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Judging for Themselves: How Students Practice Engineering Judgment

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Judging for Themselves: How Students Practice Engineering Judgment

The following case study describes and analyzes engineering judgment. The ethnography observes engineering students engaged in a design project and pays particular attention to how students make judgments. The analysis concludes that the practice of engineering judgment relies on displays to recognize and construct rhetorical tactics to satisfy the requirements of a task. This study connects to recent research in engineering education on the importance of displays [15, 16] for learning the design process, and reveals the dynamics of displays for carrying out engineering judgment.

Engineering judgment is a core competency for engineering practice. Philosophers, educators, practitioners, and historians agree that engineering judgment is necessary for ethical, sophisticated, and professional engineering practice[1, 2, 3, 4, ,5]. While scientific and mathematical knowledge undergirds engineering practice, and communication skills facilitate it, engineering judgment governs the appropriate and ethical application of engineering knowledge. The influential historian of technology, Eugene Ferguson, makes just this point to close his book, *Engineering and the Mind's Eye*:

> If we are to avoid calamitous design errors as well as those that are merely irritating or expensive, it is necessary that engineers understand that such errors are not errors of mathematics or calculation but errors of engineering judgment—judgment that is not reducible to engineering science or to mathematics.
>
> Here, indeed, is the crux of all arguments about the nature of the education that an engineer requires. Necessary as the analytical tools of science and mathematics most certainly are, more important is the development in student and neophyte engineers of sound judgment and an intuitive sense of fitness and adequacy.
>
> No matter how vigorously a "science" of design may be pushed, the successful design of real things in a contingent world will always be based more on art than on science. Unquantifiable judgments and choices are the elements that determine the way a design comes together. Engineering design is simply that kind of process. It always has been; it always will be. [2]

Ferguson implies that engineering judgment is something informed by mathematics and science, but states that engineering judgment is not reducible to them. The relationship between engineering judgment and science and mathematics is one of deployment and application. This deployment and application is "more important" than the learning of "analytic tools" for understanding the "nature of the education that an engineer requires." For Ferguson, engineering judgment is not only a fundamental competency for engineering, it is of the utmost importance for producing a professional engineer.

While the priority of judgment over analytic tools is debatable, engineering education in the United States and elsewhere has put engineering judgment on equal footing with analytic tools as necessary components for an engineer's education. The ABET criteria do not use the word "judgment", but Criteria 5 (b) on curriculum requirements does define engineering design as “a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet [the client’s] stated needs.”[6] As a decision-making process, engineering design includes the act of judgment[7]. Decisions are arrived at through judgment; it is judgment that recognizes when a decision is to be made and the reason for making each decision[1].

Engineering judgment cannot be taught directly, since its application requires the context of the unforeseen, the in-process, contingent, and indeterminate. What educators do is put students in situations that call for the practice of engineering judgment, hence the proliferation of design courses in undergraduate engineering programs in the last two decades that seek to emulate the constraints and requirements of professional engineering. It is in these classes where the development and practice of engineering judgment is most likely[1], owing to the necessity of making decisions to satisfy contrary demands[8].

In delineating the importance and implementation of judgment, there is left unanswered the question of just what engineering judgment is. In a survey of the literature, engineering judgment is understood in different ways and with emphasis on different aspects. Michael Davis thoroughly evaluates the slipperiness of engineering judgment and the way it cannot be said to equate to decision-making, phronesis, discretion, discernment, or common sense, but is related to all of them[1]. Case studies of professional judgment make experience a primary component of judgment, providing the practitioner with the ability to recognize mistakes, foresee problems, and economize attention[4, 5]. The earlier quote from Ferguson suggests that deployment and application are two components of judgement, a point with which Vincenti concurs[5]. Holt makes judgment a skill of appreciation of the fitness of an idea to a purpose[3]. Holt also echoes Ferguson’s emphasis on “non-verbal thinking” in engineering judgment, suggesting judgment means the ability to visualize reasons for making decisions. Taken together, engineering judgment is described as a distinct visual/mental capacity to artfully deploy and apply lessons from past technical knowledge to fit emergent situations. So how is it done? How do students do it? And how can such an abstract definition become a little more concrete?

In the following pages, a case study will be introduced, describing the videotaped actions of engineering students working on a design problem. The description will provide a fine-grained perspective on student engineers’ judgement. The focus will be on the ways they coordinate their work, their opinions and ideas, and how the resources they use to judge and make decisions influences the act of judging itself. The promise of this study is in giving an in-depth look into a common activity that takes place in engineering design classes across the country and providing empirical data on its constituents.

Methods & Methodology:

The study is part of a larger project investigating student engineers learning to attend to engineering problems like professional engineers. The study spans a semester of an engineering design course and focuses on how engineers go from seeing engineering as math and science problems to seeing engineering as problem-solving under real-world constraints. The course, EMAE 260, is the second in a three course design sequence for aerospace and mechanical engineers (though the class is heavily populated by biomedical and biomechanical engineering students) at a Midwestern University. The class introduces students who are sophomores and juniors (though a few are seniors) to the design process and is similarly structured to other engineering design curricula across the country. The class was split into groups, assigned to develop one of three products (a portable desalinization device, a chainless bicycle, or a solar tracker), and present their plans to the class and professor. The study focused on one group of seven students, but collected interviews from an additional half dozen others. The methods comprised classroom observation and fieldnotes, semi-structured interviews, and video-recordings. The study was approved by the university's internal review board (IRB).

Data for this portion of the study come from visual ethnographic methods such as video recordings of group work, videotaped interviews, and fieldnotes[9]. All of the field notes, interviews, and group work were transcribed using the NVivo10™ program. For the interviews, the dialogue was transcribed word-for-word and chunked by interview question. Each chunk was then coded with a descriptive category that named the content of the text. In transcriptions of the students' group work, the group's activity was transcribed according to task or topic of discussion. Descriptive coding of the content of the activity was used, paying attention to not only what was said but also how it was said, whether it was sketched, gestured, displayed on a computer, written on a whiteboard, uploaded on Google Drive, etc. The method of coding, inspired by Emerson et al.[10], was designed to build up an inventory of codes and categorize data in such a way that one strip of action could be assigned any number of overlapping codes. This method demonstrated the complexity of the classroom and design group activity.

The selection of the data below will show the subtle work of judgment by engineering students. It is a description of six students (Bob, Steven, Silvio, Nico, Pranav, and Sedat, all pseudonyms) attempting to calculate the wind force their planned solar tracker would need to withstand. (The seventh member of the group, Benny, was absent that day). During the process of calculating, students refine their aims for the solar tracker's structure based on what the process of writing out the calculations reveals and how, the study will argue, judgment is constituted and articulated.

This particular portion of the study adheres closely to a methodology for studying philosophical and epistemological topics in science and technology studies (STS) developed by Michael Lynch[11]. Lynch proposed that the way to understand general and ordinary activities often used in scientific and technological work, like "measuring, counting, depicting, observing, describing, and so forth" is to look in "perspicuous settings" for "primitive examples" of the action and to see how they are accomplished *in situ* [11]. Judgment, shrouded as it is in various abstract definitions, is in need of an approach that focuses on its performance rather than its classification. A design course is particularly suitable for this kind of investigation for the reason that judgment is inherent in the design process. Additionally, the course is comparatively low-tech, and so intelligible to observers. It includes only a few participants (unlike many professional engineering settings), deals with less complex problems, and occurs in an instructional setting that fosters the practice of designing. Design is more centralized and concrete in this case because it is not distributed across contexts and participants, not interrupted by other activities, and thus offers to analysis a perspicuous setting for studying engineering judgment. Lynch then suggests that the activities be described in detail, and the actions of participants be set down in the sequence of their occurrence, allowing the reader to see how the actions are carried out. Lynch recommends that investigators suspend “judgment on whether the activities of scientists and mathematicians are epistemologically ‘special’” in order to allow the bare, ordinary character of the activities observed to become evident [11]. He recommends that the methods of analysis be “uniquely adequate” to the setting, meaning the investigator ought to use methods suitable to the case, and forgo particularly technical jargon, in order to make the actions of the participants and observational methods of the researcher clear. Finally, Lynch recommends bringing discussions from the disciplinary literature back into discussion of the findings, so a more defined explanation of an activity may displace vaguer ones.

The present study, then, investigates students working on a design problem through a visual ethnography and describes how and what they judge, to better understand how engineering judgment works, its features, and the implications for teaching engineering judgment. The strip of activity was chosen as an example of the routine work of design and a setting where the complexity of judgment was evident. First, the activity will be described as it unfolded, and then the implications of the case study for engineering judgment will be discussed.

The Case Study:

A group of six students came together in a study room to break down the work required for the next several weeks of the assignment. They agreed to begin working on calculating the amount of wind force their solar tracker would need to withstand for customers in southern Ontario, their targeted client area. Students are told in the course lecture to “get things to numbers” in order to provide a clear way for others to understand how their device works, of what it is composed, how much energy will it provide/use, and how much it will cost. The engineering design class, EMAE 260, posits that numbers are the language of engineering.

The idea of turning things into numbers as a goal of the class is testified to in an interview with the professor. When asked what EMAE 260 hopes to accomplish, the professor remarked that engineering as way to problem-solve is heightened by her class: “…I think what's a little different about the class that I'm teaching is that sometimes we're trying to figure out how do we quiantify something when we don't have a good basis for quantification." Students in EMAE 260 are asked to turn design ideas into calculations, to quantify them, and students are often without a strong basis for quantifying. Meaning, they have the knowledge of the requisite mathematical operations, but the ability to fit and apply their knowledge to underdetermined circumstances provides a unique challenge. Students must research where and how their products will be used and by whom, in order to better determine the circumstances they must account for in designing the product. And these conclusions must be understood and presented numerically.

One such circumstance was how sturdy their solar tracker needed to be. The students set themselves the task of calculating just how much force their solar tracker needed to withstand. The group of six surrounded a whiteboard and each had his laptop in front him. Bob took it upon himself to inscribe the calculations on the whiteboard, asking the rest of the group for the equations and factors.

They wanted their solar tracker to withstand the force of 100 mph winds, a number they found from a website selling solar trackers, and characterized as “what competitors guaranteed.” They first tried to list all the forces that would act on the solar panel, but settled on the immediate task of determining the weight and shape of the solar panels. Sedat found an equation on Wikipedia to calculate the force of drag: $F_D = \frac{1}{2} \rho v^2 C_D A$[a]. Bob asked members of the group to fill in the variables and they called out numbers generated from internet searches, which Bob recorded on the whiteboard, erasing variables and putting numbers in their place.

After all of the variables were assembled, Bob noted that the numbers were in various units, inches, feet, slugs, pounds, and so on, and needed to be consistent. The group then converts units and Bob changed the units as conversions were made, and pointed out which units still needed to be converted. After each unit was converted, he went back over his changes saying, “This is fine. This is fine. This is fine.” tapping each converted unit with his marker.

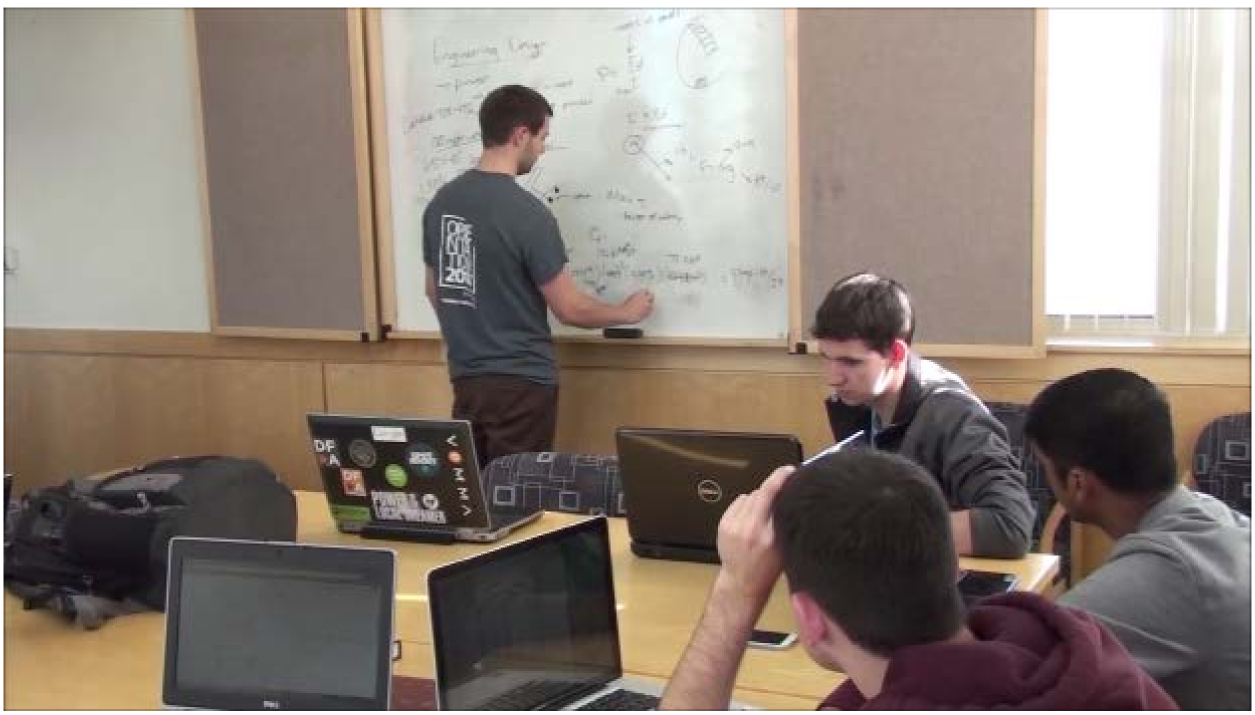

Figure 1. Bob checking off converted units. Clockwise from Bob: Nico, Pranav, and Steven.

The group then started to calculate the numbers. The calculating was the work of Nico and Steve, primarily. Bob stood awaiting the calculations, standing aside from the whiteboard so Nico and Steve could see the equation. Nico and Steve reach different values. After checking

[a] This is the drag equation and not a formula for determining wind load. The group will soon see their mistake.

with Bob, it was revealed that Nico neglected to square a number. Steve's number, 9.2 lbs. of force, was determined as the correct value given the equation on the board.

The conclusion that 9.2 pounds of force is the result of 100 mph winds on square solar panels of 72.2 ft. squared was met with incredulity from Silvio.

> Silvio: "If you think of a hundred mile an hour wind acting on, what is it, what is it, 72.2 square feet of solid surface and it's just nine pounds of force? That doesn't seem even remotely possible."

The tone of Silvio's question relayed to the rest of the group his own thinking process and conclusion on what he had just heard. Each member of the group looked back to the board and started to question the numbers. Nico thought perhaps the 72.2 square feet of surface area was too much. Bob had the group recalculate to check if 72.2 square feet was the correct surface area and it was. Silvio insisted that Steve's conclusion was nonsensical. He took up a marker and designated the tip of the marker as a point of 72.2 square feet and pushed against the marker with his finger to illustrate just how insignificant 9 pounds of force would be.

Figure 2. Silvio demonstrating with a marker

Rob suggested the group look up wind load. Pranav already had and gave the two equations for calculating wind load. Bob asked Pranav to explain the values, such as the height of the object. Pranav explained which values were given, which have to be found, and the operations performed for all of them. After he finished, Bob stated that "This might be air resistance" while tapping the equation on the whiteboard. Nico smiled at the group's mistake. Bob asked Pranav to calculate the wind load using the equations he found and Pranav did. Bob read the values from the board to Pranav and he calculated them on his computer. After a few moments, he announced the wind force as 2,546.98 pounds. There was an immediate reaction from the group. Nico leaned over to look at Pranav's computer and Pranav recited all of the operations he performed with the "wind force calculator."

Bob asked the group what the average wind speed of a hurricane is. The group laughed, but Pranav did look up the average speed, and told the group the average speed was 138 mph. Bob then tapped the whiteboard at the point where 100 mph wind speed is written, the wind speed the group agreed was the maximum speed the solar tracker could endure, and asked "Did we make this number too big?" Silvio immediately reminded the group that the wind speed was arrived at by meeting an industry standard, represented by a solar tracker manufacturer he had researched. Bob replied, the weight for their solar tracker would need to increase if they were to keep to 100 mph. He asked to hear the average wind speed of Southern Ontario and Steven said it is 14 mph. Again, everyone laughed, and Bob asked the group to vote on dropping the wind speed to 40 mph. Nico still thought that the speed too high. Silvio balked at the proposed change. He insisted that their solar tracker should meet industry expectations for durability.

Questions about the likelihood of extreme weather in Southern Ontario were asked, and the group looked up the frequencies with which tornados or hurricanes could befall the area. After determining the small likelihood of such a weather event, Steve brought up the fact that the maximum wind speed for the region was 32 mph. Bob went to the whiteboard and asked for the wind force for 100, 50, and 40 mph. Pranav gave him the numbers, 2, 546 lb., 636.7 lb., and 407 lbs., and he wrote each on the board. Nico said he could not imagine what that (meaning, 2,546 lb. of force on a solar panel) would be like. Steve offered that it is over a ton. "It's like you threw a truck at our solar panel," said Silvio. "Constantly. Constantly throwing a truck at our solar panel," corrected Bob. The entire group laughed at the absurdity, but they continued to make similar comparisons. Bob noted the difference between 50 mph and 40 mph of wind force amounted to the weight of a large person. Silvio remarked on the difference between 50 and 100 mph being vast and could not imagine building a solar panel to withstand 100 mph winds. Silvio reminded him they were to design a solar panel not build one.

A debate ensued between Silvio and the rest of the group about whether a solar tracker should be able to survive extreme weather. Bob reasoned that if a tornado were to afflict a household, there would be no expectation that the family solar tracker would be still be standing. "In our promotional video, are we going to say that out solar tracker is tornado-proof?" asked Bob. The group again broke up in laughter. 40 mph was agreed to and the group moved on to discuss the thickness of the solar panels.

Discussion:

A striking feature of the activity was the role of representation, or displays. The description above shows how student engineers use displays[b] to engender judgment. By putting

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[b] The word "display" is used rather than more familiar terms such as representation or inscription to include not only graphic or written modes of recording or presenting objects, but additionally discursive or gestural modes of appearance. Additionally, display rather than inscription or representation highlights the rhetorical function of creating images or appearances [13].

tasks, data, and equations in a space where each participant can examine the sequence and progress of the group's activity, points are discerned where the group activity has gone awry in the eyes of the participants. The ability to discern points where the group activity has gone wrong rest on students' ability to account for conclusions at odds with the group's understanding or common sense. In other words, judgment is the accomplishment of participants to account for inconsistencies, incongruities, or puzzling conclusions and decisions, and to reset the group's attention on further tasks. Judgment is both perceptual and communicative.

There are several points in the above description serving as evidence for how judgment works. The first occurs when Bob sees the need to convert all of the differing units (inches, slugs, pounds, and feet) into more computable units for wind force. The display on the whiteboard reflects back to the participants that their task cannot continue as it had been accomplished up to the present moment. The goal of calculating was impeded by the various units of measurement, which Bob saw, recognized, and decided to have changed. For the participants, the whiteboard "structures mutual orientation to a shared interactional space" [12]. It brings the group's attention to a space where everyone can see the agreed-upon record of the group's activity and appraise its progress in satisfying the task. Bob noticed the impediment and acted in a way to further the group's desired activity. He refined the equation to make simpler computations.

The whiteboard serves as the agreed-upon record of the group's activity and as a guide of their future activity for the task (i.e. which calculations were to be done next), and also works as a resource to settle discrepancies. When Steven and Nico come to different answers for the equation, the group is able to look back at the sequence and have Nico recite his own steps. The two records are compared, with the whiteboard record as the standard and guide for how the computations should have been made. Acting as such a resource, the whiteboard equation can be re-performed to show from where a discrepancy ensued. In this case, Nico failed to square a number and Steve did not. The whiteboard allows the group to judge the validity of the participants' actions by checking them against the agreed-upon record of the group's activity and task.

Displaying the concepts, conclusions, and consequences of design were crucial for presenting to the group issues for judgment and resources for making judgments. This is especially evident when Silvio takes up a marker to illustrate how ludicrous it is to believe that 100 mph wind would only generate around 9 lbs. of force. He makes an appeal to ridicule with the marker, advocating for the group to recover their intuitive sense of force over what the equation reveals. The equation on the whiteboard affords a complex judgment here. The students had done the equation correctly, which is the record of the work and the trajectory of their task. The equation as guide for how a task can be completed, fails in that role, though, when the equation conflicts with common sense. The inscriptions on the whiteboard then become suspect and open to a different interpretation. They become resources to reassess the sequence of activity and what the group should be doing. It is at this point that Bob realizes the equation they had been working out is the incorrect equation. Silvio's holding up their conclusion to ridicule makes apparent a disjunction between the equation and common sense. Bob recognizes the implication of Silvio's illustration and interrogates the equation. After hearing the operations for determining wind load, he sees that the equation the group was working out was for "wind resistance."

Appeals to ridicule bring the group to consider their mathematical conclusions in the light of common sense. Common sense here designates the embodied knowledge of recognizing and understanding the consequences of basic physical interactions gained from experience in everyday life. Basic physical interactions mean knowledge of density, force, shape, mass, velocity and volume inherent in objects and their reactions on other objects. In other words, even if Silvio had never experienced 100 mph winds, he knows intuitively it is impossible only 9lbs. of force would be produced from such a gale on an object. This kind of knowledge is anterior and perhaps ancillary to mathematical understanding. Whatever its position, it becomes a guiding force in judging the durability of the solar tracker design.

After researching the wind force of 100, 50, and 40 mph winds, the group scrutinizes the numbers and the requirements for design by creating counterfactual scenarios using similes such as thinking of 100 mph of wind force like throwing a truck at a solar tracker. The counterfactual scenarios vivifies the numbers on the whiteboard, prompting the group to visualize the consequences of recommending the solar tracker withstand a certain amount of force. Again, common sense plays a large part in determining the design requirements. It was unnecessary to design a solar tracker able to withstand gale force winds for a place where such standards of durability were unexpected and unlikely to be tested. The role of displays in making judgments changes as the whiteboard becomes "a medium for conception of concrete objects"[12]. The whiteboard records, figures, and reflects the conceptual objects on which the group deliberates, be they sketches, equations, or agendas. In this particular case dealing with equations, the whiteboard provides a point of inception for the group's examination of incongruities between formulas and common sense, and between options for design requirements. Judgment proceeds through reflecting on and making sense of displays of activity.

Conclusion:

The case study suggests the importance of displays and appeals to common sense for engineering judgment. Displays provide engineering students a space to examine and reassess the materials and procedures that direct design activity. Students use displays, whiteboards and gestures in the preceding case, to see the trajectory of an activity and compare it with the task at hand. This is evident at the point where Bob notes the necessity of converting the various units of measure to simplify the equation. Displays are also resources for recording agreed-upon sequences of activity and judging conclusions based on the adherence to the record. Bob's adjudication between the two different conclusions of Nico and Steve serve as a point where a display served as the standard for how an action should be carried out. Displays, while being authorities in some situations, can quickly be amended, or shown to be wrong through other kinds of displays. One can imagine the act of sketching, where images are momentary, and are changed in response to emerging concerns. In the case above, the equation's grip on the process of activity was called into question by Silvio's appeal to ridicule through his illustration with the marker. Silvio was able judge the conclusion as against common sense and used rhetoric to gain adherence to his perspective. Finally, displays are resources for the construction of counterfactual scenarios illustrating the consequences of choosing different options. Options are represented and then imaginatively transformed through figurative language appealing to an engineer's sense of proportion and the satisfaction of requirements.

These conclusions make more concrete several philosophical insights about engineering judgment and adds to those insights the recognition of the material elements engendering judgment. That judgment is in some way knowing how and when to apply scientific and mathematical knowledge to problems seems justified by the case study. The equation was at different times a record of activity, a guide for activity, and that which impeded satisfaction of the task. Knowing when to trust equations and recognize how to apply them is a matter of judgment as much as technical education. In an increasingly automated and algorithmic engineering world, students need to develop awareness and a 'feel' for the engineering object in order to judge whether inputs and outputs are correct or sensible.

Several authors discussing judgment emphasize its perceptual aspect[2, 5]. The ability to see something awry and problematic is a perceptual skill necessary to exercise judgement: "Salient features calling for practical reason do not spring to the eye already tagged for recognition…Rather we have to pick them out, and this involves the ability to see fine detail and nuance and the ability to discern the difference between this situation and others that to the inexperienced eye might seem the same" [14]. The case study not only provides an example of seeing what is in need of judging, but also shows how what is seen by one is made present for the group. In other words, judgment in the engineering design context is less a mute ability of perception, and more an activity unto itself requiring recognition of an issue, appeals to reason, and demonstrations for the benefit of others. In situations where no one person is completely invested with the power of arbitration (as in design), the need to argue for and demonstrate a judgment, strengthens judgment's force and promotes cooperation.

Finally, the case study shows the creative aspect of engineering judgment. It is Davis's contention that judgment is in large part creative, that judgment is a constructing of possibilities under constraints[1]. The counterfactual scenarios of the students offer ways to discount choices, clearing away alternatives by imagining their consequences. The construction of counterfactual scenarios serve as persuasive reasons for making decisions. And again, the importance of displays come to the fore. Displays afford participants stable-for-now objects amendable to conceptual, mathematical, or rhetorical manipulation, allowing judgments to be formed and reflected upon. New alternatives or solutions following judgment can be recorded and refined by being inscribed and displayed.

The integral role of displays in engineering judgment speaks to recent work in engineering education focusing on the importance of representations[15, 16.] . Johri, Wolf, and Olds contend engineering problem-solving is fundamentally a matter of using representations [15,]. Engineers are surrounded by computer screens, drawings, graphs, equations, sketches, reports, memos, Power Point Presentations, and more. Engineers see and manipulate their professional objects through representational media or displays[17, 18]. The connection of the mediated world of engineering with the development of engineering judgment is implied by scholarly emphases on perception and non-verbal thinking, but the constitutive role of displays has not being fully recognized, and instead engineering judgment is often restricted to abstract discussions about relating general knowledge to particular situations. What the above case study reveals is how judgment is immanent in mundane engineering work, and how common tools of engineering serve as the basis for developing a type of judgment that could be called engineering judgment.

For engineering educators, the call for students to exercise judgment can be buttressed by reminding students of the importance of displays to record group activity, manipulate conceptual objects, and create rhetorical appeals to persuade participants of design decisions. Perhaps more importantly, the case study exhibits that judgment is needed for students to recognize when they are on the wrong track, using the wrong tools, or coming to suspicious answers. In the matter of using the wrong equation as described above, the mistake can be accounted to the students' less than mastery of calculating force. But that would miss the point that as students learn the science, mathematics, and tools of engineering, they still must develop the ability to judge the correctness and fit of applying their learning to real situations.

References:

1. M. Davis, "A Plea for Judgment" *Sci. Eng. Ethics*, vol. 18, pp. 789-808, 2012.
2. E. Ferguson, *Engineering and the Mind's Eye.* Cambridge MA: MIT press, 1994.
3. J.E. Holt, "The Designer's Judgment." *Design Stud*. 18, pp, 113-123, 1997.
4. H. Petroski, "Failure as Source of Engineering Judgment: Case of John Roebling. *J. Perform. Constr. Facil.*, 7, 1, pp. 46-58, 1993.
5. W. G. Vincenti, *What Engineers Know and How They Know It: Analytical Studies from Aeronautical Histor*y. Baltimore, MD: Johns Hopkins Press, 1990.
6. ABET (2016), Criteria for Accrediting Engineering Programs [Online]. Available at http://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2016-2017/
7. M. E. Gorman, "Turning Students into Professionals: Types of Knowledge and ABET Engineering Criteria." *J. of Eng. Educ*., 91, 3, pp. 327-332, July, 2002.
8. K. Dorst, "Design Problems and Design Paradoxes." *Design Issues* 22, 3, pp. 4-17, June, 2006.
9. B. McNely, "Taking things seriously with visual research" *Commun, Design Quart*. 3, 2, pp. 48-54, Feb., 2015.
10. R.M. Emerson et al., *Writing Ethnographic Fieldnotes*. Chicago IL: University of Chicago Press, 2011.
11. M. Lynch, *Scientific practice and ordinary action*. Cambridge, UK: Cambridge University Press, 1993.
12. L. Suchman, "Representing Practice in Cognitive Science" *Human Stud*., 11, pp. 305-325, 1988.

13. L. Prelli Ed., *Rhetorics of Display*. Columbia, SC: University of South Carolina Press, 2006.
14. J. Dunne and S. Pendlebury, " Practical Reason," in *The Blackwell Guide to the Philosophy of Education,* N. Blake, et al., Eds. Oxford, UK: Blackwell Publishing, 2003, pp. 194-213.
15. A. Johri et al., "The Role of Representations in Engineering Practice: Taking a Turn towards Inscriptions," *J. of Eng. Educ.* 102, 1, pp. 2-19, Jan., 2013.
16. J. Juhl and H. Lindegaard, "Representations and Visual Synthesis in Engineering Design," *J. of Eng. Educ.* 102, 1, pp. 20-50, Jan., 2013.
17. L. Suchman "Embodied Practices of Engineering Work," *Mind, Culture, & Activity*, 7, 1-2, pp. 4-18, 2000.
18. K. Henderson, *On Line and on Paper: Visual Representations, Visual Culture, and Computer Graphics in Design Engineering*. Cambridge, MA: MIT Press, 1999.