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How Engineers Negotiate Domain Boundaries in a Complex, Interdisciplinary Engineering Project

Grace Panther, Oregon State University

Grace Panther is a doctoral student conducting research in engineering education. She has experience conducting workshops at engineering education conferences and is currently a guest editor for a special issue of European Journal of Engineering Education on inclusive learning environments. Her research includes material development, faculty discourses on gender, and defining knowledge domains of students and engineers.

Dr. Devlin Montfort, Oregon State University

Dr. Montfort is an Assistant Professor in the School of Chemical, Biological and Environmental Engineering at Oregon State University

Zachary Pirtle, Human Exploration and Operations Mission Directorate, NASA Headquarters

Pirtle is a PhD candidate in Systems Engineering at George Washington University and is an engineer at NASA supporting integration for the new Space Launch System, Orion spacecraft and associated ground systems. He has written on engineering epistemology, innovation and the connection between engineering and democracy.

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Introduction

Engineering educators have an essential role in preparing engineers to work in a complex, interdisciplinary workforce. While much engineering education focuses on teaching students to develop disciplinary expertise in specific engineering domains, there is a strong need to teach engineers about the knowledge that they develop or use in their work (Bucciarelli 1994, Allenby & Sarewitz, 2011; Frodeman, 2013). The purpose of this research is to gain a better understanding of the knowledge systems of practicing engineers through observations of their practices such that the insights learned can guide future education efforts**.** Using an example from a complex and interdisciplinary engineering project, this paper presents a case study overviewing the types of epistemological (or knowledge-acquiring or –using) complexities that engineers navigate[1]. Specifically, we looked at a discussion of the thermal design of a CubeSat that occurred during an engineering review at NASA. We analyzed the review using a framework that we call 'peak events,' or pointed discussions between reviewers, project engineers, and managers. We examined the dialog within peak events to identify the ways that knowledge was brought to bear, highlighting discussions of uncertainty and the boundaries of knowledge claims. We focus on one example discussion surrounding the thermal design of the CubeSat, which provides a particularly thorough example of a knowledge system since the engineers present, explained, justified, negotiated, and defended knowledge within a social setting. Engineering students do not get much practice or instruction in explicitly negotiating knowledge systems and epistemic standards in this way. We highlight issues that should matter to engineering educators, such as the need to discuss what level of uncertainty is sufficient and the need to negotiate boundaries of system responsibility. Although this analysis is limited to a single discussion or 'peak event,' our case shows that this type of discussion can occur in engineering and suggests that it could be important for future engineering education research.

Background

Many of the engineering challenges that society faces today require the expertise of engineers from an array of disciplines. Each discipline is assumed to bring a specialized knowledge set that enables individuals to address specific components of a project (Frodeman, 2013). Components of a project are rarely isolated but instead are highly interrelated, which requires efficient coordination across disciplinary boundaries. Viewing the full set of discussions about knowledge across a project as a 'knowledge system' is one way to study the inter-relation between people, tests, institutions and general scientific knowledge as is structured across multiple disciplines. For example, organizational studies research has looked at how knowledge coordination occurs across different departments (for example Product Sales and Engineering) but few studies exist about how engineers negotiate among themselves and coordinate the knowledge required for large, intricate engineering problems (Carlile, 2002). A significant

[1] Epistemology refers to the study of knowledge, and we use that phrase here to refer to key elements tied to knowledge claims that surround discussions in an engineering review. The debate about what is knowledge versus what is belief has been thoroughly assessed, with the literature shifting focus from defining knowledge simply as 'justified, true belief' (Steup 2005). This paper focuses one epistemic issues found in the case study, including determining the appropriate level of uncertainty as well as the negotiation of what the system boundary (and associated knowledge claims) would be.

challenge in studying interdisciplinary knowledge is that it can only be observed through careful analysis of social interactions (Brown, Collins, & Duguid, 1989; Lave & Wenger, 1991; Robbins & Aydede, 2009). Studying the social interactions among the individuals of a community requires direct observation in order to capture the intricacies of the system. Therefore, the research presented here utilized ethnographic-inspired observations to study the interaction between different domains of knowledge.

Setting

We observed a knowledge system in action by attending a design review of an engineering project. The review was a Critical Design Review (CDR), which is generally performed as a project's design is nearing completion (NASA 2007). The purpose of the review was to present a thorough overview of the technical plans for the project to an Independent Review Team, which used a mixed set of technical expertise to assess the project[2]. This CDR differed somewhat from traditional CDRs because some subsystems were known to still need additional work, which is a consequence of the development timing and schedule constraints. Additionally, CubeSats for exploration beyond Earth orbit are relatively new within NASA history, and this particular project was targeting flight on a launch vehicle that is still in development.

The goal of the BioSentinel project is to measure the effects of radiation on DNA in deep space in preparation for sending humans to Mars (NASA, n.d.). It will carry specially designed strains of yeast that respond to radiation in different ways. BioSentinel is what NASA calls a "6U CubeSat," which means it is a solar-powered spacecraft about the size of a shoe box that needs to be launched into orbit on a rocket. CubeSats have become a relatively common way of sending small scientific payloads into space using a standard sized container. Many of the technical challenges involved are in getting the instrument to function and be self-sufficient within the parameters of the CubeSat footprint. BioSentinel will be loaded into a dispenser and then integrated on the Space Launch System (SLS), which will carry it into deep space[3]. The dispenser is a chassis with set dimensions that secures the CubeSat during launch to the SLS and ejects it in outer space. Once loaded, the CubeSat will be inaccessible and must be prepared to sustain ambient conditions in Cape Canaveral, FL for 6 months. Outside the Earth's atmosphere BioSentinel will be ejected from the SLS along with 12 other CubeSats. Once in space BioSentinel will maneuver itself to make measurements, charge its batteries and transmit data back to the Deep Space Network (DSN) antennae on Earth.

Methods

We used an ethnographic-inspired situative approach based on observable knowledge practices to study the knowledge system of practicing engineers based on observable knowledge

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[2] For more context on NASA's design review process, see NASA 2007. The Critical Design Review (CDR) review is used as a key milestone for the agency to decide that a project can move forward into formal implementation. The CDR is the review just prior to the time, which is colloquially referred to as the point where engineers start to 'cut hardware.'

[3] The Space Launch System was announced by NASA in 2011 (NASA 2011), with a first flight now projected for late 2018, The existence of BioSentinel and other SLS secondary payloads was added in 2015 to SLS's planned first flight, with the secondary payloads being set to deploy after launch of the Orion spacecraft (NASA 2015).

practices. Observable knowledge practices include interactions between people that require them to explain, justify, defend, and negotiate knowledge claims (Duschl, Ellengoben, & Erduran, 1999; Wooley & Lin, 2005). The design review therefore provided a unique opportunity to witness how knowledge is exchanged and negotiated within a complex, interdisciplinary setting because it brought together the scientists and engineers on the project to present their plans to an external review team with diverse technical backgrounds.

Data collection occurred during the design review by three researchers who used ethnographic methods to inform their observations and note-taking (Emerson, Fretz, & Shaw, 2011). Observational notes in the form of jottings were recorded during the review. Jottings are "-a brief written record of events and impressions captured in key words and phrases" (Emerson et al., 2011, p. 29). At the end of each day, the researchers worked collectively to review their jottings and create field notes. The jottings focused on a combination of direct quotes, a summary of what was being spoken about, and any researcher comments or personal thoughts that occurred.

We spent three months prior to the design review interacting with the Project Manager and learning about the BioSentinel project and team members to help situate ourselves in the project landscape. Being familiar with the project allowed us to focus on taking jottings about the knowledge system during the design review (Emerson et al., 2011). The purpose of our comments were to reveal aspects that were not explicitly conveyed during the presentation. An example of the format of the jottings can be found in Table 1.

Nearly all of the discussions centered on presentations supported by projected slides. We were given access to the presentation slides and considered them in parallel with our jottings during analysis. Jottings were compared across researchers to ensure as many details as possible are presented and to present the reader with the most accurate description of the design review.

Table 1. *Example of researcher jottings during the design review.*

Topic/Slide Title or #	Direct Quotes	Gist/Summary	Comments/Personal Thoughts
Predicted total heating		-model shows that they need about 2.6 Watts to run 2 cards at the same time	
	"Have you looked at worst case scenario when the transponder, cards, etc are on?"	-have looked at it but not when transponder turns on	-flexible design to account for worse case

The analysis started with identifying peak events that occurred during the design review. "Peak events" were defined as exchanges where the project expert had to explain, justify, negotiate, or defend a knowledge claim and resulted in successive questions about the same specific content. Peak events are a useful lens to gain insight about the overall knowledge system because they can represent moments where different understandings and disciplinary perspectives emerge (Wooley & Lin, 2005). One example of peak events was during the thermal design presentation where two peak events were observed. The discussion presented here about the thermal environment is a good demonstration of a peak event for several reasons: (1) it moves between technical details, general approach, the involvement of other systems, and managerial translations; (2) the system is an integral piece of the larger project; (3) the discussion ends unresolved, and; (4) it shows good examples of experts and review panel members "talking past each other." We use the phrase "talking past each other" as a symbolic representation indicating two people participating in the same discussion but fundamentally having a different debate – often times factual versus epistemological - resulting in an unsuccessful or unresolved debate.

To analyze and navigate through a peak, each question and the corresponding response was labeled as a "Move." Each move represents a time when a knowledge claim was questioned and then explained, justified, negotiated or defended by either the project expert or a manager.

The thermal design of the CubeSat is complex and dynamic with the engineer having to design for drastically different external thermal environments while balancing the changing thermal demands of internal systems. For example, the transponder produces heat when operating, and the propellant cools rapidly when being used. All of the thermal requirements had to be accomplished within the given power budget of 3 watts. As an additional challenge, most of BioSentinel's subsystems were being designed at the same time as the thermal control, so the thermal control engineer needed to allow for flexibility in the system and in the design process to account for new or changing information that often occurs in design. To meet these requirements, the engineer utilized several strategies including the use of heaters, surface treatments, and adjustable plastic washers that can be "tuned" to create different levels of thermal connectivity between objects.

Findings

The findings focus on one peak event that occurred during the thermal environment presentation. A detailed description of the peak event can be found in Table 2.

Peak Event: Thermal Environments and Uncertainties

The peak event began with move 1 and a general inquiry from a reviewer about whose responsibility it was to insulate the dispenser when integrated on the SLS, which is the main external interface for the CubeSat. (Recall, the dispenser is what secures the CubeSat to the SLS and is responsible for ejecting the CubeSat into space.) The Project Manager responded from the audience that it had not been decided yet, but there are ongoing negotiations involving the other CubeSats that would be launched with BioSentinel, the SLS team, and other stakeholders involved in the launch procedures. The manager implied that there was a path forward on how to resolve this uncertainty and that he felt confident that the people doing it were on track, although he acknowledged that there is uncertainty in the current design.

Table 2. *Thermal Peak Event 'Moves,' showing the discussion that was observed by the researchers and an interpretation of the implications and meaning of the discussion.*

		Discussion	Meaning
Move 1	Question	Who insulates? (referring to launch dispenser)	Dispenser insulation can have an impact on maintaining the thermal environment of the CubeSat during the time it is sitting in the sun in Florida in the middle of summer and once it enters outer space. Maintaining the temperature within a certain range is vital for the success of the science component of the mission. At this stage of the design, there are still uncertainties about insulation on the interfaces with the payload.
	Response	(Project Manager) Not the expert's job. It still needs to be negotiated with SLS. [Contractor] will do the negotiating. (Engineering Manager) We also have some thermo issues with batteries, so everyone else is pushing in the same direction.	
Move 2	Question	(Division Manager) You talked about the heating for biology but what about the heat rejection mechanisms?	While preserving the biological samples is of utmost importance, the reviewer is aware that other components of the CubeSat produce heat and understands the significance of what this means to the rest of the CubeSat. The balanced thermal environment needs to be.
	Response	(project expert) The actual surface coatings of the spacecraft. The problem is basically ensuring you can "eject" or dump heat	
Move 3	Question	(reviewer) What kind of thermal margin are you designing to?	The thermal margin provides leeway within the design to protect against uncertain conditions. A greater margin within the design is a way of protecting against significant unknowns at the current level of design maturity.
	Response	(project expert) Don't have enough definition on pre-launch, so we're trying to drive that with our requirements. We're using a model that is "… actually very complicated" and goes on to talk about sensitivity analysis. To answer the question, many different conditions are considered.	
Move 4	Question	(reviewer) When will you have enough information (heat data) [to know the margins and how you can change the design]?	The thermal design is as complete as it can be at this point in time and the engineer has created a design that is flexible to account for the unknowns. One of the managers is explaining this again, which implies that reviewer is still not convinced that information will arrive early enough to inform the design.
	Response	(Project Manager) We're unpowered [before launch] so there is nothing the expert can do. Potentially can get a thermal simulator [to study the environment]. (Engineering Manager) Can change out some parts to help with thermal balancing. Conductive and radiative paths are represented in the model minus [transponder].	

Move 5	Question	(reviewer) But it'll be late [in arriving in your design process]?	Completing the thermal design within the timeline has implications for other aspects of the project.
	Response	(Division Manager) We'll get thermal info first. (Engineering Manager) we might get a simulator to model thermal output. But the expert has done I think a fantastic job leaving everything flexible.	
Move 6	Question/Statement	(reviewer) I am very nervous, you basically don't know the thermal system	Reviewer implies that the thermal system is unknown. Review chair is trying to focus the conversation.
	Response	(review chair) "Stop talking"	
Move 7	Question	(review chair) What if it can't meet [the thermal environments you learn about]? You have a lot of unknowns and I don't see any mitigations or worst-case.	Echoing the reviewer, the review chair describes concern about uncertainty, focusing on worst-case conditions. The Division Manager questions whether any design to protect against worst case could fit in the time and technical constraints here.
	Response	(Division Manager) If we [designed to] worst case than nothing would fly. (Project Manager) remember battery [duration length concern],that affects everyone.	
Move 8	Question	(reviewer) Are there heaters on the dispensers?	Heaters on the dispenser could assist in maintaining temperature control after the launch of the SLS and before the CubeSat deploys. But, it would be expensive to add those and could perturb the SLS rocket design
	Response	(Project Manager) No we're too unimportant.	
Move 9	Question	(reviewer) One of the things that concerns me is the payload needs +/- 1C but your temperature sensors are +/- 0.5C so isn't that pretty close? Does that include calibration?	Concerned about the margin between what the temperature sensors can detect and what the payload needs to be maintained at
	Response	(project expert) Yes! Small makes it harder. This is a very challenging spacecraft. (Engineering Manager) Problem is not unique to BioSentinel. Other [secondary] payloads are having problems because operating range of batteries	
Conclusion	Action: Request follow-up action	Reviewers discussion indicated concern about the thermal design including pre-launch, on ascent and before BioSentinel separation.	This conversation could not be resolved to the review team's satisfaction and therefore resulted in a RID (Review Item Discrepancy)

Moves 2 and 3 transition to heat rejection mechanisms and thermal margins and away from questions about the insulation. The project expert responded as the question directly pertained to the expertise of the project engineer and their responsibilities. While the engineer briefly covered surface coatings earlier in their presentation, they did not give a detailed explanation of how surface coatings affect the thermal design (i.e. discussing how surface coatings help reject heat in space). The project expert used theory to further explain and justify this design decision so that the questioner understood the importance of the surface coatings and how they work. The thermal margins (move 3) had not been discussed directly in the presentation but had been alluded to when it was stated that the design was built to be flexible to account for uncertainties and future changes at multiple timeframes from before launch to operations. So while the project expert had implied this previously, the reviewer was either unclear in their understanding or were looking for a specific piece of information tied to another interest of theirs. The project expert went into a relatively detailed explanation of their thermal design margins explaining how they are using a model and sensitivity analysis before concluding that many different situations had been considered. Therefore, while the project expert understood the complexity of the design and discussed the actual quantified margins of uncertainty, we see by move 4’s question that this explanation was insufficient for the reviewer. At this point, we see the manager interject in move 4 in an attempt to explain in a different manner by indicating that some parts can be changed out to help with the thermal balancing, suggesting the use of a simulator, and insisting that the project expert has done everything they can at this point. At a CDR there can still be uncertainties about the overall project and its interfaces, but those uncertainties need to be resolved soon in order to allow building to begin soon after the review, so these interactions had significant weight for the project. An incomplete or impractical thermal design could prevent the project from launching.

Move 5 transitions back to a more global-in-scale question and refers to the timeline of the project and when the project team will have more information to be able to complete their design. Again, the manager steps in and answers this question and compliments the project expert on their design as the design-to-date addresses the current state of knowledge.

Continuing on, we see the reviewer in Move 6 state “you basically don’t know the thermal system,” followed by the review chair calling for a pause in the discussion. The review chair goes on in Move 7 to clarify the concern in an attempt to understand what mitigations or worst-case scenarios have been thought of during the design process. This required an extended discussion to negotiate the criteria by which the credibility and relevance of design components were assessed and to create a shared meaning of what “worst-case” meant. This discussion was centrally important to the technical success of the project and was unequivocally an “engineering” discussion, even though it was light on technical detail. This aspect of engineering work is focused more on the epistemic criteria by which knowledge is assessed (i.e. on the foundations of the knowledge system), rather than the technical knowledge of the design itself.

Move 8 relates back to move 1 and asks about heaters on the dispenser, which is an external interface for the CubeSat. Again, the manager answers the question as the dispenser is beyond the scope of the project expert’s negotiating powers and responsibilities. Little discussion ensues which implies that there is an existing shared understanding of what it means to have “heaters on the dispenser” and the thermal design implications.

Move 9 shifts back to an expert specific question and asks about sensors. The response by the project expert conveyed excitement, as if the question being asked indicated to the project expert that the review team was starting to understand the complexity of the design and the issues surrounding it. A manager also adds an additional global perspective to this discussion to demonstrate that this particular project is not the only one dealing with the issues that have been debated. The question in and of itself signaled to the project expert that they were starting to make some headway in bringing the two groups to a similar point in their understanding. The review team still wanted to have a follow-up discussion and analysis, which in NASA parlance is captured through a Review Item Discrepancy (RID). A RID flags the issue as something that the project should track and discuss, and must be resolved with future involvement from the review team.

After the RID was written up, the project expert then continued with their presentation and attempted to alleviate some of the review board's concerns by showing additional models. Again, while the peak event had resulted in a RID, we see the project expert attempting to negotiate domain boundaries by using different forms of evidence. The overall review culminated in a recommendation that the BioSentinel project had successfully met the requirements of the CDR with the expectation of responding to the RIDs and that it was recommended to proceed to the next design phase.

Discussion

In most academic settings, engineering is organized into content-based domains or divisions. In some ways, NASA similarly organizes knowledge into content-based domains, for example by assigning personnel to the team based on categories such as "mechanical," "electrical," or "thermal." While this may be how they administratively deal with structuring a project, we see during the peak event that content-based domains can quickly dissolve during important negotiations. Instead, interactions were based on domains of responsibility and trust. Responsibility refers to what an individual is accountable for guaranteeing, with specific emphasis on what they are expected to be the 'expert' about. Move 1 is an explicit example of this when the manager says that questions about the insulation prior to launch are "not the expert's job." Although the content was clearly and directly related to the expertise of the thermal engineer, their responsibility only extended to the outer surface of BioSentinel itself, and not toward external interfaces such as the payload dispenser. The project expert was accountable for guaranteeing that the thermal control system would maintain internal temperatures under the expected conditions; negotiations concerning the accuracy or precision of the prediction of those conditions were outside of their responsibilities.

Exploring these different levels of responsibilities, we see the project expert's job, as defined by the peak event, is analogous to having a narrow-but-deep area of responsibility. This is seen in Moves 2 and 3 when the project expert answers content specific questions and goes into detail about the design and analysis of the system in isolation. The project expert's responses drew from technical details and a deep understanding of the system to provide evidence that their design will accomplish its goals. The continued and escalating questioning of the reviewer does not question the project expert's evidence or technical expertise, but instead implies that the precision might not be sufficient due to uncertainty in the projects' broader assumptions about its interfaces.

Unlike the project expert, the managers' responsibilities focus on verifying that the thermal design is trustworthy and can interface and communicate with the systems and anticipate the changes it will need to deal with. We see an example of this in Move 1 where the Engineering Manager and Project Manager are talking about a negotiation with a contractor and a thermal issue with batteries. The managers use a similar approach as the thermal system expert in their responses; they use their deep understanding of the system (the human system of engineers in this case, as opposed to the thermal control system) to present evidence in support of the design decisions. They also have a sense of the appropriate amount of uncertainty that can exist at different phases in a project's development, and tried to defend that their work was good given the current state of the design.

Further up the management ladder, we see the Division Manager responsibilities are focused on the need to be able to trust the Project Manager and Engineering Manager and make sure that the overall approach is appropriate. This is evident in Move 7 where the Division Manager's argument is based on a deep understanding of the broader managerial system. The Division Manager addresses the reviewer's assumption that all designs should be robust against "worst case" conditions by arguing that this approach is not appropriate for this particular project given the constraints on time and information. It is worth noting that each level of managerial responsibility includes more people and therefore requires a broader awareness of the project systems and their interactions.

Conclusion

This exchange is an example of a peak event because it marked one of the few discussions that did not result in a fairly immediate (less than 10 minutes) agreement among the participants. We argue that this is because the disagreements presented here are fundamentally about epistemology: What level of certainty is required? What is acceptable? How well understood are the thermal systems? Can you trust a model to be reliable in the relevant system boundaries? However, these questions were never directly addressed in the discussion. There was extensive back and forth conversation about uncertainty in the thermal environment but there was likely no way to more definitively answer the question until the design maturity and understanding of the mission environment improved[4]. The debate between reviewer and project managers and experts thus depends on epistemic issues and value preferences about risk that cannot be objectively assessed (Douglas, 2009). Instead, in contrast to most other disagreements during the entire review, this disagreement needed to be settled by an authority[5]. Such an intervention helped clarify the point of the conversation and to forestall what could have been a much longer discussion.

While it may be unsurprising that a group of engineers and scientists preferred to discuss technical details instead of epistemological nuances such as acceptable levels of uncertainty, this preference is significant because it marks a basic feature of the design process. The reviewers and presenters negotiated many complicated issues, including who's responsibility it is to resolve key issues. Even in this brief excerpt they developed a shared understanding about expected

[4] There may even be uncertainty after BioSentinel has eventually flown – successful or not, there may be difficulty in knowing exactly what happened as well as how BioSentinel might behave in periods of abnormal solar radiation that could be part of the uncertainty space. For a comparable example, see ongoing conversations about how safe that Space Shuttle was (Gerstenmaier, February 2017 briefing to the Commercial Space advisory committee). Engineers learn a lot from successes or failures but always have uncertainty about how the design would perform in other conditions.

[5] Note that the "stop talking" from the review chair to the review member in move 6 was recorded in the jottings as a direct quote and, although it was delivered with some warmth and humor, it still marks an unusually directive statement in the collegial atmosphere of the review. That said, one of the authors can attest from experience that strong statements and pointed conversation is not an infrequent event inside an engineering context.

insulation levels, heat rejection mechanisms, thermally reflective surface coatings, and a thermal model that required hours of computation time per run. It can be easier to focus on specific questions rather than to look holistically at the entire system. The question, “do you know enough about the thermal conditions?” seems relatively simple in comparison. The amount of time spent on this question suggests that even simplistic processes for addressing epistemological concerns could significantly affect engineering projects. Explicitly addressing macro-issues about knowledge, such as uncertainty and system boundary, can be an important complement to engineers’ discussion of focused analysis of components and technical details.

Engineering students do not get much practice or instruction in explicitly negotiating knowledge system boundaries and epistemic standards on uncertainty. Although this analysis is limited to a single discussion, we argue that such discussions are important in many engineering projects. Educators can incorporate the findings here into their classroom practices by providing more system-level context but less definition (e.g. ill-defined) to students when assigning problems, forcing students to think beyond the necessary calculations and more about how their work interacts with other components and the system as a whole. Understanding how engineers communicate across different epistemic and disciplinary viewpoints is another step towards creating an engineering curriculum that more closely aligns with engineering practice. Furthermore, it shows that engineering knowledge is not only something to be possessed but instead something that must be negotiated, at varying levels of uncertainty, as part of an interconnected and socially situated knowledge system.

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References

Allenby, B.R. and Sarewitz, D. (2011). The techno-human condition. MIT press.

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational researcher*, *18*(1), 32-42.

Bucciarelli, L., (1994). *Designing engineers*. MIT press.

Carlile, P. R. (2002). A pragmatic view of knowledge and boundaries: Boundary objects in new product development. *Organization science*, *13*(4), 442-455.

Douglas, H. (2009). Science, policy, and the value-free ideal. University of Pittsburgh Press.

Duschl, R. A., Ellengoben, K. & Erduran, S. (1999). Understanding dialogic argumentation among middle school science students. Invited paper at the annual meeting of the American Educational Research Association (AERA), Montreal, April 1999.

Emerson, R. M., Fretz, R. I., & Shaw, L. L. (2011). *Writing ethnographic fieldnotes*. University of Chicago Press.

Frodeman, R. (2013). Sustainable knowledge: A theory of interdisciplinarity. Springer.

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge university press.

NASA. (n.d.). BioSentinel. Retrieved from http://www.nasa.gov/centers/ames/engineering/projects/biosentinel.html

NASA, 2007. NASA systems engineering handbook. NASA/SP-2007-6105 Rev1.

NASA 2011. Space Launch System announcement. https://www.nasa.gov/exploration/systems/sls/sls1.html

NASA 2015. SLS Secondary Payload announcement: https://www.nasa.gov/exploration/systems/sls/space-launch-system-to-boost-science-with-secondary-payloads.html

Robbins, P., & Aydede, M. (Eds.). (2009). *The Cambridge handbook of situated cognition*. New York, NY: Cambridge University Press.

Steup, M., (2005). "Epistemology", The Stanford Encyclopedia of Philosophy (Fall 2016 Edition), Edward N. Zalta (ed.), URL = <https://plato.stanford.edu/archives/fall2016/entries/epistemology/>.

Wooley, J. C., & Lin, H. S. (Eds.) (2005). Illustrative Problem Domains at the Interface of Computing and Biology. *Catalyzing Inquiry at the Interface of Computing and Biology, Computer Science and Telecommunications Board, The National Academies Press,* 329.