgrounds role-played as biomechanical engineers designing character prototypes for an upcoming animated film. Players used *SodaConstructor*, an online spring-mass modeling system, to engage in rapid and iterative design-build-test cycles to create their designs. Drawing from the engineering practicum (Svarovsky & Shaffer, 2006a), the players also maintained a design notebook and worked under the guidance of an undergraduate design advisor while developing their designs. In addition, the players presented to their clients – role played by engineering graduate students – on a regular basis to provide updates and receive additional feedback.

Data Collection

Pre-, post-, and follow up interviews were conducted with each player, with the pre-interview being administered immediately before the start of Digital Zoo, the post-interview immediately after the conclusion of the game, and the follow up interview approximately three months after the end of the game. Designed as clinical interviews, the pre-, post-, and follow up protocols each contained a wide range of questions, asking players to explain concepts in engineering and physics, provide opinions about far-transfer problem scenarios (Shaffer, 2004b), and engage in design assessment activities. While no two of the protocols were identical, several questions were repeated on all three instruments in order to be comparable during analysis.

In addition, *in situ* data was collected during the game. Copies were made of participant-produced work, design meetings and conversations were recorded, and occasional videos and photos were taken. Research meetings after each program session were recorded and the research team generated field notes when appropriate. By the end of the design experiment, the data set included over three hundred and fifty audio files, thirty video files, five hundred digital notebook pages, and numerous drawings, photos, and other artifacts.

Analysis of Learning Outcomes

Drawing on the methods of Verbal Analysis (Chi, 1997), pre-, post-, and follow up interviews were transcribed and qualitatively coded for the five main elements of the engineering epistemic frame, as seen in Table 1. Code frequencies were tallied, and the mean number of references per student from pre- to post-interview were compared with a paired-sample t-test. Learning gains were indicated by a statistically significant positive difference between pre- and post-interview question means. After this initial comparison, the same analytical techniques were used to compare player responses from post- to follow up interview, conducted three months after the conclusion of the epistemic game, to look for any sustained learning outcomes.

Epistemic Network Analysis

Exploring the trajectory of players' learning during Digital Zoo required the measurement of epistemic frame development over time. A novel assessment technique, Epistemic Network Analysis provides a method for conducting this type of exploration, employing techniques analogous to those frequently used in Social Network Analysis (SNA) that look at complex relationships within dynamic systems. The methods of Social Network Analysis allow sociologists (and other researchers) to examine, characterize, and often quantify the relationships between groups of people within an interactive space, such as a cocktail party, multinational corporation, or social networking site such as *Facebook* (Newman, 2003). Instead of examining the connections and relationships between people, Epistemic Network Analysis (Shaffer *et al*., 2009) examines the connections and relationships between different elements of the epistemic frame. Of course, frame elements are not independent actors like guests at a social event, but using SNA techniques to model the development of the relationships between them can still be a helpful way to understand how different frame elements are connected over time. Thus, by positioning the five major epistemic frame elements of skill, knowledge, identity, values, and epistemology as the "guests" at the epistemic "social event" (or the "friends" within a "Facebook network"), epistemic network analysis provides a theoretically grounded method for assessing epistemic frames and their development over time.

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Table 1
Coding scheme with engineering-specific epistemic frame elements

Code	Operational Definition	Description
Skills	References to engineering abilities or competencies	Brainstorming, comparing alternatives, interpreting feedback, communicating with teammates, keeping a design notebook, DBT cycle
Knowledge	Appropriate use of professional terms of art and scientific vocabulary	Design alternative, center of mass, cross bracing, swing phase, stance phase, even gait, antalgic gait
Identity	References to roles held by player or engineers as professionals	Engineer as innovator, engineer as communicator, engineer as presenter, engineer as someone who tinkers with devices
Values	References to concepts that are important to engineering practice	Creating an optimized and/or reliable design, adhering to client need, developing several design alternatives
Epistemology	References to professionally accepted justification for engineering activity	Ruling out a design because it is too costly, evaluating tradeoffs when making a decision

The full derivation of the basic Epistemic Network Analysis equations have been outlined in an earlier paper (Shaffer *et al.*, 2009). However, because Epistemic Network Analysis is such a new technique, it may be useful to take a moment to define the variables and equations that were used in the ENA calculations for Digital Zoo. The engineering epistemic frame, *EEF*, is characterized by individual frame elements, f_i, where i=*S,K, I, V,* or *E* for skills, knowledge, identity, values, and epistemology respectively. At any time *t*, and any player, *p*, there will be a "snapshot" of data, $\mathbf{D}^p{}_t$, which will contain the evidence of player p using one or more of the epistemic frame elements. Moreover, the complete game history of player *p* will be represented as the collection of snapshots, $D^p{}_{1\ldots e}$, where t=1 is the first snapshot seen at the start of the game, and t=e is the final snapshot seen at the end of the game for one given player. The connections between epistemic frame elements, *fi,* for player *p* at time *t* can be quantified by creating an *adjacency matrix*, $\mathbf{A}^{p,t}$, a construct taken from social network analysis:

$$\mathbf{A}^{p,t}{}_{i,j} = 1 \text{ if } f_i \text{ and } f_j \text{ are both in } \mathbf{D}^p{}_t. \tag{1}$$

This process can be continued for each design alternative, and then the epistemic network for a particular player can be quantified by summing, for each pair of frame elements, the number of times both elements are recorded in the same design alternative. In other words, for any player, *p*, a cumulative adjacency matrix, $\mathbf{F}^p$, can be constructed by summing the adjacency matrices, $\mathbf{A}^{p,t}$, for a given time period that starts at $t=a$ and ends at $t=b$:

$$\mathbf{F}^{p,t[a:b]} = \Sigma_a^b \mathbf{A}^{p,n}. \tag{2}$$

Once the adjacency matrices are generated, specific quantities that provide information about the nature of the overall epistemic frame as well as the relationship between the individual frame components can be calculated. For example, it may be useful to analyze the centrality, or "connectedness" of the individual frame elements, f_i. Within social network analysis, actors become more central to the social network the more frequently and strongly connected they are to other actors. Thus, in Epistemic Network Analysis, the more central an epistemic frame element, the more tightly bound it is to the other frame elements. In order to eventually calculate the relative centrality, *R*, of a particular frame element, it is first necessary to initially quantify the "connectedness" of each frame element within an epistemic network, *F*. The connectedness, or weight, *C*, of an individual frame element, *fi*, within epistemic network, *F*, is calculated as its sums of squares centrality *C*(*fi*):

$$C(fi) = \sqrt{\Sigma_j \left(F_{i,j}\right)^2}. \tag{3}$$

The sums of squares centrality of a frame element can have values of zero or greater, and provides an absolute measure of the "connectedness" of a particular element within an epistemic network. The relative centrality, *R*, of a particular frame element, f_i, is then calculated as a percentage by dividing its weight, *C*, by the heaviest weight, C_{max}, within the epistemic network, *F*, and multiplying by 100:

$$R(fi) = \frac{C(f_i)}{C_{\max}(F)} \times 100. \tag{4}$$

The relative centrality of a frame element can have values ranging from zero to 100, and provides a ratio of a particular element's connectedness to that of the most connected element in the network at a given moment in time.

Thus, Epistemic Network Analysis is a flexible technique that can be used to examine linkages between frame elements over a defined time period. Using ENA instead of simply tallying code frequencies allows the researcher to consider the connections between frame elements, thus allowing for a more aligned representation of complex, highly interconnected learning. By using ENA to examine linkages to frame elements during specific periods of time within Digital Zoo, it was possible to identify when particular frame elements – such as engineering values and epistemology – were more or less emphasized during gameplay. As such, ENA provided a way to characterize and measure players' learning during particular game activities, and was therefore instrumental in the cultivation of a grounded theory of learning within the game.

Analysis of Learning Processes

A subset of the collected *in situ* data from the first two weeks of Digital Zoo was transcribed and assembled into design histories (Shaffer, 2004b) for each player that documented her experience in the game. Given the importance of design meetings, design notebooks, and client-focused activity in the earlier work that informed Digital Zoo, design histories were further segmented along these dimensions, resulting in eight *macrostructures* (Gee, 2005) per player. The first segmentation was by project week, dividing the data into "Week 1" and "Week 2" pieces. The next segmentation was by the focus of the activity, further dividing the data into "Client-focused activity" and "Non-client focused activity" pieces. Finally, the last segmentation was by type of reflection, dividing the data into "Design Meeting" and "Design Notebook" pieces. After all of this data parsing, there were 80 total segments of *in situ* data (with eight macrostructures per player, and ten players total).

These 80 segments were then subjected to Epistemic Network Analysis, with a particular focus on the relative centralities of different frame elements over time. Patterns of increasing or decreasing relative centralities across different activity structures were explored and identified when possible.

Results

The results of this study are presented in two parts. The first section outlines players' learning outcomes of the after participating in Digital Zoo. The second section explores how different components of the epistemic frame were connected during different activities within the game.

Learning Outcomes

Results from pre-, post-, and follow up interviews show that participants were able to develop their understanding of the different engineering epistemic frame elements as a result of Digital Zoo. References to each of the five frame elements in matched pair questions increased significantly from pre- to post-interview, and these elevated levels were sustained through the follow up interview three months after the game was completed, as seen in Figure 1.

Skills

References to engineering skills increased significantly from pre- to post-interview (mean pre = 0.9, mean post = 3.1, $p < 0.01$, Figure 1.) This learning gain was maintained through the follow up interview as well (mean pre = 0.9, mean follow up = 2.7, $p < 0.01$, Figure 1). For example, when asked what engineers do, one player responded, "they create stuff." After the game, the same player provided a more articulate answer, stating:

> "Well they design stuff and execute it …. They have to first look at the problem letting them know what their design is for, what's it got to do, and then a lot of trial and error. If they are trying to make something, and it fails, they just do something a little bit different to see if that works, and keep changing things. Eventually [they] come up with a result… and then they've got to do it all over again. Make an alternative and see if that comes out better. Maybe because they had all that trial and error, it might be easier the second time. Then present, present, present [to teams and clients]."

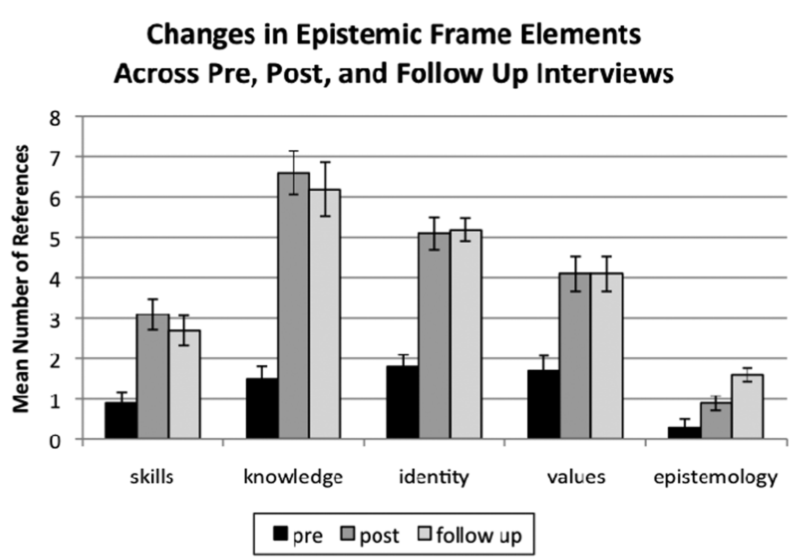

Figure 1. Mean number of correct references to the five primary elements of the engineering epistemic frame across pre, post, and follow up interviews.

This player describes several skills involved in an engineering design process, including understanding the problem statement, the design-build-test cycle, developing multiple design alternatives, and presenting work in design and client meetings.

Knowledge

References to engineering knowledge increased significantly from pre- to post-interview (mean pre = 1.5, mean post = 6.6, $p < 0.01$, Figure 1.) This learning gain was maintained through the follow up interview as well (mean pre= 1.5, mean follow up = 6.2, $p < 0.01$, Figure 1). For example, when one player was asked to define the concept of "center of mass" during the pre-interview, she responded, "It's like the center of the object?" In the post-interview, the same player said,

> "It's the center where everything balances. (pause) Well, it's not always the center…. [it is] the point where everything balances… something could be a structure where it's built kind of awkwardly... The center wouldn't always be the right place because things might be hanging off [one edge]."

Here, the player has a more sophisticated understanding of center of mass, realizing that it is not merely the geometric center of an object and that having an uneven weight distribution would potentially shift the center of mass to a different location. In another matched-pair question, players were asked to define the concept of gait. One player, who stated she didn't know what gait was in the pre-interview, responded in this way on the post-interview:

> "It's the way you walk. If you have an even gait that means you are walking evenly, like at an even pace. But if you have, let's say, an antalgic gait then you might be limping or walking a different way than you normally would."

In this response, the player not only demonstrates her understanding of the concept of gait, but also goes on to provide different examples of gait that were used within the context of the game.

Identity

References to engineering identity increased significantly from pre- to post-interview (mean pre = 1.8, mean post = 5.1, $p < 0.01$, Figure 1.) This learning gain was maintained through the follow up interview as well (mean pre= 1.8, mean follow up = 5.2, $p < 0.01$, Figure 1). For example, when asked if she had ever thought of herself as an engineer in the pre interview, one player said, "No." In response to the same question in the post-interview, the same player said:

> "Not until the day, like I was thinking about it yesterday, when we were like starting to design… the presentations, the client meetings, and making what they asked for in the problem… Yeah. And meeting their needs for that design."

Out of the eight players that responded positively to this question in the post interview, six of them reported some form of interaction with the client as the reason they felt like an engineer, with the other two players identifying the use of computers and technology.

Players also demonstrated more understanding of an engineer's professional identity after gameplay. For example, when asked what it meant to be an engineer, one player in the pre-interview responded, "I don't know." The same player, in the post-interview, said:

> "I think it means to help people. Doctors help people, too, but engineers can help people in different ways, making their life easier and making sure the environment is okay, things like that. Someone had to design the car. So, kind of designing things that people need… like backpacks, shoes, bikes, and lights."

This player's response is particularly interesting for two reasons. Not only is the player more descriptive in her characterization of the engineering profession after the game, she also articulates specific ways engineers help people that are different from other professions like medicine.

Values

References to engineering values increased significantly from pre- to post-interview (mean pre = 1.8, mean post = 4.1, $p < 0.01$, Figure 1), and this increase was maintained through the follow up interview (mean pre = 1.7, mean follow up = 4.1, $p < 0.01$, Figure 1). For example, when asked to describe what engineers care about during the pre-interview, one player said, "I don't know, science?" The same player responded in this way on the post-interview:

> "Well obviously their family and stuff, but probably what their client's going to think. They want to put the client's needs first, and they probably just want to make it something that's original. Something else that isn't out there… maybe if they're designing [a product], they don't want it to look like every other single one."

With this response, the player describes two specific engineering values: the importance of understanding and addressing the client's needs, and creating an original and innovative design solution.

Epistemology

References to engineering epistemology increased significantly from pre- to post-interview (mean pre = 0.3, mean post = 0.9, $p < 0.01$, Figure 1.) This learning gain was not only maintained in the follow up interview, it actually increased (mean pre = 0.3, mean follow up = 1.6, $p < 0.01$, Figure 1). For example, during each interview, players were presented with information on three different choices for seating on some form of public transportation (bus, subway, or train) in a large city. Players were asked to identify the best option and explain their selection. In the pre-interview, one player identified and explained her choice in this way:

> "I think this one… it doesn't seem like it would be very comfortable, but it is small and it has a 4 star safety rating. This one looks very comfortable but it only has a 3 star safety rating and only 36 units [can fit]. This one doesn't look comfortable, but it has a 4 star safety rating and plus it's not too expensive… I guess it's kind of like the happy medium."

In the post-interview, the same player said:

> "I think it's this one… because it can fit 52 units, which is more… [that one] has 40, and the other one is 45, and this one can hold 52. Plus it has… the same safety rating as this one and a better safety rating than this one. Granted it's not as comfortable as this one, but it looks a lot more comfortable than this one, and it actually costs less. The seats can't flip up when they're not in use, but that doesn't really matter… why would you really need them to flip up since you can only fit a certain number [of units] in there anyway? So it looks like it's really easy to clean, which would be good so that they don't get dirty. And it's the same price as this one. I just looked at them and compared. I knew that one wasn't going to be it because it has a luxury rating of, who cares about [that]? It's a train, why would you want a comfort rating of 6 stars if it's only a 3-star safety rating? I wouldn't really feel safe with that. And also it's very costly at $105. Then I compared between these two… I just compared the number of units that fit the price, and the safety rating, and then looked at the special features, and kind of figured out which one was best."

In the pre-interview response, the player examines the information and chooses the "mid-range" product that neither too expensive nor the most comfortable, without providing additional reasoning behind her choice. However, in the post-interview, she not only asked for more time to make her decision, but she was also able to more fully articulate the tradeoffs she considered in her choice. In particular, she initially focused on the key design features (the number of units that could fit in the train, the safety rating, and the price) before considering additional information provided in the product descriptions.

Relationships Between Frame Elements and Game Activities

The analysis of the *in situ* data collected during Digital Zoo provides insight into how and when players reflected on different frame elements and linkages within the engineering epistemic frame during gameplay. As seen in Figures 2 and 3, players' reflections appeared to emphasize engineering skills and knowledge throughout the first two weeks of the game, while engineering identity appeared to be mostly emphasized at the beginning of the game. In contrast, reflections that emphasized engineering values and epistemology seemed to be concentrated within certain participant structures during the game.

Average Relative Centralities of Skills, Knowledge, and Identity

Throughout gameplay, the relative centralities of engineering skills and knowledge followed similar trajectories. Both of these frame elements started out highly central, and then remained so throughout the first two projects of the game, as seen in Figure 2. The calculations from the Epistemic Network Analysis suggest that both skills and knowledge were strongly emphasized from the start of the game and then continued to be central within player's reflections throughout Digital Zoo.

Both skills and knowledge demonstrate a low point in relative centrality during the "Week 1, Client Project, Design Meeting" macrostructure. Because the sums of squares centralities of skills and knowledge in this macrostructure are similar to those in the "Week 1, Non-client Work, Design Meeting" macrostructure, this dip may explained by the increase in the centrality of other frame elements – particularly values and epistemology – during this macrostructure, as seen in Figure 3.

The relative centrality of identity starts off at a high level at the beginning of the game in "Week 1, Non-client Work, Design Meeting" macrostructure, and then quickly drops and remains low for the rest of the game. These relative centralities suggest that engineering identity was mostly emphasized during the initial stages of Digital Zoo and then not strongly emphasized afterwards. Players' explicit references to engineering identity were uncommon after the first few days of the game, which resulted in the low relative centrality numbers for that particular frame element as seen in Figure 2.

Average Relative Centralities of Values and Epistemology

Unlike the relative centralities of engineering skills, knowledge, and identity that tended to be either consistently high or consistently low throughout most of the game, the relative centralities of values and epistemology appeared to follow a different pattern, as seen in Figure 3.

These frame elements seemed to become more central during client-focused activity and notebook-based

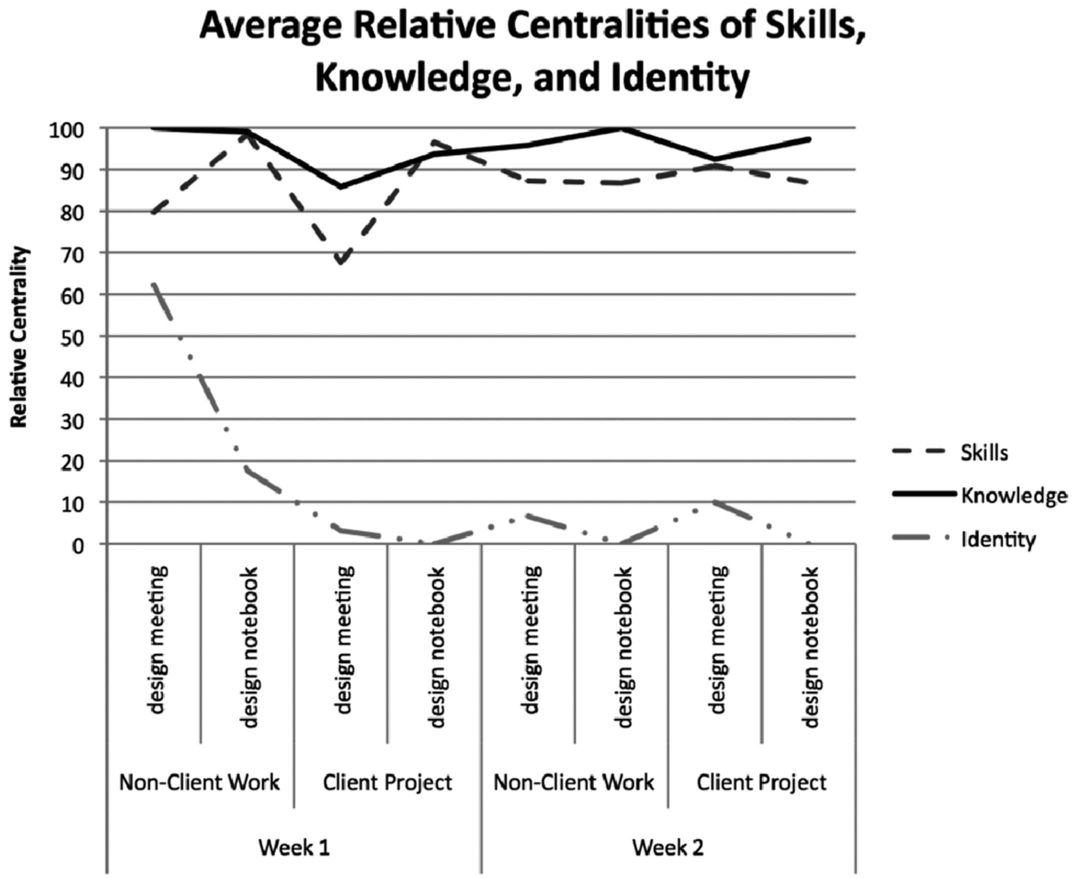

Figure 2. Average relative centralities, or connectedness, of engineering skills, knowledge, and identity across different activities in the first two weeks of Digital Zoo.

reflection. While both frame elements decreased in centrality after the conclusion of the first client project, they rose again at the start of the second project. These patterns suggest that players' reflections on engineering values and epistemology are tied to Client-focused Activity and Notebook Based Reflection.

These frame elements seemed to become more central during client-focused activity and notebook-based reflection during the "Week 1, Client Project" macrostructures, as seen in Figure 3. While both frame elements decreased in centrality after the conclusion of the first client project, they rose again at the start of the second project, as seen in the "Week Two, Client Project" macrostructures in Figure 3. These patterns suggest that players' reflections on engineering values and epistemology are tied to Client-focused Activity and Notebook Based Reflection.

Additional analysis of the relative centralities for values and epistemology was conducted in order to probe further into the relationships between these frame elements and specific participant structures. The average relative centralities for both frame elements were computed across non-client (design challenge) and client-focused activity, as seen in Figure 4. Both frame elements appeared to be more central during client-focused activity than in non-client-focused activity.

Similarly, in order to better characterize the relationships between the relative centralities of values and epistemology and the different types of reflection present in Digital Zoo, the average relative centralities for both frame elements were computed across meeting/discussion based reflection and notebook-based reflection, as seen in Figure 5.

While both frame elements appeared to be more central during notebook-based reflection than during meeting based reflection, the differences were not as pronounced as with the client-focused activity. In addition, the relative centrality of engineering values did not appear to be as impacted by notebook-based reflection as the relative centrality of engineering epistemology.

Discussion

The research questions for Digital Zoo were addressed with a two-part analysis. In response to the first question which asked about players' learning outcomes from the game, the results from pre-, post-, and follow up interviews show that players were, in fact, able to develop their understanding of the different engineering epistemic frame elements. References to each of the five frame elements in matched pair questions increased significantly from pre- to post-interview, and these elevated levels were sustained

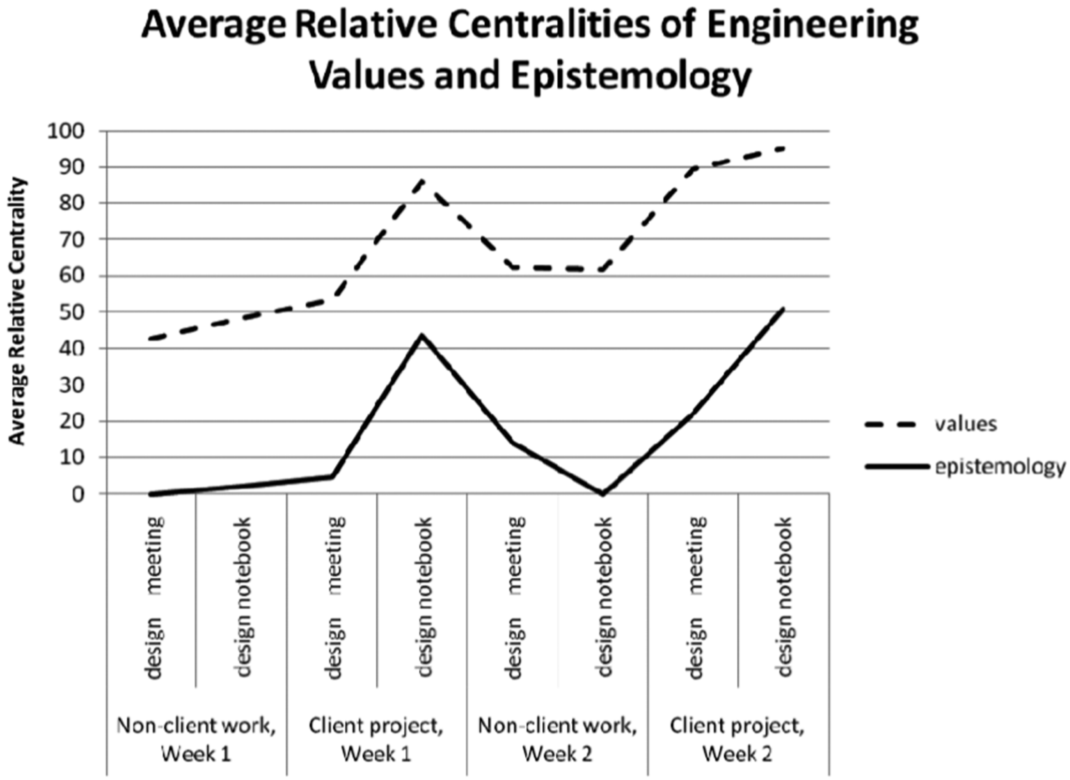

Figure 3. Average relative centralities, or connectedness, of engineering values and epistemology across different activities in the first two weeks of Digital Zoo.

through the follow up interview three months after the game was completed. As such, these findings uphold the theory of epistemic games (Shaffer, 2006a, 2006b), which suggests players would be able to develop engineering skills, knowledge, identity, value, and epistemology as a result of engaging in authentic engineering activity within a simulated practicum context.

The second research question asked whether player reflection on specific frame elements was linked with specific parts of the game context, particularly for engineering values and epistemology. The initial Epistemic Network Analysis (Shaffer *et al*., 2009) of *in situ* data showed that three of the frame elements – engineering skills, knowledge, and identity – did not appear to be tied to a specific type of activity. Engineering skills and knowledge appeared to follow similar trajectories in the game and were emphasized throughout the entire experience. Given the context of Digital Zoo and the engineering work being done by the players, it is not surprising that they utilized and reflected on these frame elements throughout the game.

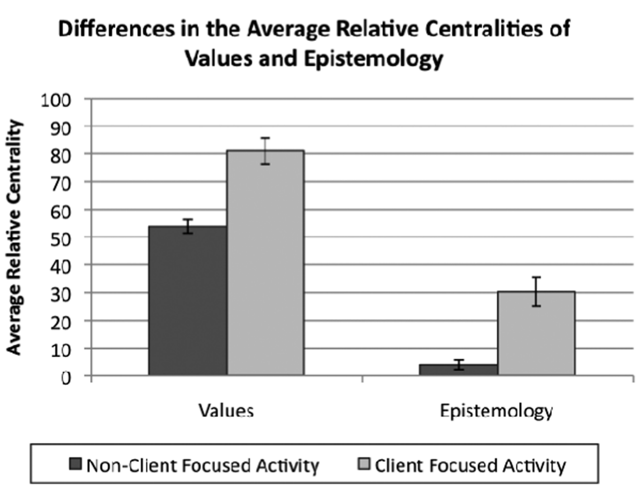

Figure 4. Average relative centralities for values and epistemology across client-focused activity and non-client-focused activity.

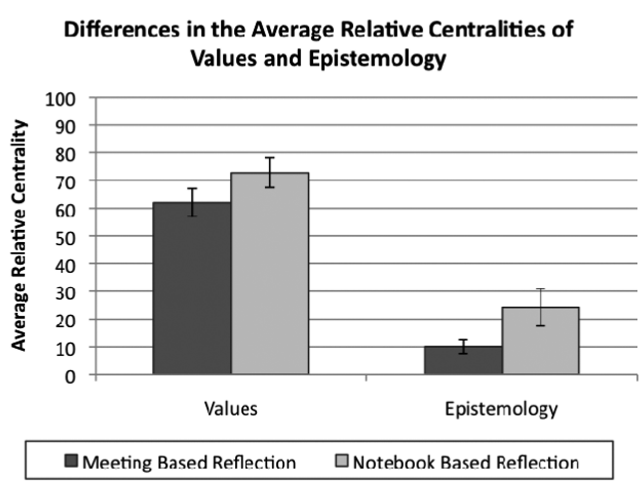

Figure 5. Average relative centralities for values and epistemology across meeting-based reflection and notebook-based reflection.

Engineering identity, on the other hand, appeared to be strongly emphasized at the beginning of Digital Zoo, and then was not particularly relevant after the opening days of the game. This may suggest that players achieved a level of comfort with playing the role of an engineer after the first few days of the experience, and as such, no longer needed to remark or reflect on it explicitly.

In contrast to the patterns with engineering skills, knowledge, and identity, layer reflections on the other two frame elements, values and epistemology, did appear to vary with certain types of activity. Based on the increases in relative centrality observed in the Epistemic Network Analysis, there appeared to be relationships between values, epistemology, client-focused work, and notebook-based reflection. These patterns were similar to those seen in the study of the engineering design course, which suggested working with a client and using a design notebook helped undergraduates make more sophisticated connections between the different frame elements. As such, these results are aligned with a specific feature of the theory of epistemic games, which suggests that young people can develop an epistemic frame by engaging in recreated versions of reflective participant structures from the professional practicum (Svarovsky & Shaffer, 2006a, 2006b).

The study presented in this paper is one example of how the construct of an epistemic frame and the use of epistemic network analysis can be used to explore and assess the development of engineering skills, knowledge, and ways of thinking within authentic engineering activities. Certainly, this study has several limitations, including the small number of participants and the use of only a subset of *in situ* data for the analysis. However, this work also has several implications for the ongoing study and design of authentic engineering learning environments across the educational spectrum. First and foremost, further research must be conducted in order to more clearly define and articulate engineering epistemic frames, both at the profession and sub-discipline levels. While there are of course similarities in the skills, knowledge, and ways of thinking of all engineers, developing more specific and nuanced understandings of how the epistemic frame of a chemical engineer may differ from a mechanical engineer as well as a civil engineer may be a potentially powerful and fruitful endeavor for the engineering education community. In addition, the use of Epistemic Network Analysis to both examine and measure how learning happens within different learning environments can lead to the development of more engineering-specific theories of learning that can greatly impact the quality and scope of engineering education writ large. Finally, by beginning to explore not only what, but how, players were able to connect engineering skills and knowledge to other facets of the profession, this work can inform the design of future engineering experiences for pre-college youth – and in particular, for young women.

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