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Actor-Networks of Sophomore Engineering: Durability and Change in Required Mathematics Courses

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ACTOR-NETWORKS OF SOPHOMORE ENGINEERING:

Durability and Change in Required Mathematics Courses

by

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Durability and Change in Required Mathematics Courses

written by Janet Yi-Jen Tsai
has been approved for the Department of Mechanical Engineering

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Dr. Daria A. Kotys-Schwartz

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Dr. Michael Hannigan

Date_______________

The final copy of this thesis has been examined by the signatories, and we
Find that both the content and the form meet acceptable presentation standards
Of scholarly work in the above mentioned discipline.

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Abstract

Tsai, Janet Yi-Jen (Ph.D., Mechanical Engineering)

Actor-Networks of Sophomore Engineering:

Durability and Change in Required Mathematics Courses

Thesis directed by Senior Instructor Dr. Daria Kotys-Schwartz

This study analyzes the social and cultural environments of gateway engineering mathematics courses of the sophomore year, specifically Calculus 3 for Engineers and Differential Equations & Linear Algebra. We ethnographically examine the experiences of undergraduate students, graduate student teaching assistants, and faculty instructional staff as they traverse these courses, in order to map out the social and cultural terrain upon which learning, status, and grades are negotiated. Inspired by a novel theory from Science and Technology Studies, we take an *actor-network* view of sophomore engineering, tracing connections between human actors and non-human elements including mathematical concepts, places, objects, and resources to demonstrate how students are *translated* to varying degrees through sophomore mathematics courses into *actor-networks* of engineering. *Actor-Network Theory* encourages a fresh perspective of sophomore engineering that affords a systems-level view of these crucial gateway courses and suggests fundamental questions regarding the nature of our courses and how they got this way in the first place.

To understand the current organization of *actor-networks* in sophomore engineering, our study extends back in time through history, examining the conditions in which our current building and curriculum were constructed during the Cold War era. Our findings indicate that the content and general format of these sophomore math classes have not changed significantly since the 1960s, in spite of the rapid advances in technology. Yet communication channels between professors and students have proliferated in recent years, allowing alternatives to the lecture hall for student learning while simultaneously making information delivery more difficult for faculty. We map out student progressions through these critical math courses, looking at how some students flow through smoothly while others fight and tussle around obstacles and challenges in their way. We illustrate the impact of non-human actors like exams on the organization of student *actor-networks*, pointing out that their power over students may be excessive. We conclude with a discussion of the implications of our findings and recommendations for practice, noting that these *actor-networks* are complex and ripe for continued research.

Dedication

To my Dad, who showed me that being an engineer isn't all that bad;

To my Mom, who taught me how to work hard;

To my Sister, who has blazed countless trails in life that I have followed;

To all of my partners-in-crime who have been there by my side;

And to my teachers, all of them.

Acknowledgements

I am very grateful for the support of many individuals and institutional structures which have enabled my graduate career. My family has been a great source of support and inspiration here in Colorado, I am especially thankful to have my sister, Dr. Yi-Hsin Erica Tsai, available as a sounding board and guide. Many friends, both here in Boulder and far beyond, have listened and offered advice, and have stood by my side in celebrating highs and lows throughout the last five years. Specifically I thank Dr. Jacob Segil and Carrie Segil for their kind attention in preparing my defense presentation, and Sarah Boman for serving as an architectural consultant and wealth of contextual information. I am also appreciative of the strong engineering foundation and critical eye my undergraduate training at Olin College of Engineering has provided, as well as the connections throughout the field of engineering education that my Olin years helped me to develop and maintain.

At CU, I have been fortunate to have a strong cohort of graduate students and researchers in the field of engineering education and the Learning Sciences. Without these folks, my work would have been entirely less fun and likely less interesting – their companionship along the pathway of graduate school has been hugely valuable, and I look forward to continuing these research partnerships going forward. I have also been lucky to know many role models and amazing women in engineering at CU, including Dr. Bev Louie, Dr. Tanya Ennis, Dr. Jackie Sullivan, and Dr. Virginia Ferguson. Their mentorship and involvement in my development has meant a lot to me, our conversations have broadened my perspective on the field and have deepened my understanding of undergraduate engineers and learning.

The historical element to this project would not have been possible without the robust library network at CU and the Denver Public Library. I would like to thank the staff of the CU Heritage Center, who started me on my research path with newspaper clippings and back issues of

the *Colorado Alumnus*. The Western History/Genealogy group at DPL provided me with access to the archives of W.M. Muchow, partner-in-charge of the Engineering Center's architecture, which was graciously donated by his estate and family. I was lucky to spend several days in the CU Archives at Norlin Library, where I met Dr. David M. Hays, the CU archivist. Dr. Hays provided a wealth of contextual information for my project, and was very helpful in locating relevant institutional documents including the personal correspondence of Dean Max Peters and the past Presidents of the University of Colorado. I am also indebted to Dr. Alexander Watkins, also in Norlin Library, who answered my questions related to fair use and copyright. Thank you the staff at the Facilities Management Department including Philip Martin of the CAD/GIS & Document Management Office who provided electronic access to the wealth of architectural and building plans for every building and remodel in the university. I am also grateful to the staff of the Gemmill Engineering Library for tirelessly retrieving books and resources for my review, the library system is an impressively durable and effective network that enables projects like mine to flourish.

My graduate career has been supported by a variety of funding sources, both public and private. I am thankful for the Department of Mechanical Engineering at CU for offering a variety of fellowships, grants, and teaching opportunities that have supported me over the last five years. The National Science Foundation Graduate Research Fellowship #DGE1144083 provided three years of generous funding, and the on-campus Center for STEM Learning also supported me through a Chancellor's Award for Excellence in STEM Education. I have been very lucky to be supported through the Philanthropic Educational Organization (P.E.O.) Scholar Award, and to be the recipient of an American Society for Mechanical Engineering (ASME) Graduate Teaching Fellowship. Furthermore, I am incredibly grateful for the guidance from our department's graduate advisors, Sharon Anderson and Vera Sebulsky. Sharon has been a tireless champion of mine, she has always celebrated my victories and helped me stay on-track to graduate. Sharon and Vera have saved my bacon more times than I can count, and it is through their efforts that I have been able to move through my graduate trajectory without too many emergency petitions or obstacles in the way. In the same vein, I would like to thank Kassie Ferraro for her steady and gracious support as well.

I would like to thank Dr. Derek Reamon for serving on my committee, for being interested in my project, and for listening to my status updates with patience and good humor. I am also thankful for Dr. Michael Hannigan who partnered with me on the active learning intervention which led ultimately to my dissertation project, for being open to my ideas and always supporting my work, and for serving on my committee. I am incredibly grateful for the guidance of Dr. Margaret Eisenhart, whose qualitative methods class started me on the path of ethnographic research, and whose thoughtful questions have strengthened my project and made us all think. I would also like to thank Dr. Kevin O'Connor for punctuating my graduate experience with insight and curiosity, and for guiding me through my first Actor-Network Theory readings. These four committee members have graciously enabled my nontraditional thesis in Mechanical Engineering, without their support and involvement my research would not be institutionally possible.

I would like to thank my research team of Dr. Daniel Knight and my committee chair, Dr. Daria Kotys-Schwartz. Daniel has listened tirelessly to my ideas and data analysis, while providing a calming outlook and a great deal of perspective on this project and engineering education as a whole. It is hard to imagine this project being successful without his input; it is hard to imagine my own progress without his mentorship. Thank you, Daniel, for being there throughout this project, for pushing the Dissertation through, and for providing valuable feedback on early drafts. Thank you, Daria, for being my champion throughout graduate school. I really could not have done this without Daria! Her enthusiasm and encouragement have led me through all the challenges of graduate school, and have bolstered me to strive for excellence in research and teaching. Daria is inspirational by example, from her I have learned immeasurably about both academia and life. I am very grateful for the opportunities she has furnished and for her positive, outgoing, and engaging spirit.

Finally, this work would not be possible without the participation of research subjects at many levels. I am grateful to the undergraduate students I interviewed, observed, and chatted with, the graduate students who shared their lives with me, and the faculty who agreed to interviews and let me into their classrooms. I have endeavored to represent these individuals accurately, and I hope I do their experiences justice.

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Chapter 1 – Introduction

This study employs qualitative methods to analyze the experiences of students in critical courses along the engineering undergraduate degree path, the required mathematics courses of sophomore year or the second year. Our approach is motivated in part by prior experience implementing active learning activities in a sophomore level mechanical engineering course, an intervention that highlighted how much is unknown about the perceptions and attitudes of students enrolled in impactful and large-enrollment courses of the sophomore year. As discussed in Chapter 2 –Motivation, the sophomore year is an understudied yet pivotal time for undergraduates navigating the engineering curriculum. This year includes completion of the final required math and science course requirements while initiating students into major-specific technical coursework. We choose to focus on the mathematics courses typically taken during the sophomore year, as they are prerequisites for subsequent layers of specialized engineering courses. These math classes, called Calculus 3 for Engineers (Calc 3) and Differential Equations & Linear Algebra (Diff Eq), determine if a student will proceed through the engineering curriculum or remain stalled, repeating a class until it is passed. As described in detail at the close of Chapter 2 – Motivation, the sophomore year carries considerable retention risk as students who pass through the first year but encounter obstacles in the second may choose to switch out of engineering in time to graduate with a different undergraduate degree in four years.

To understand what happens during these critical mathematics classes of the sophomore year, we adopt an approach at the intersection of the Science and Technology Studies and engineering education. As detailed in Chapter 3 – Background, we first summarize relevant literature on engineering sophomore year to situate our study within the growing tradition of examining the middle years of undergraduate engineering education. We then describe the qualitative research on engineering cultures and power dynamics that informs our work, encouraging a sociocultural investigation of the existing situation instead of attempting any quantitative measurement of an intervention's effect size. Special attention is given to describing research in engineering education that takes a critical view of the power structures and dominant ideologies in contemporary engineering culture, as these criticisms of engineering culture inspire and ground this study in the existing literature.

The second subsection of Chapter 3 – Background introduces and contextualizes the conceptual framework we utilize in analyzing the impactful math courses of sophomore year. Actor-Network Theory, or ANT, provides the theoretical foundation upon which our study rests, so we spend considerable space explaining the theory and illustrating ANT with canonical examples. We describe where and how this novel theory was developed and how it has been applied in Science and Technology Studies, before moving chronologically forward in the literature to describe applications of ANT in educational research and engineering education research in turn. After-ANT scholarship is also reviewed, as the wave of reactions to initial ANT studies further informs how we understand and employ the theory today. We find evidence of ANT approaches in leading engineering education research journals, indicating that the field of engineering education is overdue for an in-depth study of sophomore engineering utilizing ANT.

With the literature summarized and conceptual framework in place, the last section of Chapter 3 – Background describes the gap in the current engineering education knowledge base that our study aims to bridge. We present our research questions at the close of this section, and below for reference:

1. How are students *problematized, interessed, enrolled, mobilized, and translated* in the actor-networks of engineering sophomore year and to what consequence?

2. What can we learn about engineering sophomore year by stepping outside of the network metaphor, or by shifting the focus away from central actors towards those at the margins?

The first research question describes our approach to investigating the math classes of engineering sophomore year from a traditional ANT lens. The second research question incorporates after-ANT scholarship into the tenets of our study.

Chapter 4 – Methodology justifies our choice of a qualitative research design to answer our research questions and gives an overview of qualitative versus quantitative approaches. Ethnography is explained briefly before introducing our research design in depth. We detail our data sources and data collection methods and explain the context of our study and its participants. We describe our processes of qualitative data analysis, referring to the relevant Appendices for supporting documents and data displays. Threats to validity and our efforts to preserve validity and reliability throughout this research project are discussed in the context of our methodological approach. We introduce an interpretive quality framework from recent research in engineering education that we utilized to robustly analyze our study for counterarguments and missing pieces.

Following Chapter 4 – Methodology, we embark on a historical Interlude to demonstrate the application of ANT concepts on a local example, our Engineering Center building. We go back to the Cold War era in the US to understand how engineering was transformed from its blue-collar roots into the calculating discipline we know today. With help from historical documents and records, we describe how the turn towards engineering science became both widespread and durable, affecting engineering schools nationwide and also here at the University of Colorado Boulder. As the ideology of engineering science has persisted to the present day, we identify the influential administrators and faculty who initially popularized this science-based view of engineering at CU, and connect their actions to the growth of the engineering college and the case for constructing a new building. We utilize ANT in describing the process wherein taxpayers statewide and nationwide became compelled to fund the construction of the Engineering Center in the 1960s. We follow the building committee, architects, contractors, and consultants who designed and constructed the building, using their words to explain what the building signified when it was officially dedicated to the public in 1966. Finally, we compare the Engineering Center of 1966 to the Engineering Center of 2015, examining what has changed and what has remained stable during the intervening decades. This history informs our present educational situation in ways that extend far beyond the building itself; we trace out connections between current practices and historical artifacts to understand the impact of our forefathers' actions on our activities today. In analyzing the building and the activities surrounding its construction, we gain a broad view of engineering and the local movements that inform our study and set the stage for our findings.

Chapter 5 – Findings builds directly off the historical Interlude by first describing the specific ways the Calc 3 and Diff Eq courses have been made durable, how they have been able to persist through the last five decades largely unchanged. We rely on instructor interviews and fieldnotes from class observations to illustrate the overriding stability of these mathematics courses, detailing how the content has remained immutable and how the lecture format has remained the default although communication channels from faculty to students have shifted and expanded in the recent years. By mapping out what is new and what is old, we begin to shift our understanding of these mathematics courses, to see them as amalgams of longstanding traditions, new ideas, and outdated beliefs. Disconnects and new questions are raised, questioning what is actually critical for inclusion in these courses, what can be let go of as resources shift, and what makes sense given the developments in technology and preferences of the current generation of students.

The second and third sections of Chapter 5 – Findings examine this highly durable system of sophomore mathematics from the perspective of the students navigating their way through the courses. The research questions are directly addressed in these sections as ANT concepts are employed to describe the *four moments of translation* that students experience as they are translated through the math courses. Each moment or stage of *translation* involves specific characteristics with unique consequences. We first look at students that are easily *translated,* that fit easily into the existing system and flow through each *moment of translation* without duress. Once the framework of *translation* is explained via those at the centers, we turn our attention to those at the margins, the students who do not flow easily through the *moments of translation,* whose experiences are contentious and fraught along the way. We explore both the official and unofficial views of controversial issues like cheating, learning and being weeded-out, in the context of ANT. Powerful non-human artifacts including syllabi and exams are identified, and their impact on students and student trajectories is discussed. At the close of the findings, actor-networks of sophomore mathematics have been mapped for students that are centralized powerful actors and students who are silenced, ambivalently belonging at the edges and periphery of the actor-networks under investigation.

We conclude with a robust discussion of the findings and their implications for practice in Chapter 6 – Discussion. In Chapter 7 – Recommendations, Limitations, Future Work, and Conclusions, specific recommendations are explained in the context of our data, and are meant to be actionable for administrators, faculty, graduate students, and undergraduate students. Care is given to acknowledge counterarguments and differing interpretations of the data, and potential avenues for future work are described to further explicate the findings of this study.

Chapter 2 – Motivation

This chapter describes the purpose for this study, the reasons we initially became involved in this topic and why we believe this work is impactful. The research problem is introduced as well as historical statistics and description of the social and cultural setting in which our research study takes place.

2.1 How Did We Get Here?

The topic of engineering sophomore year is understudied in the engineering education literature, yet it is a critical time for understanding student development and socialization into engineering cultures. I came across the need to study the sophomore year after attempting an educational intervention within a Mechanical Engineering sophomore gateway course during the fall 2012 semester. Collaborating with Dr. Michael Hannigan and advised by Dr. Daria Kotys-Schwartz, we reconfigured a large 200 person lecture-based course by replacing one lecture period a week with a smaller active learning recitation section, team-taught by a Graduate Teaching Assistant and an undergraduate Learning Assistant. Active learning recitations (comparing two different active learning interventions) were held over the 16-week semester with the intention of increasing student interest, engagement, and confidence with the fundamental course material. Post-assessments including surveys and qualitative interviews revealed that students did not value the conceptual content of the recitations, even though the conceptual content directly aligned with the summative assessments (i.e., exams) in the course and was promoted by the course instructor (Tsai, Kotys-Schwartz, & Hannigan, 2013).

Student resistance to the authentic practice of engineering and their over-valuation of simplistic numerical problem solving as "real engineering" were clues that enticed our interest in students' value structures. Investigating student beliefs and expectations led to questions regarding of what types of students were considered publicly "smart" in these courses, and were afforded academic power and respect by peers—those who were considered "good" engineers. These questions fundamentally concerned the culture of sophomore engineering courses, and how power is distributed and experienced among students and to what effect. The sophomore engineers we spoke to often contextualized the mechanical engineering course we were trying to research by relating it to similar experiences in physics or calculus. In various ranking questions regarding course difficulty, workload, and enjoyment, calculus courses frequently ranked first in the initial two categories, and last in the third. As many students came to engineering majors because of positive experiences in high school math and science courses, we started to see how important the engineering mathematics sequence and science requirements are for setting undergraduate expectations for the rest of the engineering curriculum.

Knowing that by senior year, most engineering students were still not ready to embrace ambiguity in solving open-ended problems, we considered how they arrived as freshmen, educated as sophomores, and trained as juniors. As the freshman or first year curricula of Calculus 1 and 2, and Physics 1 and 2 is not known for encouraging creativity or divergent thinking, we considered what must happen in the "middle years" of engineering for students to be comfortable with uncertainty and problems with no clear solution by their senior year and beyond. At the same time, the engineering education community has advocated for increased awareness of divergent thinking and creativity in undergraduate, particularly with regards to design courses and experiencing the design process (Cooperrider, 2008; Crismond & Adams, 2012). Furthermore, engineering educators have demonstrated that providing open-ended experiences early in undergraduate can help retain students in engineering (Knight, Carlson, & Sullivan, 2007). Yet, it was unclear how much creativity, ambiguity, or open-ended experiences existed in the required math and science classes of the sophomore year.

We chose to focus on the mathematics courses of sophomore year, as these are locally considered 'barrier' courses that can block access to subsequent engineering coursework and degrees. A qualitative research team including Dr. Daria Kotys-Schwartz, Dr. Daniel Knight, and myself was formed in summer 2013 to investigate the cultures of these required engineering mathematics courses along two strategic branches: One branch was concerned with cultural norms and how a normative environment is established in sophomore-level engineering courses, the second branch utilized Actor-Network Theory to identify powerful actors in sophomore engineering and investigate how these actors organize space and time in engineering.

Along the first branch, the research team felt that understanding and identifying the conventional, "taken-for-granted" cultural norms that permeate sophomore-level engineering required courses would be one novel way to understand student value and power structures within these focal courses (Tsai, Kotys-Schwartz, & Knight, 2014). We viewed cultural norms as expectations, beliefs, assumptions, stereotypes and other notions that students, instructors, TAs, and staff members consciously and subconsciously ascribe to and construct dynamically (Carspecken, 1996). We wished to determine how classroom cultural norms are constructed, what actors or actions can change or reinforce a norm, and the impact on students who align with or oppose the normative environment. As such, cultural norms were an organizing concept for our research efforts to illuminate the experiences within sophomore year of engineering that encourage some students to stay in engineering majors and others to leave.

The second branch of research was an alternate path into similar questions of academic power and student value structures, using the lens of *Actor-Network Theory*. As explained further in the Conceptual Framework section, *Actor-Network Theory* is a novel social theory adopted from the field of Science and Technology Studies, helpful for tracing out the power relationships responsible for particular organizations of space and time for groups of humans and non-humans known as actor-networks.

In May of 2014 I presented to my dissertation committee in the format of the Comprehensive Exam, discussing data and research questions pertaining to both branches of our investigation, cultural norms and *Actor-Network Theory*. At that juncture, the committee encouraged me to focus and refine my research, to select one branch of research upon which to center our analysis. As the preliminary findings related to actor-networks seemed richer and more promising than those related to cultural norms, I continued to pursue the research from the standpoint of Actor-Network Theory.

This dissertation is the product of this journey, utilizing *Actor-Network Theory* to interpret the lived experiences of sophomore engineers and uncover underlying power relationships among actors, which organize space and time for salient actor-networks at this level of undergraduate engineering. Adopting the lens of Actor-Network Theory is a novel means to determine what is happening within the sophomore year of engineering that encourages some students to stay in engineering majors and others to leave. While it is unusual for a Mechanical Engineering graduate student to undertake the application of a novel social theory from Science and Technology Studies, I believe it is warranted and in fact long overdue to connect these two fields and see how they can mutually inform one another from an engineering education perspective. This study breaks from traditional engineering education research by incorporating methods from the learning sciences and observing the development of student culture ethnographically through the lens of Actor-Network Theory (Johri & Olds, 2011).

2.2 Engineering Sophomore Year & Retention at the University of Colorado Boulder

The sophomore or second year is a critical period of development for an engineering student. The sophomore year curriculum consists of the final math and science requirements for all engineering disciplines. Students who have difficulty with or fail a fundamental class during their first two years can seriously delay their graduation date or be discouraged from finishing the degree. Such experiences are known to dissuade students and have been correlated with early departure from engineering majors (Seymour & Hewitt, 1997). Nationally, 82% of engineering students return for the second year, while only about 65% continue into the third year; there is a much smaller attrition rate between the third and fourth years (Fortenberry, Sullivan, Jordan, & Knight, 2007).

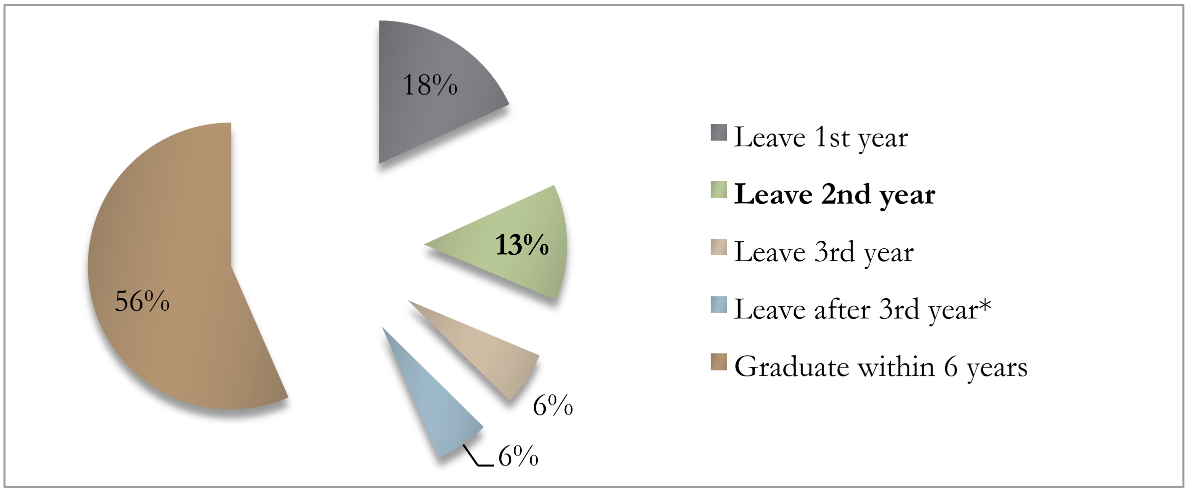


Figure 1: CU Boulder CEAS Graduation and Attrition Rates, Average Over Previous 10-years (* Leave after 3rd year or take greater than 7 years to graduate)

While 82% of students return for the second year of engineering school at the University of Colorado College of Engineering and Applied Science (CEAS), the overall percentage returning for the third year drops to 69% (Figure 1, Office of Planning, Budget, and Analysis, 2012). Engineering educators have focused on curricular interventions to improve the first-year experience (e.g., Sheppard & Jenison, 1997) and studied the development of student cognitive characteristics such as attitudes and skills. However, little attention has been given to understanding the environmental or structural barriers that engineering students face during the second year of their education, a year which represents considerable retention risk in engineering. The courses of the sophomore year mark the descent into "the valley of despair" as students are confronted with a seemingly endless march of technical requirements chained together with little wiggle room for electives or failure (Kotys-Schwartz, Knight, & Pawlas, 2010). The second year features gateway courses that eventually lead to the practice of engineering, courses that initiate students into greater levels of abstraction and analytical engineering problem solving. Consequently, we have chosen gateway courses endemic to the sophomore year as our main study sites for understanding power relationships.

2.3 Mathematics Gateway Courses

All majors in the CEAS require at least four math classes: Calculus 1, Calculus 2, Calculus 3, and Differential Equations & Linear Algebra. As the naming scheme implies, the Calculus courses must be taken in sequential order with minimum passing grades determined by each department (Aerospace and Mechanical Engineering require a C or higher, while a C- or higher is passing in most other engineering departments for a prerequisite course). Students with advanced math preparation may take Calculus 3 or Differential Equations in their first year, while other first-year students begin with Pre-Calculus and/or choose to take a yearlong Calculus 1 course designed to allow more time for students to learn fundamental material. There is immense variety in how and when students proceed through the math sequence, though all engineering majors must pass through each course in order to graduate. As evidenced by departmental curriculum flowcharts and course numbering, APPM2350: Calculus 3 (Calc 3) and APPM2360: Differential Equations & Linear Algebra (Diff Eq) are typically taken during sophomore year. Appendix B provides additional information about each department's mathematics prerequisite requirements.

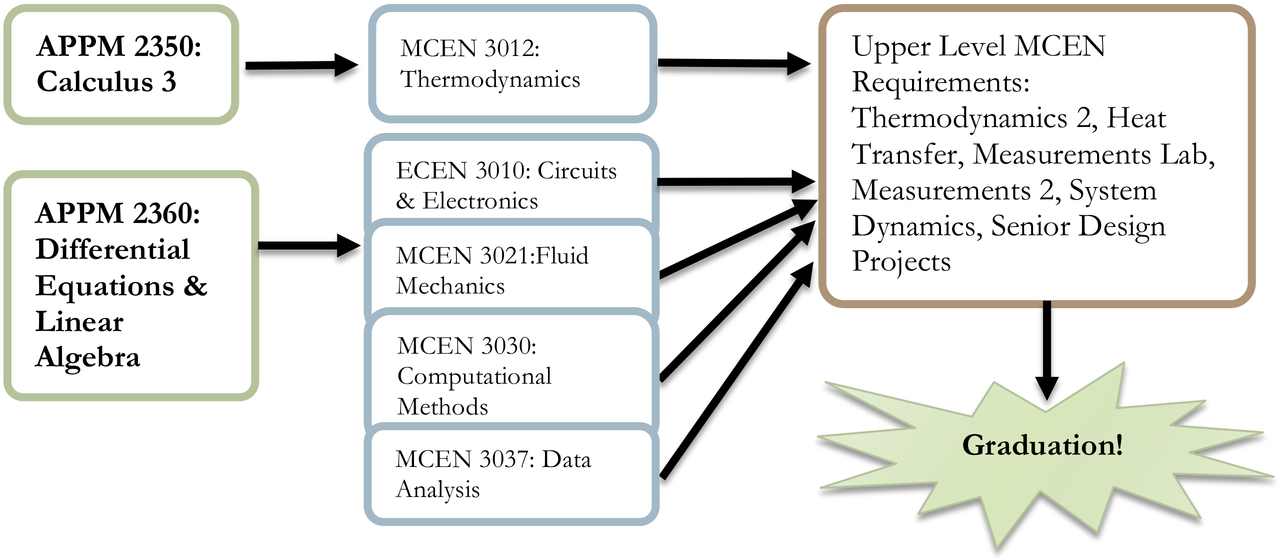


Figure 2: The Rigid Prerequisite Network of the Mechanical Engineering Curriculum

We focus on Calc 3 and Diff Eq because they match our desire to focus on the sophomore year, and because these two courses are the predominant prerequisites for subsequent major-specific technical courses across the CEAS. In the Mechanical Engineering curriculum, for example, Calc 3 is a prerequisite for one required course (Thermodynamics), while Diff Eq is a prerequisite for 4 required courses. In turn, these required courses then serve as prerequisites for the next level of technical coursework, eventually leading towards degree completion (see Figure 2). Consequently, difficulty with or failure in either Calc 3 or Diff Eq can severely impact a student's ability to progress into subsequent courses within their major, causing a compounding effect for students navigating the inflexible curriculum, opening the door to thoughts of attrition. In other words, the engineering curriculum is a rigid network that can only be traversed along officially acceptable prerequisite pathways. No deviations are allowed, as students must achieve passing grades in Calc 3 and Diff Eq before they can proceed towards graduation.

These two courses are also known for being difficult, both in workload and in content, as they mark the transition into more ambiguous and nuanced material. As one instructor of Calc 3 explained to students on the first day of classes in Fall 2013:

> [This class is] somewhere between Calc 1, where everything is perfectly defined, and the 4-year end where nothing is defined and you don't know all the answers… it [uncertainty] has to start somewhere and that is *here* [emphasis added].

This transitional environment is ripe for high-impact educational research and analysis, particularly given the large number of students in each of the courses and the importance of these courses along *every* engineering student's educational trajectory. Examining the five-year average of grade distributions for Calc 3 shows 18% of students receiving a D or F in the course, with an additional 7% receiving a C-. For Diff Eq, 11% of students received a D or F with an additional 6% receiving a C- averaged over the last five years. Given departmental requirements, 15-25% of students are failing these classes. This is another reason to study these sites.

Table 1: Number of Students Passing and Not Passing Calc 3 and Diff Eq Over Last 5 Years

	APPM 2350 Calc 3					**APPM 2360 Diff Eq**				
Semester	# Students	#C-, D, F	%C- D F	#D, F	%D, F	# Students	#C-, D, F	%C- D F	#D, F	%D, F
2009 F	397	88	22%	70	18%	301	62	21%	48	16%
2010 S	290	77	27%	53	18%	368	45	12%	29	8%
2010 F	373	70	19%	61	16%	289	60	21%	48	17%
2011 S	220	44	20%	35	16%	399	60	15%	43	11%
2011 F	389	94	24%	64	16%	301	58	19%	32	11%
2012 S	237	65	27%	48	20%	426	38	9%	19	4%
2012 F	379	86	23%	56	15%	326	100	31%	62	19%
2013 S	239	37	15%	27	11%	447	46	10%	33	7%
2013 F	370	159	43%	111	30%	364	16	4%	9	2%
2014 S	233	73	31%	51	22%	396	123	31%	83	21%

As enrollments in the CEAS are scheduled to grow (in some departments double) over the next few years, engineering educators must be proactive in supporting student survival through the attrition-heavy first and second years of undergraduate. While the first year has been rigorously studied in the engineering education literature, understanding the second year and the climates of gateway courses such as Calc 3 and Diff Eq is critical for understanding the experiences of our undergraduates and how we can best inspire them to remain in engineering (M. Lord, 2014; National Science Foundation, 2014).

Recent scholarship in the field of engineering education has also indicated the critical importance of student experiences in mathematics courses to subsequent completion or transfer out of engineering degrees (Meyer & Marx, 2014). For instance, Meyer & Marx (2014) asked four engineering student 'dropouts' to visually illustrate their journey through engineering on a "journey map" inspired by Nyquist et al. (1999). Math courses feature prominently in two of the four journey maps, depicted as a giant stumbling block or as a nearly insurmountable cliff. One figure is reproduced below for reference, as it visually and unforgettably captures the lived experience of one exemplar student's path out of engineering due in large part to Calc 3 and Diff Eq.

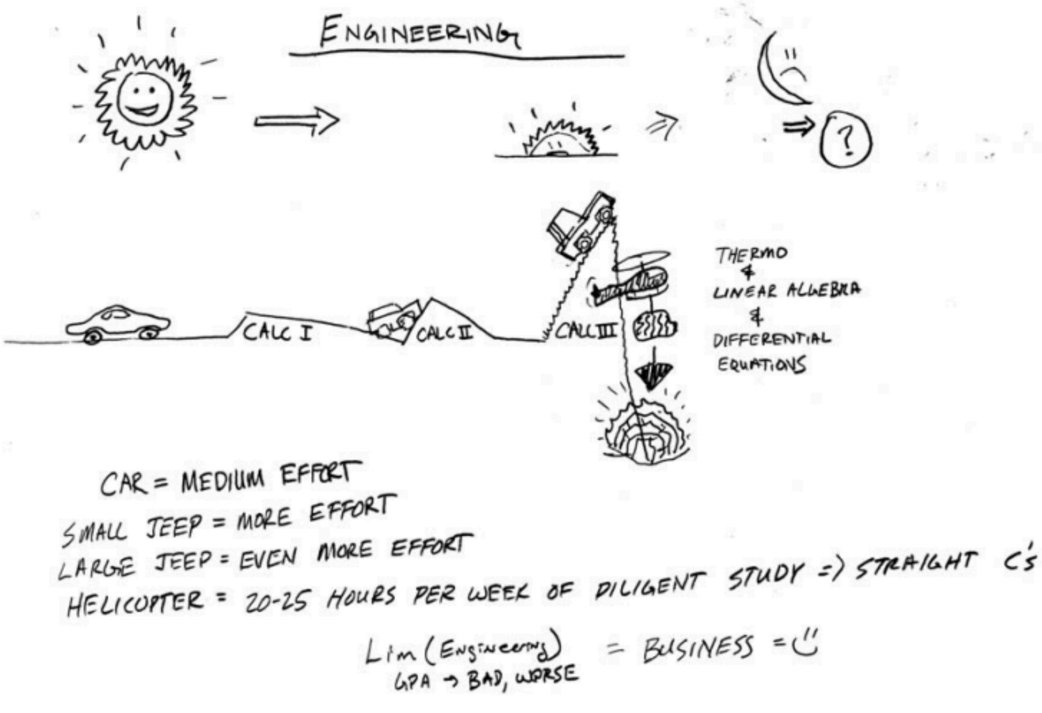


Figure 3: Bob's Journey Map, Excerpted from Meyer & Marx (2014, p. 533)

As shown above, the "even more effort" represented by the large jeep to get over the cliff of Calc 3 was surpassed by the rescue helicopter of "20-25 hours per week of diligent study" resulting in "straight C's" and an eventual crash at the base of the cliff, representing the student's transition out of engineering and into a business major. While Meyer & Marx (2014) provide this visually compelling account of student trajectories out of engineering and how they are impacted by mathematics courses of Calc 3 and Diff Eq, we seek to expand our understanding of student experiences in these courses through ethnographic methods.

The sophomore year marks the transition from well-defined, closed-ended problems into greater degrees of analytical problem solving. Calc 3 and Diff Eq are critical prerequisite gateway courses through which engineering students must pass in order to reach their major-specific coursework. The high failure rates of these courses correspond with severe consequences for the students who do not receive passing grades, as repeating a single mathematics course causes cascading effects through the rigid chain of curricular requirements for an engineering bachelor's degree. This study looks intensively at the social and cultural environments of these courses, investigating how students organize around resources including textbooks, professors, peers, solutions manuals, teaching assistants, and more. While prior research has mentioned and illustrated the impact of math courses on student progress through 4-year undergraduate degree programs, we focus specifically on what happens to students during the sophomore year. The ultimate aim of the study is to understand the organizing conditions for student success or lack of success in passing these critical courses, to better explain how a student can climb over or fall down from the metaphorical cliff of mathematics.

Chapter 3 – Background

The Background chapter contains three distinct subsections, each with a different focus on explaining the current study in the context of prior work. The Literature Review Section reviews prior research on sophomore engineering, the cultures of engineering, and social interactions in engineering school. The literature in these salient areas is discussed with the intention of highlighting our study in contrast with what has been done before, building on the work of others to shed light on important yet previously unexamined phenomena of sophomore engineering. Once the stage is set by the discussion of sophomore year engineering education literature and the social and cultural studies of engineering disciplines and environments, the next section introduces the conceptual framework of Actor-Network Theory. As Actor-Network Theory is a novel means of studying sociocultural interactions in an educational context, this section ties together some of the concepts discussed in the Literature Review section but with much different operating assumptions and perspectives. Following the Literature Review and Conceptual Framework sections, the Research Need section introduces the study's research questions and describes how this study bridges a gap in current engineering education scholarship.

3.1 Literature Review

This section begins with a review of engineering education research focused on the sophomore year, then moves on to discuss studies of engineering cultures and belonging before closing with studies of sociological power and social interactions in engineering. Each grouping of literature informs the current study and refines the lens through which we examine the social environments and cultural interactions of the engineering sophomore year.

3.1.1 Sophomore Engineering Education Research

Engineering education is a relatively new field, with dramatic shifts occurring over the past century in terms of how we educate engineering students and what we perceive as important topics for engineers to learn. One of these shifts has been the purposeful addition of design courses to the undergraduate curriculum (Froyd, Wankat, & Smith, 2012). These team and project-based design courses generally occur in the first “cornerstone” year and/or in senior “capstone” year, while the middle two years of engineering undergraduate coursework have remained relatively untouched since the Cold War era (Harris, DeLoatch, Grogan, Peden, & Whinnery, 1994). Froyd et al. conclude “there is a gulf between student experiences with engineering design in the first year and the capstone culminating experience,” with only a few engineering institutions reforming all 4-years of their curriculum instead of just the bookends (2012, p. 1348). In particular, the experiences of first-year students on design teams have been researched extensively as one means of increasing retention rates past the first year of engineering (Courter, Millar, & Lyons, 1998; Dally & Zhang, 1993; S. D. Sheppard & Jenison, 1996). Similarly, Capstone Design research has spawned its own conference occurring every two years.

In addition to the inclusion of design experiences in the freshman year, many engineering colleges have created first-year programs specifically to aid students transitioning from high school environments to college, which provide some mixture of mentorship, socialization, advising, time management training, and academic help (Budny & Paul, 2004; Crisp & Cruz, 2009; Marszalek, Snauffer, Good, Hein, & Monte, 2005; Mathias & Nicklow, 2007; Mitchell & Daniel, 2007). The first-year of engineering undergraduate has also been the focal point for engineering education research focused on institutional climates and retention, as seen by the growing number of publications submitted to the American Society for Engineering Education (ASEE) First-Year Programs Division, founded in 2004, and the annual First-Year Engineering Experience Conference, founded in 2005 (American Society for Engineering Education, 2014; FYEE Planning Committee, 2014).

Yet, engineering education research studies and academic programs focused on the engineering sophomore year are rare compared to the wealth of attention given to the freshman year. While large-scale longitudinal studies and smaller-n case studies highlighting student trajectories through all 4 years of engineering undergraduate have touched on the experiences of sophomores, very few publications focus exclusively on this critical second year. The articles that do focus on the second year mostly investigate and detail curricular interventions employed in sophomore-level courses, reporting students' performance/grades and instructor opinions of the courses post-intervention (Hollister, Crawley, & Amir, 1995; Starkey, Ramadhyani, & Bernhard, 1994; Wankat, 1999). Several articles discuss the process of integrating design as a learning objective into sophomore level courses, with details regarding curriculum, assessment, faculty experiences, and student course ratings (Carroll, 1997; Starkey et al., 1994; Tsang, 2000). A few studies investigate novel means of peer learning in which sophomore students interact with seniors or compare their knowledge with graduate students, generally focused on conceptual knowledge gains and student feelings of confidence in problem solving skills (Montfort, Brown, & Pollock, 2009; Tao, 1993).

While valuable for engineering curriculum developers and instructors of sophomore year courses, the literature on sophomore year as summarized above takes a generally narrow and positivist view to understand the effect of a single course on a student's grade and/or internal attribute of interest (e.g. confidence in problem solving skills, conceptual knowledge, etc.). The legacy of logical positivism, or the belief that processes including learning and identity develop linearly in a logical progression, remains prevalent in engineering education and engineering education research (Achinstein & Barker, 1969; Duffy & Bowe, 2014; Sismondo, 2010). These positivist studies sidestep the sociocultural elements of these courses, instead focusing on identifying causal relationships between a course intervention and a measurable outcome seen through either instructor or student ratings. Though the individual details of novel curriculum and/or assessment techniques are pedagogically interesting, the reality of many engineering degree programs is that without passionate instructors to implement these novel approaches, the bulk of undergraduate coursework students are hit with in the second year remains unchanged from the longstanding traditions of heavy lecture, problem sets for homework, and make-it-or-break-it exams. These mainstays of undergraduate engineering coursework and the overall focus on engineering science and mathematics has remained unchanged since the end of World War II (Seely, 1999). We feel that examining the environment of these highly durable, competitive gateway courses is particularly warranted for the understudied sophomore year.

With the publication of the 2014 *Cambridge Handbook of Engineering Education Research* (CHEER), the field has acknowledged the relative lack of studies focused on sophomore year and junior year (Johri & Olds). One chapter from the handbook focuses on these middle years (sophomore and junior), again recognizing that the majority of the curricular design of the middle year courses has remained unchanged for decades (S. M. Lord & Chen, 2014). The chapter demonstrates a need for meaningful transformation of the courses that typify the middle years, and the authors declare a research and reform agenda for these middle years of engineering education that includes:

- Research focused specifically on the sophomore year and junior year in engineering. This could build on and contribute to the multidisciplinary discourse on the 'sophomore slump'.
- Engineering educators should be more purposeful and thoughtful in designing educational experiences for the second and third year by integrating content, outcomes, assessment, and pedagogy. Think of it as design. Bring in engineering expertise.

- Make the learner and community an integral part of teaching process beyond the first year. Address diversity as part of the equation, not as an afterthought. Learn from decades of research on gender and race. (S. M. Lord & Chen, 2014)

This three-part call to action for the middle years curriculum is meaningful though not highly targeted. The first part explicitly addresses the need for research on the sophomore and junior years, while the second and third parts are practitioner-based, suggesting actions for engineering educators and administrators. While generally warranted, this call to action is not specific or easily actionable. Well-intentioned engineering educators and administrators of the middle years who wish to enact change have little foundational research to guide them in implementing new policies or new educational experiences.

The National Science Foundation (NSF) has further propagated this call to action on researching the sophomore year. The new "Revolutionizing Engineering Departments" or RED program solicitation included deadlines in late 2014 for proposals specifically addressing the 'sophomore slump' of the middle years of engineering education (M. Lord, 2014; National Science Foundation, 2014). Policymakers and researchers alike thus see the contemporary need to intensively study the sophomore year of engineering, and are taking steps to address the current lack of information on this understudied period in an undergraduate engineer's trajectory.

Our study seeks to address these calls for action and research agendas by focusing on the sophomore year in engineering undergraduate, which remains a critical transition time for students pursuing engineering degrees. Instead of encouraging the continued development and assessment of novel interventions designed to impact the sophomore year, our study inquires into the current state of sophomore engineering, so that we can be informed when making and advocating for changes, or trying to 'revolutionize engineering departments' in line with funding opportunities from the NSF. We wish to examine the social complexity of the everyday lives of sophomore engineers, to unearth the elements that are not accounted for when looking at the impact of a single intervention on a designated class or program. Moving away from cognitive studies that isolate individual factors like 'motivation' or 'self-efficacy' for investigation, we attempt a socio-cultural examination of the lived experiences of sophomore engineering students within complex learning environments. This provides for a nuanced, exploratory study of the individually, socially, and culturally complex intersecting phenomena which constitute engineering education and its adherents. We initiate a new paradigm in engineering education research on the middle years, departing from the intervention-assessment model to conduct innovative research investigating sociocultural relationships across environments, events, and effects on students.

3.1.2 Previous Qualitative Research on Culture and Power in Engineering

Engineering educators, learning scientists, organizational behaviorists, and sociologists have all undertaken qualitative research to better understand aspects of engineering cultures and practices in both workplace and educational settings. Two exemplar studies from the 1990's adopted a qualitative method known as ethnography to make sense of power dynamics within the engineering workplace: Fletcher's *Disappearing Acts: Gender, Power, and Relational Practice at Work* (1999) and McIlwee & Robinson's *Women in Engineering: Gender, Power, and Workplace Culture* (1992). As their titles suggest, both books explore the underrepresentation of women in engineering workplaces through various conceptual frameworks related to power. In the same era, engineering educator Karen Tonso performed ethnographies of engineering students to determine the influence of certain types of engineering culture on women, underrepresented in undergraduate design teams (1996a, 1996b). Perhaps the most influential and well-known qualitative study of engineering and scientific culture was conducted by Seymour & Hewitt and explained in their book *Talking About Leaving: Why Undergraduates Leave the Sciences* (1997). This section reviews the work of McIlwee & Robinson, Fletcher, Tonso, and Seymour & Hewitt, explaining how our study builds on these authors' findings from a different theoretical standpoint.

3.1.2.1 McIlwee & Robinson – Deficit Model of Women in Engineering

Sociologists McIlwee & Robinson combine *gender role* and *structural* theories to introduce their observations that "women are doing well in engineering, but not as well as men…what seems to matter most is which group has the power to define the formal and informal criteria for success – what we call the 'culture of the workplace' " (1992, p.5). The book maps out connections between women's status at work and the corporate definitions for success, drawing contrasts at several specific sites. The *gender-role perspective* considers women's socialization into traditional gender roles (mother, nurturer, etc.) as the main determining factor in the status of women's work while the *structural perspective* utilizes both the structural features of the workplace and larger social structures outside of work (e.g. political and economic systems) to explain women's status at work. Interestingly enough, the book presents the power structure in the university years of schooling as a positive counterexample to the power dynamics present in the engineering workplace. The authors see engineering workplaces dominated by "tinkerers" and overwhelmingly male, to the detriment of women. In contrast, the power dynamics at the university are dictated by faculty who control the culture and success of students somewhat more equally. McIlwee & Robinson explain:

> The culture of engineering as defined in the university is quite compatible with the resources of women students…the emphasis on technical orientation – the image of the tinkerer – is at its weakest. It exists, and the women are aware of it, but it is temporarily overshadowed by the emphasis on math and theory. **This makes engineering school a rewarding experience for most of them**, even though they are bothered by feelings of doubt about their technical skills. (p. 51, emphasis added)

Some 20 years later, facing national retention numbers around 60% of those originally enrolled after 5 years, with the representation of women in engineering still well below 30% nationally, the concept of engineering school being "rewarding" for the majority seems inaccurate (National Center for Science and Engineering Statistics (NCSES), 2011; U.S. Department of Education, National Center for Education Statistics, 2012). At least, it is worth investigating the "culture of engineering as defined in the university" to determine the veracity of McIlwee & Robinson's claim that "the image of the tinkerer" is still being "overshadowed by the emphasis on math and theory," and whether or not the emphasis on math and theory is actually rewarding for today's engineering students. The book concludes with a variety of suggestions for change in engineering schooling and workplaces to better support women, with "recognizing the 'tinkering deficit' produced by female gender socialization" among them (p.181). The concept of a "tinkering deficit" drives home McIlwee & Robinson's deficit paradigm in analyzing the presence of women in engineering, as their book details various ways women are lacking in certain characteristics or preparation, which they must make up for in order to be successful. The long quotation above illustrates this deficit thinking as well, stating that "[women] are bothered by feelings of doubt about their technical skills," thus assuming women lack technical skills and doubt themselves for it.

Instead of adopting this deficit paradigm, our study wishes to trace out the pathways through which a system was set up in the first place that identifies women as deficient in these categories. Instead of identifying what individuals lack, or creating categories of people that lack these prized attributes, we endeavor to look more broadly into the alliances between both people and things that allow this type of evaluative system to be initially established, and how these systems are taken up by participants and reinforced collectively. By fundamentally questioning what it means to "lack" a certain skill or for someone to "doubt" a "technical" skill and how these were defined in the first place, we take a novel perspective into seeing what engineering culture means and how it is produced for sophomore students.

3.1.2.2 Fletcher – Feminist Theory Analysis of Engineering Workplaces

Fletcher's *Disappearing Acts* adopts three different research perspectives as conceptual frameworks to explain gender and power relations in engineering workplaces: *feminist post structuralism, a feminist sociology of work,* and *relational psychology* (1999). While a fascinating book, engineering educators have seemingly ignored Fletcher's novel use of feminist theory to describe engineering workplace power relations, as it is rarely cited in the engineering education literature despite being more recent than McIlwee & Robinson's study. Fletcher explains *feminist post structuralism* as seeing "the production of knowledge as an *exercise of power* where only some voices are heard and only some experience is counted as knowledge," pointing out various ways engineering workplaces formally and informally recognize only certain types of experience as valid knowledge (1999, p. 23). The *Feminist Sociology of Work* perspective combines with the post-structural perspective to bring up serious questions regarding the separation of public/private spheres and men/women's work, respectively, asking "how did it happen that these masculine values of abstraction, rationality, and control dominate organizational life, and what systems of power between the sexes do these masculine norms keep in place?" (1999, p. 26). To help answer this question, Fletcher uses a perspective from *relational psychology* to contrast masculine norms for adult growth and achievement with an alternative model based on women's experiences "called growth-in-connection…rooted in private-sphere characteristics of connection, interdependence, and collectivity" (1999, p. 31). This alternative model interprets specific types of interactions as fostering adult growth, indicated by mutual empathy, empowerment, vulnerability, and the ability to experience and express emotion. Seeing these characteristics as strengths instead of weaknesses in the workplace is a fundamentally different view than what is usually used as evaluation criteria in engineering, and perhaps discomfort with this shift contributes to the lack of attention this work has received from the engineering education community. Nonetheless, Fletcher paints a compelling portrait of women "getting disappeared" in engineering workplaces through normative cultural processes and power relations, which render women's work invisible during promotion or performance reviews while simultaneously rewarding masculine knowledge and masculine work styles.

Our study differs significantly from Fletcher's in that we are studying undergraduate engineers at school and not the professional workplace, but we find much common ground with her study in regards to examining the impact of cultural norms and culturally specific success criteria on all types of students. Instead of setting out with feminist theory and perspectives, however, we choose to utilize *Actor-Network Theory*. This choice of conceptual framework allows for interesting investigations into engineering cultures, environments, and normative practices without the stigma unfortunately attached to feminist perspectives in engineering education. As our primary audience is the field of engineering education, we feel justified in being inspired by Fletcher's work and others with explicitly feminist viewpoints while utilizing a novel conceptual framework that may allow the work to be more easily read by engineers. We also hope that our work will help disseminate and publicize Fletcher's book to the engineering education community so that it can influence other researchers and gain traction for the use of these feminist perspectives in our field.

3.1.2.3 Tonso – Ethnography of Undergraduate Engineering Design Teams

Within the field of engineering education, several ethnographic studies have achieved wider recognition for novel explanations of the experiences of engineering undergraduates and new perspectives on understanding the climates of engineering school with suggestions for improvement. Relevant to our work is the precedent established by Karen Tonso throughout the 90's and 00's, the ethnographies of engineering design teams performed at a state-supported engineering college in the Rocky Mountains (Tonso, 1996a). Her paper titled "The Impact of Cultural Norms on Women" is particularly germane to our work, as it discusses the creation of cultural norms within a sophomore-level design course and the effect of these norms as she observed on two specific student teams (Tonso, 1996b). While this paper does not identify a specific conceptual framework or theoretical orientation to ground the work, it does generally focus on cultures and the importance of engineering culture on student socialization and identity formation – other work by Tonso in the same era identified *situated learning theory* as providing the theoretical foundation (Tonso, 1996a). Overall, Tonso explains what is culturally appropriate in engineering and how engineering classroom practices are influenced, reinforced, and changed, all through discourse/speech heard during her observations. Examples of discourse in two contexts, whole-class settings as well as teamwork settings, are given which explain how engineering culture is constructed by the instructors of courses as well as within engineering design teams, with differing effects on women and men.

In the whole-class setting, Tonso identifies three impactful types of discourse employed by the primary course instructor: profanity in the classroom; semi-sexual, double-entendre humor; and violent metaphors (1996b). These types of discourse, she argues, became "part of the accepted practices of engineering classrooms" as they were used by the instructor in charge of the course and were not challenged or questioned by students (1996b, p. 220). Tonso suggests, "For these women to be accepted in engineering, to fit in and not stand out as different, they must appear to accept these norms and not openly resist or challenge them" (1996b, p. 220). In team settings, meanwhile, Tonso uses several team examples to illustrate how gender makeup of teams can impact the team's working dynamics and normative discourse. Contrasts are made between a 5-person student team with a lone woman versus a 5-person student team with three women, highlighting differences in the treatment of the women on the teams, what was recognized as skills contributing to the team, and how professional dress became a subject of conversation for the team with three women but not the team with a lone woman. Tonso's conclusion here is "women working with men on teams changed engineering practices, but only in very limited ways" (1996b, p. 223).

Tonso's work has undoubtedly influenced what are considered best practices within undergraduate design teams, as her work is a major reason engineering educators prefer creating project teams with women in at least pairs instead of placing a "lone woman" on a team with men (1996a). As one of the first engineering education researchers who employed ethnographic and qualitative methods, a great deal of her work was explaining and justifying these processes to an unfamiliar and skeptical audience. Several other engineering educators have since taken up this mantle, advocating for the potential of qualitative methods to better address key questions in the field (Case & Light, 2011). In the less than 20 years since Tonso published her paper regarding cultural norms and women, the *Journal of Engineering Education* has continued to feature qualitative and ethnographic studies of engineering undergraduate, further attuning the field to standards of qualitative work and recognizing the continued necessity of qualitative approaches to understanding the lived experiences of undergraduate engineers (Baillie & Douglas, 2014). As such, the field of engineering education is becoming more accepting of qualitative research and ethnography, so contemporary studies like ours can require less explanation of the method and can become more nuanced in terms of utilizing conceptual frameworks and novel qualitative analysis processes.

The intensive study of engineering design courses and student teams has been Tonso's main focus throughout her publication record (1997, 1998, 2006, 2008, 2014). Our study differs from her work in study sites and contexts, as we choose to examine lecture-based gateway courses of the sophomore instead of team-based design classes of the freshman, sophomore, and senior years. Where Tonso utilized Lave and Wenger's *situated learning theory* to illustrate how learning occurs through social interaction and participation in communities of practice, we choose to look at the situation a bit differently (Lave & Wenger, 1991; Tonso, 1996a). Instead of looking for causes and motivations in what another person (or collective) did, said or allowed, our perspective sees the individuals involved as part of a vast network of people and things that shape what happens, and how those happenings are interpreted. Specifically, Tonso's analysis of discourse in an engineering design class looked at how male students interacted with their female teammates and how a male professor interacted with his students to create a culture in which masculine speech dominated and women were generally silenced (1996b). The Actor-Network Theory conceptual framework encourages a different outlook on the gendered interactions observed by Tonso, instead examining the different network connections and relationships formed by men and women in the courses, looking to see how varied alliances develop and the accompanying consequences for student movement through undergraduate degree programs. Our analysis looks at sophomore engineering gateway courses, observing interactions among people including students, TAs, and instructors, as well as interactions with things like concepts, assignments, and technologies. Instead of looking for the effect of cultural norms on women in engineering, we are trying to understand how the category of woman affects the development of student actor-networks and to what consequence. That is, instead of choosing the demographic of women to analyze how engineering cultures may effect them, we look at all students, irrespective of their placement on spectrum of gender and analyze how they form actor-networks and how these networks vary.

3.1.2.4 Seymour & Hewitt – Talking About Leaving

Talking About Leaving, published in 1997, remains a landmark work in the field of engineering education and STEM (science, technology, engineering, and mathematics) education literature overall for its longitudinal study of student enrollment patterns over three years at seven different campus sites. Seymour & Hewitt coined the terms "switchers" and "non-switchers" to discuss the students that switched out of STEM majors or remained, finding no significant differences in academic preparation or performance between the two groups. Utilizing surveys and interviews for data collection, Seymour & Hewitt concluded that both switchers and non-switchers complained of poor pedagogy at the university including faculty teaching, advising, assessment practices and curriculum design, particularly compared to their experiences in math and science courses at the high school level. While both switchers and non-switchers complained, the authors determined that the differentiating factor between the two groups was that the switchers were unable/not willing to cope with these factors while the non-switchers were. Switchers cited loss of interest in STEM fields, the belief that a non-STEM major would be more interesting or better educationally, poor teaching by STEM faculty, and feeling overwhelmed by the overly demanding workload and pace of STEM courses and curriculum as their primary reasons for leaving.

Seymour & Hewitt's findings led to their main conclusion that college teaching in STEM majors needs to be improved in order to retain students. One of the main criticisms of their work is that this conclusion is simplistic and does not sufficiently acknowledge the historical, structural and cultural traditions embedded in university STEM majors (Eisenhart, 1998). Consequently, our study aims to integrate the findings of Seymour & Hewitt with greater understanding of the local cultures and cultural norms at play within engineering majors. While Seymour & Hewitt looked at individual student demographics and grouped their student responses into salient categories to explain why and how students left STEM majors, we are not as concerned with identifying individual causal factors for students leaving or staying in engineering. Instead, we are interested in how student actor-networks are formed and expressed in engineering courses, and the accompanying consequences for student progress through course requirements towards eventual graduation. The findings of Seymour & Hewitt indicate that students who switch out of STEM majors are lacking the ability to cope with the poor pedagogy of the university, again identifying a deficit in student characteristics that is to blame for their actions. Our study attempts to get out of this deficit model and deficit thinking, adopting *Actor-Network Theory* to understand how "learning to cope" with poor pedagogy can be viewed instead as a process wherein students form alliances with alternate resources in order to get through required courses or find other actors outside engineering to meet their needs. We seek to understand the effects of this unofficial network organization and how these networks become stabilized and durable within the culture of engineering.

3.1.3 Analyses and Critical Views on Engineering Culture

Engineering culture has been analyzed primarily in connection to strategies for recruiting, supporting, and retaining women or in the context of needing to understand engineering culture in order to transform it. For instance, Godfrey (2001, 2003, 2007, 2014) and colleagues (Godfrey & Parker, 2010) found that much of the research explicitly investigating the culture of engineering has been motivated by women's lack of participation (Dryburgh, 1999; Faulkner, 2000, 2009; Hacker, 1989; Tonso, 1996b). In contrast, Godfrey conducted multiple studies in order to broadly map the cultural landscape of engineering education and, in accordance with Schein's (1985) framework of culture, develop a six-dimension framework to guide subsequent studies of engineering culture. Godfrey's premise is that in order to change engineering culture, we must first identify it in practice and be precise in theoretically defining it instead of assuming that everyone understands culture in the same way. Citing Eisenhart (2001), Godfrey explains how post modernism has challenged the view of cultures as enduring, coherent, and bounded, particularly for educational environments in colleges and universities which feature a wealth of diverse influences that are relatively unbounded. Yet, "though untidy, culture is still useful" (Eisenhart, 2001, p. 20) for understanding the actions and sense-making of individuals living within them. For cultures in engineering education, Godfrey (Godfrey & Parker, 2010; 2014) identifies six dimensions of relevance: 1) An engineering way of thinking, 2) an engineering way of doing, 3) being an engineer, 4) acceptance of difference, 5) relationships, and 6) relationship to the environment. These dimensions are offered as "a practical tool for evaluating and positioning the culture of engineering education," (2014, p. 441) generally a framework for interpreting local cultures of engineering. Godfrey encourages follow-up studies and reflection on questions of local values, beliefs and attitudes, suggesting that any department, discipline or institution endeavoring cultural transformation first consider their understanding of these six dimensions.

Godfrey's fifth cultural dimension, relationships, refers to "the nature of relationships, the 'right' way for people to relate to one another in a culture" (2014, p. 445). This dimension includes the concepts of belonging, fitting in, or sticking out within engineering culture; concepts that have also been researched in connection to identity development and retention in engineering undergraduate degree programs. For instance, feelings of belonging in engineering have been positively correlated with retention in engineering in a variety of studies including Seymour and Hewitt's landmark work *Talking About Leaving* (1997). Belonging and retention in engineering majors have also been connected to student identity formation, with previous research demonstrating that students who are able to forge an identity that belongs with the prevailing culture of their programs are more likely to remain in engineering while those who cannot are more likely to switch out of engineering majors (Stevens, O'Connor, & Garrison, 2005; Stevens, O'Connor, Garrison, Jocuns, & Amos, 2008). Recent case studies of undergraduate engineers have demonstrated unique individuals who survive in engineering majors by adapting their identities to accommodate compromises between engineering cultures and the student's original identity (Danielak, Gupta, & Elby, 2014; Foor, Walden, & Trytten, 2007). Quantitative studies have also shown lack of belonging with engineering culture as a significant factor in a student's choice to leave engineering (Marra, Rodgers, Shen, & Bogue, 2012). Unsurprisingly, relationships and associated feelings of belonging in engineering culture matter for engineering retention.

Other scholars including Riley, Pawley and colleagues (Jaffee & Riley, 2010; Riley, Pawley, Tucker, & Catalano, 2009; Riley & Pawley, 2011; Riley, 2003, 2013) have discussed transformative possibities for engineering culture utilizing critical theories and frameworks instead of Godfrey's cultural dimensions framework. These authors have engaged critiques of mainstream discourses in engineering education, highlighting the ways in which these discourses embrace masculinist and heteronormative values and practices, and perpetuate these values through aspects of engineering cultures. On a related critical note, Cech (2013) challenges two problematic yet dominant ideologies in engineering culture: depoliticization, or the belief that engineering is purely 'technical' and free of social or political issues, and meritocracy, the belief that those who work hard will be fairly rewarded, that inequalities are the result of an orderly society in which talent and effort are all that matter. Cech demonstrates ways in which these two ideologies frame social justice issues as irrelevant to engineering, making it difficult for engineering educators to incorporate social justice meaningfully into engineering courses. Accordingly, Cech advocates for engineering educators to be proactive, confronting these two ideologies, discussing them with engineering students, in order to carve out sufficient cultural for students and instructors to deeply consider issues of social justice.

This study is different than any of these prior examinations of engineering culture – we are interested in many of the same topics, but are guided by a different conceptual framework and are aiming at different targets. While we generally agree with Godfrey that we must understand engineering culture before trying to transform it, we wish to illuminate the formations and arrangements of local actor-networks in engineering, networks that will combine and cut across Godfrey's six dimensions of culture. Inspired by Riley, Pawley, and Cech, we are similarly interested in disrupting the power structures and dominant ideologies of engineering, but first wish to identify how these ideologies manifest in the entrenched curricula of the mathematics courses of engineering sophomore year, and how these ideologies affect the development and organization of actor-networks in this local setting. We learn from these authors' studies of engineering that engineering culture does exist in many forms, extending to New Zealand and other nations in addition to the

United States. These studies also illustrate the impact on retention that feelings of fitting in and belonging with engineering culture can have, and reaffirm our desire to map out actor-networks of engineering to determine the various ways in which we are successfully and unsuccessfully supporting our students today. Generally, this study looks to fill the gap between survey-based research and case studies by examining the cultural and social environments of critical gateway mathematics courses in engineering. By identifying the organizing conditions for engineering actor-networks, we have a fresh angle to study and investigate the relationship between feelings of belonging and student retention in engineering degree programs.

3.2 Conceptual Framework

This section details our use of *Actor-Network Theory* as conceptual framework for the current study. We journey through the Actor-Network Theory literature, moving forward through time as we selectively review studies which explain relevant aspects of the theory, progressively moving towards our work in engineering education. We pick up the story in the mid-1980s, starting with early Actor-Network Theory expressions in the field of Science and Technology Studies. About a decade later, we move towards educational research and see novel applications of Actor-Network Theory entering the twenty-first century. Finally arriving at engineering education in 2010 and afterwards, we see recent indicators that the field is primed and ready to take up Actor-Network Theory as a novel approach to understanding sociocultural issues in engineering education.

3.2.1 What is a conceptual framework?

Engineering audiences may be unfamiliar with the idea of a conceptual framework, though they are a critical part of most research in the social sciences. Generally, a conceptual framework is a set of interconnected ideas or theories about a phenomenon of interest and provides a basis or lens for interpreting relationships between events, observations, experiences, opinions, data, etc.

(Svinicki, 2010). Just as engineers would not undertake the design of a new engine without considering combustion processes, heat transfer, materials science, and more, engineering education researchers do not conduct research without considering theories which scaffold and support the research design, data collection, and interpretation. Conceptual frameworks guide researchers in asking meaningful questions and in putting research findings within existing contexts so that they can be better understood. This study is supported and framed by the conceptual framework of *Actor-Network Theory*, abbreviated as ANT.

3.2.2 Actor-Network Theory from Science and Technology Studies

Science and Technology Studies (STS), also known as Cultural Studies of Science and Technology, is a notable field whose beginnings can be traced back to major thinkers and philosophical debates of the 20th century. STS scholars have continued influence in the learning sciences, educational research at large, and engineering education research as well.

Logical positivism was a philosophical movement that began in the Vienna Circle during the 1920s and spread around the world in the 1930's. The Vienna Circle was a group of scientifically trained philosophers and their counterparts, philosophically interested mathematicians and scientists (Feigl, 1969). Logical positivism represented a revolutionary turn as it broke from the traditions of metaphysics and theology to instead place the methods of physical science and mathematic logic at the forefront of philosophical thinking (Achinstein & Barker, 1969). The logical positivists, including Carnap and Wittgenstein among them, maintained that any scientific statement must be "capable of being in some degree confirmed or disconfirmed by observation"(Ayer, 1959, p. 14). The theorists from this school built on this fundamental tenet to view as valid only knowledge and scientific theory which arose from empirically validated observations (Sismondo, 2010). Other philosophers and theorists later attacked this focus on empirical validation, yet the legacy of the logical positivists remains intact today in the cultures and views of many scientists, mathematicians and engineers, as evident through references to scientific objectivity and 'pure' science.

Scholars in the 1960s and 1970s began to question the assumption of science as 'objective', instead examining science-in-the-making to uncover the uncertainties and contingencies present in the development of scientific 'fact'. The field of Science and Technology Studies developed from a foundational assumption that science and technology are inherently and thoroughly social activities, socially constructed that is, that there is no sacred objective process that makes scientific or technological knowledge different from other knowledge. As summarized retrospectively, "The field investigates how scientific knowledge and technological artifacts are *constructed*. Knowledge and artifacts are human products, and marked by the circumstances of their production" (Sismondo, 2010, p. 10). STS scholars made significant contributions by explaining the ways in which specific social conditions lead to the creation of specific types of scientific knowledge, and by tracing out the pathways through which a single scientist is able to transform the world in their image. Instead of following the legacy of logical positivism in which truth was explained by 'Nature' and error a byproduct of human societies, a new type of symmetry was introduced which advocates for explanations of 'Nature' and 'Society' in the same terms (Latour, 1999). We learn from prominent scholars from STS who have conceptualized, applied, and disseminated Actor-Network Theory*,* initially in the context of the construction of scientific knowledge and now applied to the processes of institutionalized education. We absorb the STS perspective regarding the social nature of science and technology, or *technoscience,* recognizing the situated nature of these disciplines and the historical and cultural legacies that surround the people and institutions involved in developing scientific knowledge, new technologies, and engineering students.

3.2.3 What is Actor-Network Theory (ANT)?

As used in this study, ANT is a standpoint, a set of concepts, a way of looking at social and cultural situations that encourages examination of how heterogeneous items like people, things, courses, cognitive constructs, and more become connected to one another to form a network, the conditions under which these varied connections develop, and how different strong and weak connections are expressed. We purposely endeavor to trace the associations and connections between social elements instead of drawing system boundaries around them for ease of analysis. In other words, this study starts with the sophomore year as the general focus and expands to include all elements that flow in, out, and around this transitional year of engineering undergraduate. A slogan of ANT is to "follow the actors themselves" as they establish diverse and dynamic connections in the social terrain being investigated (Latour, 1987). An actor can be human or non-human, as objects like curricula and textbooks can be connected as meaningfully to other elements in the network as a student to an instructor. Following the heterogeneous actors in this sense means tracing the associations made between all actors and artifacts in a given system, adding new elements as new connections are made and letting go of elements whose connections fade. We employ ANT in this nuanced, exploratory study of the individually, socially, and culturally complex intersecting phenomena which constitute engineering education and its adherents.

The following sections detail ANT approaches utilized in prior research, with specific attention on explaining the concepts and ideas that have influenced our current study and analysis.

3.2.4 Actor-Network Classic Examples & Applications

ANT has been used to analyze a wide variety of situations, from the domestication of scallops to the modern experience of ordering food at McDonalds. This section summarizes a few of the classic works from the early days of ANT (1986-1992), providing a backdrop of studies from STS to compare and contrast our current study of sophomore engineering.

3.2.4.1 Callon's Scallops, Fishermen, and Scientists, 1986

Perhaps the most well known early encapsulation of a scientific situation from an ANT approach was written by Michel Callon and first published in the Sociological Review in 1986. Titled "Some Elements of a sociology of translation: domestication of the scallops and the fishermen of St. Brieuc Bay," Callon's article memorably introduces and defines what is classically known as the central work-process of ANT, *translation* (1986; Fox, 2005). The context of Callon's article is the desire to preserve the population of prized corralled scallops growing in St. Brieuc Bay, as similar scallops had all but died out in the neighboring area of Brest due to marine predators, hard winters, and fishermen who dredged the ocean floor without allowing sufficient time for the scallops to reproduce. The story begins in 1972 at a scallop-focused conference in Brest, France, where it becomes clear that very little is known about the scallops of St. Brieuc Bay, as they have never really been studied by scientists or fishermen. In Japan, however, scallops have been cultivated intensively by means of providing collectors in the seas and oceans upon which the scallops can anchor and be protected from currents and predators alike. As the scallop industry of St. Brieuc has been particularly lucrative, both fishermen and their representatives would like to keep the stocks of scallops in St. Brieuc thriving. Callon explains what happens in St. Brieuc Bay as a process of *translation* that includes four concurrent, overlapping *moments of translation*: *problematization, interessement, enrollment,* and *mobilization.*

Problematization: Callon describes three scientific researchers who attend the conference and become leaders of a research program to keep the scallops alive. These researchers make distinct connections with three groups of heterogeneous actors that become differentially intertwined together in this issue of keeping the scallop population thriving: (1) the fishermen of St. Brieuc, (2) the scientific colleagues interested in the scallops of St. Brieuc, and (3) the scallops of St. Brieuc themselves. As Callon demonstrates, the researchers define the issue of keeping the scallops alive in a way that appeals uniquely to each of the three groups of actors and positions the researchers as an *obligatory passage point (OPP)* through which all interested parties must pass in order to resolve the scallop issue satisfactorily. This is a process of defining identities for each of the groups of actors, as the fishermen are characterized by their economic interest in the long-term availability of scallops, the scientific colleagues are identified by their interest in the advancement of scientific knowledge on the previously unknown development processes of the St. Brieuc scallops, and the identity of the scallops themselves remains unknown yet vital to the success of the researchers' program to keep the scallops alive. The researchers define the problem of keeping scallops alive in a way that attempts to convince the scientists, fishermen, and scallops to work together as allies in order to collectively benefit from the hopeful result of a thriving scallop population. In the language of ANT, this is *problematization* - defining a problem and the allowable actor identities to form alliances and progress through the *obligatory passage point (OPP)* of the research program (Callon, 1999, p. 70).

In the context of our study, the required engineering mathematics courses of Calc 3 and Diff Eq serve as *obligatory passage points* that engineering students must progress through in order to continue with their engineering coursework. The prerequisite dependencies exhibited in curricular flowcharts make this positioning unmistakably clear: students must pass these courses or else they will not be engineers, their identities as engineers are partially defined by their ability to do math. This is *problematization* in undergraduate sophomore year.

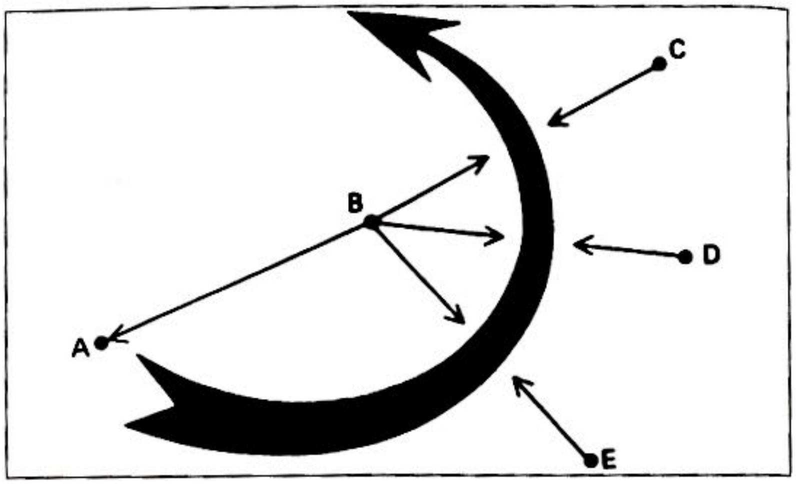


Figure 4: A Diagram of Interessement, A interests B by cutting off ties to C, D, and E (Callon, 1999, p. 72)

Interessement: The alliances between actors, which were initially defined through the *problematization* process, become strengthened via the devices of *interessement.* This occurs both by strengthening the connections between actors and by eliminating possibilities for alliances with anyone (or anything) else. As Callon puts it, "to interest other actors is to build devices which can be placed between them and all other entities who want to define their identities otherwise" (1999, pp. 71–72). In the narrative of the scallops of St. Brieuc Bay, the scientists and researchers devise a physical collector device to be placed on the sea floor that provides space and shelter for larval scallops to adhere to and be protected – to Callon, this is a literal device of *interessement.* Each time a larval scallop adheres to this collector device, it is robustly connected to the collector and the research program instead of an alternate natural actor like the sea floor, a sea rock, a starfish, etc. The alliance between the scallops and researchers is then a physical connection, locked into place. When *interessement* is successful - if the scallops do adhere to the collectors in large quantities - the validity of the *problematization* suggested by the researchers and the alliances of actors including fishermen and scientists is confirmed.

Interessement in our study appears through the time-intensive workload of Calc 3 and Diff Eq, and engineering in general. The 'greedy curriculum' of these mathematics courses effectively cuts engineering students off from alternate pursuits or interests, as there is little time to spare for extracurricular clubs, sports, or socializing with non-engineers (Nespor, 1994). As these courses are also mandatory *obligatory passage points (OPP)*, engineering students must be *interested (interessed)* in passing these courses if they wish to progress through the curriculum towards eventual graduation with an engineering degree.

Enrollment: The flipside to the strengthening of allies as described in *interessement* is that alliances between actors are never certain, as human actors like the fishermen and scientists can change their minds and non-human actors like scallops can change their anchoring habits. Callon defines the third moment of *translation* as when actors actually become *enrolled* in alliances and partnerships, as what started as questions and suggestions of identities and interests become definitive statements which are certain: scallops do anchor on man-made collectors on a sea floor, the fishermen do want to restock the bay with scallops, the scientists do care about how scallop larvae develop in St. Brieuc Bay. "*Interessement* achieves *enrollment* if it is successful. To describe *enrollment* is thus to describe the group of multilateral negotiations, trials of strength, and tricks that accompany the *interessements* and enable them to succeed" (Callon, 1999, p. 74). Put another way, *enrollment* includes the details, the back-and-forth pushing and pushing back required to stabilize and make durable relationships, alliances, or partnerships of any type. In the case of the scallops, the *enrollment* is complicated by the conditions of the sea, which tangle up some of the towlines connected to the collector, preventing scallops from adhering to the research program. For the scientists, their *enrollment* came at the price that the researchers recognize the prior work done in Japan that indicated that scallops would adhere to man-made collectors provided for them. The *enrollment* of the fishermen is slightly different, as they were not particularly interested in the research program but in its results; hence they were waiting for the final verdict from the scientists and researchers alike.

Enrollment in our study occurs at multiple levels – students who are *interessed (interested)* in progressing past Calc 3 and Diff Eq must do their homework, complete projects, and most importantly, study for and pass exams. Students' *interessement* is confirmed through the official processes of grading, of passing midterms and final exams, and thus becoming *enrolled* into subsequent semesters and junior year. Each assignment/test is an opportunity for negotiation between student and instructors, *interessement* and *enrollment*. In engineering sophomore year, *enrollment* takes the form of passing grades on transcripts, institutional recognition that a student has appropriately adhered to their undergraduate engineering coursework and can proceed to the next phase of their education.

Mobilization: The fourth moment of *translation* examines how the enrolled and allied actors in question are mobilized through representation – how the actors are able to speak at a distance in different places, frequently through a spokesperson or written inscription. The scallops themselves are a striking example of this *mobilization*, as the entire population of scallops in St. Brieuc Bay are represented by the few larval scallops which the scientists found clinging to collectors, once the collectors were dragged up and onto the shore. These representative scallops are taken by the scientists, researchers, and fishermen as speaking for the masses; since a few scallops adhered then it follows that all scallops can adhere. These adhering scallops are counted and analyzed, converted by scientists into written inscriptions like figures and tables, which can then be *mobilized* into scientific publications. This process, this chain of *mobilizations*, results in the researchers and scientists speaking on behalf of the scallops, supported by their displays of data, which can be traced back to individual scallop representatives. Callon describes a symmetrically related process occurring for the fishermen, as their representatives are elected by the few from the population that submit votes into official ballot boxes, which are then counted and analyzed to declare whom shall serve as the official spokesman. For both groups of actors, scallops and fishermen, "A series of intermediaries and equivalences are put into place which lead to the designation of the spokesman" (Callon, 1999, p.

77). The point is that at each stage, the spokespeople are more *mobile* than the groups that they represent. A table or figure is much easier to transport than a collector with some scallops stuck on it, an individual fisherman is easier to meet with than the entire group of fishermen. For the scientists, it follows that the scientific articles produced are mobilized in publications, on discrete pages that can be passed from person to person, travelling more easily than the people who performed the research or the lab equipment and specimens that the research represents.

In this study of sophomore mathematics prerequisites, *mobilization* occurs in several ways. The process of condensing a semester of work, learning, and student experience into a single letter grade is one example of a chain of *mobilizations* that results in one highly mobile representative, the final course grade, encapsulating many subsidiary events and assignments. Occasionally these representatives are wrong, in the cases of students passing classes without really learning the material, or vice versa - students failing the classes due to test anxiety or other causes while possessing adequate command of the material. *Mobilization* in this context can also refer to the vast amounts of resources that are enlisted in the efforts of teaching and learning Calc 3 and Diff Eq: the many graduate teaching assistants (TAs) that are required to administer recitations, office hours, and teach the lab courses which enable students to learn the required software for completing course projects; the hours and hours of grading performed by the instructional staff in order to assign representative grades to each assignment, test, and overall; and the number of lecture halls, classrooms, help rooms, online resources, and more that provide space for instructors to teach and students to learn as they circulate through these spaces throughout a given semester.

In 1974 a second conference is held in Brest, France, featuring the researchers of St. Brieuc Bay, serving as spokespeople for the scallops, fishermen, and scientists alike, presenting their result that scallops are indeed adhering to the collectors as hypothesized. Viewed through the four moments of *translation – problematization, interessement, enrollment, mobilization* – this demonstrates how "a constraining network of relationships," or an *actor-network*, has been built (Callon, 1999, p. 79). As the story continues and time passes, however, the shifting dynamic nature of this *actor-network* is revealed as each actor changes alliances. The scallops stop following their initial larval representatives, refusing to adhere to the collectors placed in the bay during subsequent years, bringing into question how representative those initial spokes-scallops truly were. Perhaps it was just a fluke, an anomaly that those few scallops ever connected with the collectors, that the scientists and researchers unfortunately mistook for a representative sample (and a stable alliance). Meanwhile, as the years go on, the fishermen similarly betray their spokesmen, as a group of fishermen long-starved for a bountiful haul of scallops to sell on the market can no longer be patient and wait for the restocking of the scallop population in the bay. As the story goes, the scallops are "shamelessly fished, one Christmas Eve, by a horde of fishermen who could no longer resist the temptation of a miraculous catch" (Callon, 1999, p. 80). In doing so, the fishermen are severing their alliance with their spokesman and with the researchers, scientists, and research program overall. The *actor-network* that appeared stable in 1974 dissolves quickly once the scallops and fishermen betray their representatives.

The takeaway ideas from this story of scallops, fishermen, and scientists are deceptively simple: both humans (fishermen, scientists, researchers) and nonhumans (scallops), the social and natural, operate together and must be considered together, all at once, instead of separately. The interests of both natural and social actors are constantly in flux, unpredictably changing and altering their relationships with other actors and changing the organization of the overall (actor-) network. *Translation* is the entire process, in which disparate actors are transformed, convinced, selected, and mobilized to join a network. The scallop story serves as an example of this process:

> At the beginning, these three universes were separate and had no means of communication with one another. At the end a discourse of certainty has unified

> them, or, rather, has brought them into a relationship with one another in an intelligible manner. But this would not have been possible without the different sorts of displacements and transformations presented above, the negotiations, and the adjustments that accompanied them. To designate these two inseparable mechanisms and their result, we use the word *translation.* The three researchers translated the fishermen, the scallops, and the scientific community. (Callon, 1999, p. 81)

The mechanisms of *translation* are different for each unique combination of interests, entities, and settings, yet the overall concept is relevant for examining the relationships common in the modern world. For sophomore engineering, we will see how the students, course materials, curriculum, and more are collectively translated by the administration and educational system, and the consequences of this translation process for an engineering education.

3.2.4.2 Star's Allergy to Onions, 1990

In the years following Callon's article, Actor-Network Theory expanded rapidly with the influential works of Bruno Latour. Latour's book *Science in Action: How to Follow Scientists and Engineers Through Society,* establishes the "rules of method" and "principles" for utilizing Actor-Network Theory in studying (researching, understanding) scientific controversies, the creation of facts, and technological innovations (1987). Among his ideas:

- The concept of being *black-boxed*, a process in which something (e.g. course testing practices) is rendered such that, "no matter how controversial their history, how complex their inner workings, how large the commercial or academic networks that hold them in place, only their input and output count" (Latour, 1987, pp. 2–3).
- *Symmetry* between *heterogeneous* actors, an insistence on not imposing "any distinction between 'things' and 'people' in advance (Latour, 1987, p. 72).

- The well-known aphorism: “Science is politics by other means” (Latour, 1988).

These ideas revolutionized Science and Technology Studies and opened up new sociological possibilities in studying how networked systems become durable and widespread, exemplified in Latour’s telling of how Louis Pasteur built his empire by creating new facts and technologies which went on to permeate France and beyond. Similar to Callon’s description of researchers tying diverse interests together in the name of scallops, Latour describes how Pasteur linked the heterogeneous interests of three groups: the farmers to whom he brought healing, the statisticians who took up his method of accounting for data, and the public health workers that combined his theory of disease transmission with their medical research (Latour, 1988). Latour applied Actor-Network Theory to reveal Pasteur at the center of the network, doing the work of *translation* to robustly link together these groups of different interests.

Latour’s stories of such scientific exploits focus on protagonists like Pasteur in power, at the center of the creation of knowledge, not those actors at the margins of the story. In contrast, Susan Leigh Star saw these marginalized actors as an important yet missing part of the Actor-Network metaphor as applied so far, and in 1990 published one of many articles and thoughts concerning how Actor-Network Theory could and should be expanded to further illustrate power differences and effects. Heavily influenced by “feminist and interactionist analyses of power and technology,” Star points out the need to look not only at those central to the story, but also those that are outcasts or somehow excluded from participation (1990, p. 29). Taking up concepts of multiplicity in identity and social roles, Star explains the concept of *invisible work* performed by marginal entities that are quickly forgotten about once a process or technology is *black-boxed* and taken for granted. Star advocates for moving among the variety of perspectives held within a network, uncovering the viewpoints of the laboratory technicians, janitors, wives, and others at the margins that enabled Pasteur to be seen at the center of this powerful new network. Seeing, acknowledging, investigating the multiple points of view involved in one phenomena entails doing more than just adding on new perspectives to an otherwise monolithic model, but is "using multiplicity as the point of departure for *all* analysis" (Star, 1990, p. 34).

To uniquely illustrate "the problems of standards and invisible work," Star uses her own experience of being seriously allergic to onions (p. 34). This allergy is invisible yet pervasive in everyday life, hence "it is a good vehicle for understanding some of the small, distributed costs and overheads associated with the ways in which individuals, organizations, and standardized technologies meet" (p. 34). A counterpoint to her onion allergy is the stable, durable, and standardized experience of eating at McDonald's, the international fast-food chain juggernaut. Star recounts two distinct experiences in which asking for 'no onions' on a hamburger caused delays of upwards of 30 minutes each visit. She recalls, " 'Oh,' I said to myself, I get it. 'They simply can't deal with anything out of the ordinary' "(p.35). As Star suggests, if there was sufficient number of similar people with an onion allergy, McDonald's would develop 'some institutionalized process' to signal a difference and/or provide options as with vegetarians and those who keep halal or kosher diets. Star cautions, however, against believing that organizations and technologies can endlessly differentiate to address the full spectrum of individual needs, stating instead "there are always misfits between *standardized* or *conventional* technological systems and the needs of individuals" (p.36).

Star sees the power of combining feminist analysis and Actor-Network Theory to highlight not just how an empire like McDonald's was built in the first place, but also how it 'might have been otherwise,' that there is nothing "necessary or inevitable about any such science or technology" (p. 38). The inclusion of onions at McDonald's is a *convention*, a *standard*, but it did not have to be that way. Star encourages questioning the *'distribution of the conventional'* to recognize that "part of the public stability of a standardized network often involves the private suffering of those who are not standard – who must use the standard network, but who are non-members…" (p.43). Bringing attention to the private suffering of these non-members is one means of expanding the focus of an actor-network study, looking away from the center to see the diversity or multiplicity of those not fully included. Further, realizing the consequences of not belonging or fitting in with a standardized network illuminates the underlying power dynamics, which scaffold the creation of *conventions, standards*, and *stabilized networks* in the first place.

Star's conclusion that "Power is about *whose* metaphor brings worlds together and holds them there," has profound implications for how to conduct an actor-network study and how we conceptualize actor-networks and connections between heterogeneous actors (p.52). We take away from her work a renewed desire to look not just at the center of stable actor-networks, but also towards the margins, for actors at all levels of inclusion and exclusion. Instead of assuming that identities are singular and non-contradictory, we prepare ourselves to accept *multiplicity* and the accompanying complexity. Inspired by Star, we question how durable systems got that way in the first place, and seek alternates.

3.2.4.3 Latour's Aramis, 1992

Finally, we arrive at Bruno Latour's *Aramis, or the Love of Technology* (Latour, 1992a [french], 1996 [english translation]). I have chosen this work to summarize last in this section as it ties together the *four moments of translation* as introduced by Callon and the scallops and takes up Star's criticisms gamely, in the format of a story about a technology that was never actually made. *Aramis* is the code name given to the novel automated personal rapid transportation project with roots tracing back to 1969, that was conceptualized, prototyped, tested, scaled, funded, and finally terminated in 1987 before actually being built (Latour, 1996, pp. 12–15). The book is written in a unique way that Latour named *scientifiction,* a hybrid word representing a hybrid style which intermixes at least three distinct narrators and typefaces: a young engineering student, novel to sociological research, assigned to study *Aramis* under the guidance of an STS advisor; his advisor who provides a running and experienced commentary as the project unfolds; and verbatim primary-record accounts (interviews, transcriptions, artifacts) which explain aspects of *Aramis*. Occasionally *Aramis* itself speaks aloud too, a fictive liberty taken by Latour in the name of *scientifiction*. While many of Latour's works focus on science-in-the-making, *Aramis* is a fundamentally an engineering project and a story about the engineering process. Consequently, those familiar with engineering will hopefully find aspects of *Aramis* that ring true, even through the lens of ANT.

Many other foundational ANT works by authors including John Law, Michel Callon, Langdon Winner, and Madeleine Akrich concentrate on science instead of technology or engineering as well (Akrich, 1992; Callon, 1980, 1991; Law & Callon, 1988, 1992; Law, 1991, 1992a; Winner, 1986). *Aramis* is in this sense an outlier for being written entirely about an engineering project, even among Latour's books. For instance, Latour's more recent *Reassembling the Social: An Introduction to Actor-Network Theory*, acknowledges sociological history and refutes alternate approaches to sociology of science and technology before expounding abstractly on the application of Actor-Network Theory (2005). *Aramis* is different, focused on explaining the techno-social mystery of the novel personalized rapid transit project that was all at once feasible yet simultaneously impossible; a case study in how a technology was un-made instead of made. Furthermore, *Aramis* remains contemporary in the United States as we continue to theorize about the possibility of constructing new public transportation systems, and relevant locally as a public transit railway between Boulder and Denver remains forever on the table for future development (Aguilar, 2013).

Latour introduces *Aramis* in the context of an engineer, Bardet, a founder of the *Technical Automation* company and one of the two inventors who come up with the idea of *Aramis* to begin with. Bardet's vision of *Aramis* is a fully automated, modular, personal transit device which picks passengers up at their doorsteps and then delivers them safely to their destinations, automatically coupling with other automated Aramis cars along the route before decoupling as necessary to reach any final destination. Bardet recruits partners who are interested in his novel personalized rapid transit solution, and convinces them his solution and his solution alone (Aramis) can solve the problems of French traffic congestion. In doing so, he is situating himself, his expertise, his company, as the *obligatory passage point* for the resolution of this contemporary issue, and is performing a nifty trick of *problematization* by defining the problem and the allowable identities for partners who believe in his solutions. As Latour explains in the voice of the experienced advisor:

> People always wonder how a laboratory, or a science, can have any impact at all on society, or how an innovation arises in the mind of its inventors. The answer is always to be found in the chains of translation that transform a global problem (the city, the century) into a local problem (kinematics, continuous transportation), through a series of intermediaries that are not 'logical' in the formal sense of the term, but oblige those who are interested in the global problem to be come interested, through a series of imperceptible shifts, in the local solution (1996, p. 33).

Thus *Aramis* is introduced in the context of Actor-Network Theory and the process of *translation.* By explaining Bardet's sell to investors and politicians, Latour demonstrates how Bardet sets up the problem, defining it in a way that puts him directly in the path of innovation.

Next up is *interessement*, or how Bardet as an engineer and innovator *generates interest* among diverse actors. Latour describes how "innovations have to interest people and things at the same time" and how "assemblages of things often have the same uncertain nature as groups of people" (1996, p. 56). The things that must be assembled to render *Aramis* a reality include motors, sensors, software, electricity, circuits, doors, activators, cabins, seats, and more. Latour draws parallels between soliciting involvement from these inanimate things as well as from the social organizations – the companies, the airports, the government organizations that must work together and be committed to the project in order for it to succeed. The experienced advisor explains, "The full difficulty of innovation becomes apparent when we recognize that it brings together, in one place, on a joint undertaking, a number of interested people, a good half of whom are prepared to jump ship, and an array of things, most of which are about to break down" (1996, p. 58). Anyone who has pleaded with a computer to behave or begged a program to run without errors can likely understand what Latour is getting at in the above description; not being human does not prevent an object from not cooperating. Further compounding the difficulty of innovation is the diversity of users who test the system at every turn. For *Aramis*, for example, engineering designers need to make sure people will not get stuck in the doors and that the transit switches cannot get stuck 'on'. They need to make all of the systems failsafe, foolproof, "idiot-proof" in the words of Latour's expert narrator, as any robust and successful system design includes the "*taking into account* of an infinite number of unanticipated details that have to be mastered or done away with one by one" (1996, p. 72). This need to take into account an infinite number of details is also reflected in the educational system; in the myriad ways students come up with questions, special situations, conflicts, travel needs, emergencies, and more that instructors and educators must respond to at every turn. As shown in the tale of *Aramis*, this *taking into account* is part and parcel of *generating interest*, moving towards *translation*.

The flipside to *interessement* is *enrollment*, how alliances become stable and held in place within actor-networks. Through *Aramis,* Latour is able to speak out against the idea of *inertia* as a social quantity that restricts action or stabilizes relationships, instead stating that it's a word "inspired by sheer cowardice, [behind which] there is the ongoing work of coupling and uncoupling engines and cars, the work of local officials and engineers, strikers and customers" (1996, p. 86). Instead of using social *inertia* as an explanation for the ubiquity of certain technologies, Latour and his narrators look for the allies, friends, and the 'long chains of translators' that enable technologies to stay alive.

According to them, “All you have to do is reconstruct the chain of permissions and refusals, alliances and losses, to understand that a project may not budge for a hundred years or that it may transform itself completely in four minutes fast” (1996, p. 88). For *Aramis*, this chain of permissions and eventual refusal can be traced both to human actors who voted for the project and funded it for decades before changing their minds and striking it down, and to the non-human actors in the form of mechanisms, circuits, and devices that worked in the laboratory or at the prototype track before refusing to work on a larger scale. The researchers in *Aramis* uncover these changing alliances just as in this study we attempt to locate alliances and see the conditions under which they remain durable (staying at the prototype track) instead of being broken (when they try to scale up *Aramis*). This argument is further extended to *time*, as *time,* like *inertia*, are quantities to which much social activity is attributed, but which Latour believes are mistakenly put in this place of causation:

> In fact, time does not count. Time is what is counted. It’s not an explanatory variable; it is a dependent variable that needs to be explained. It doesn’t offer a framework for explanation, since it is an effect that has to be accounted for among many other, more interesting ones. Grab calendar time and you’ll find yourself empty handed. Grab the actors and you’ll get periodization and temporalization as a bonus (1996, pp. 88–89).

This peculiar perspective on *time* is instructive for this study, and will re-emerge later on in the context of sophomore engineering mathematics courses. When the *Aramis* project is eventually terminated, it can be seen as a breaking of alliances and severed *enrollments*, instead of being attributed to social *inertia* or the passage of *time.* At least, that’s what Latour and his narrators would say, and a novel spin on conventional explanations that we wish to explore in the space of engineering sophomore year.

Finally, we investigate what it means to be *mobilized* in the situation of *Aramis*. As the story concerns a novel method of transportation, there is a literal *mobilization* that the story's *actors* are moving towards. However, the technology is never fully realized or implemented, as each of the subsidiary component *actors* begin to betray their spokespersons, as they cease to remain *enrolled* in the network. In Latour's interpretation, this is partially because the *Aramis* technology was not flexible enough to withstand the *translations* necessary at every stage to satisfy the needs of all the *actors,* it could not adequately *take into account* the spectrum of complaints, requirements, specifications, and political desires that were demanded of it. In seeking the eventual cause of *Aramis's* death, Latour offers the following words in the perspective again of the expert advisor:

> A technological project is not *in* a context; it gives itself a context, or sometimes does not give itself one. What is required is not to 'replace projects in their context,' as the foolish expression goes, but to study the way the project is contextualized or decontextualized. To do that, the rigid, stuffy word 'context' has to be replaced by the supple, friendly word 'network.'… To get rid of one's own responsibility, the big explanations are useful; but as soon as one stops trying to blame someone else, these big explanations have to be replaced by little networks (1996, pp. 133–134).

The work of the researchers, both novice and expert in Latour's story, is to find all of the 'little networks' which can explain the death of *Aramis*, not the 'big explanations' that are written up in newspapers or given in official speeches. Latour points out that all decisions, big or small, can be traced back to a 'little network' that gathers somewhere – be it people in a room making a choice, or a mechatronic system that works or breaks together, with resulting consequences. As the student in Latour's story complains about the endless work required to chase down the trails of all of the 'little networks' instead of accepting the 'big explanations', the experienced advisor soothes him by explaining that they will stop when the actors stop, that not everything is connected to the same networks. This description of replacing 'big explanations' with 'little networks' is exactly what we are trying to do in this study, as instead of taking the statements made by professors, TAs, or students at face value, we seek to trace out the 'little networks' that stand behind them. Investigating how these 'little networks' come to act at a distance, *mobilized* in explanations or contexts, is the task of Latour's protagonists in *Aramis* and our task in this study as well.

From *Aramis* we see how Actor-Network Theory can be applied convincingly to the analysis of engineering projects. We see the *four moments of translation* exhibited in groups of people and things, fully symmetrical. Also, we take away a simple method for highlighting chains of translation and the shifts in meaning and definition that occur along the way, a strategy for tracing change by writing out "a list of the most significant interpretations" of *Aramis* or any object under study:

> 1. Aramis has been perfected and will be built soon.
>
> 2. Aramis has been perfected but is too expensive for industrial construction.
>
> …
>
> 6. Aramis has been perfected and is very expensive, but has been abandoned politically by the local Parisian elected officials despite the support of the ministries concerned with technology.
>
> …
>
> 15. Aramis cannot be perfected, but pieces of Aramis have been perfected and have repercussions for other activities.
>
> …
>
> 19. It is impossible to judge. The question of the technological possibility of Aramis is a black box. … (1996, p. 277-278).

All in all, the novice researcher lists out 21 interpretations of what *Aramis* is, and each interpretation is wholly 'true' based on the account of at least one informant – this is one way to trace out the *multiplicity* of specific actors. Looking over the list of interpretations coupled with a document dated one month before *Aramis* is officially killed, the researchers are able to come to the conclusion that there was no single person responsible for *Aramis's* death, rather it was a mutual action, or lack of action, which caused the project to be terminated with nothing to show for it at the end of ~20 years of development. As the expert advisor says, "…there's no scandal, no wrongdoers. It's a collective drift, there were only good intentions" (1996, p. 298). While the education system under study is not exactly a terminated project along the lines of *Aramis*, there may be a 'collective drift' despite 'good intentions' that we wish to uncover. Unpacking how this drift occurs, how the actors at hand interpret it, is our mystery to investigate.

3.2.5 Actor-Network Theory in Education

From the classic studies of ANT in STS we move towards more recent applications of ANT in education and educational research. Again, we highlight 3 specific works from the ANT canon for detailed review in this section, recalling the work of Callon, Star, and Latour but focused in the arena of students, learning, and educational systems instead.

3.2.5.1 Nespor 1994

Jan Nespor is an educational anthropologist whose book *Knowledge in Motion: Space, Time and Curriculum in Undergraduate Physics and Management* serves as inspiration and model for our use of ANT in this study to understand the conditions that shape the dynamic actor-networks of undergraduate engineering (1994). Nespor studied two undergraduate programs, physics and management, explaining the distinctive processes that enrolled students into disciplinary networks with unique educational trajectories in both physical space and time. The undergraduate physics program described by Nespor has many parallels to the undergraduate engineering program of our study, particularly with regards to the rigid course sequencing and prominent material spaces of lecture halls, austere buildings, and depersonalized textbooks. Nespor uses ANT to illustrate how the learning processes of physics students can be thought of as changes in the organization (both temporal and spatial) of student actors and networks. Here, the operational definition of actor-networks is given as "fluid and contested definitions of identities and alliances that are simultaneously frameworks of power," indicating that these networks are always shifting and changing but hold different consequences for members who belong to these networks at various levels, in various places (1994, p. 9). Specifically, Nespor gives examples of different sites and events of undergraduate physics, which influence the educational trajectories of the students.

As told by Nespor, the physics building itself is a primary example of a material (physical) space that organizes student activities and student networks through its unwelcoming appearance, mislabeled offices and closed doors, and small spaces designated for undergraduate use. The few physical spaces undergraduates were allowed to access effectively narrowed the possibilities for where they could go to work or socialize, a phenomenon Nespor calls "compression of space-time" (1994, p. 30). This compression is further illustrated through the nationally standardized undergraduate physics curriculum, which severely constricted the allowable identities and interests of physics students by mandating certain emphases on physics, math, and chemistry courses, leading to a globally accepted 'canonical' progression of undergraduate coursework. Nespor explains how the prevalence of weed-out courses at introductory levels in the physics curriculum further narrowed and compressed the student body, as a 25% failure rate was typical (1994, p.32). The sheer difficulty and workload of these weed-out courses monopolized student time from the freshman year onward, continually narrowing the possible activities a physics student had time for, effectively shutting physics students out of alternative, non-physics networks through the processes of *problematization* and *interessment.*

In addition to the social and human aspects of the physics actor-network that restricted student time and access to alternative student networks, artifacts and non-human elements also acted within the actor-networks to constrain and organize student trajectories through the program. Nespor describes the roles of artifacts including textbooks, note taking, and exams, in creating representational practices of physics that could be mobilized for use in actor-networks across the globe. For instance, Nespor explains how the use of everyday, real-world examples in physics classes can be interpreted as a process of *translating* a concrete, physical experience (like seeing a ball drop under the force of gravity) into the abstract symbolic language of idealized physics, equations and variables. Once encoded into this specialized language of physics, the once-familiar life experiences become a different type of entity that exists separate from personal experience and can only be accessed from the vantage point of physics – in this way, the equations and symbols become enrolled as "actants" or elements within the physics actor-network (1994, p. 59). Lectures, the process of taking notes, homework assignments, and exams, are additional examples of how the once concrete experiences of real life became abstract representations of physics in specific ways with increasingly limited access to outsiders.

To summarize the actor-network of undergraduate physics, Nespor states:

> The undergraduate program can be understood, then, not as a site for the infusion of physics knowledge into students' heads, but as a path shaping a lock-step trajectory through a curriculum that restricted students' activities to a small set of material spaces dominated by the discipline. The end product was a highly restrictive social space that tied together practices spread across great physical distances (1994, p.32).

We are curious to see what results from applying Nespor's concepts to undergraduate engineering instead of undergraduate physics. The similarities of the curricular constraints alone suggest that the path of undergraduate engineering may be in some ways similar to the "lock-step trajectory" of undergraduate physics, though we feel that the "end products" of the two disciplines are different. Where physics undergraduate aims to train students for highly specialized employment in prestigious graduate schools and international laboratories, engineering undergraduate is supposed to prepare students for an immense variety of industry positions. Consequently, we are excited to trace the mobilization of engineering concepts and enrollment of engineering artifacts and students into actor-networks to examine differences in how these actor-networks operate, change, and flow.

3.2.5.2 Roth and McGinn 1998

Subsequently we turn our attention to a somewhat radical article published in the *Journal of Science Teaching* by Roth and McGinn in 1998. This article introduces and describes the actor-network concepts of *inscriptions* and *boundary objects*, culminating in a revealing analysis of grades as an important type of *inscription* that mediates knowledge and power in educational systems. Roth and McGinn's setting is primary schooling, particularly a physics course taken by students in their senior year of high school, and how the grades achieved in the course by two exemplar students affects their subsequent enrollment and mobility in university actor-networks. Overall, the article describes revolutionary ideas for educational systems, questioning practices that have gone unexamined for centuries and hardened into contemporary fact. By analyzing and unpacking grades, a fundamental practice of educational systems, Roth and McGinn are also taking up the line of inquiry suggested by Star (1990) in tracing how the widespread practice of grading became so durable in the first place and then proposing alternates.

Latour (1987) introduced the term *inscription* to refer to diagrams, photographs, figures, tables, x-rays, drawings, schematics, and more – basically anything that can be recorded on a piece of paper or computer screen and transported from one location to another, or reproduced for dissemination. *Inscriptions* are different than the "representations" or internal mental processes studied in the domains of psychology and cognitive science, and important in ANT as artifacts that can act and be enrolled into various actor-networks. Roth and McGinn explain grades and standardized test scores as a particular type of *inscription* that is similarly recorded on paper or computer screens, and transported via transcripts or report cards from location to location. "Because inscriptions integrate the substantive, mathematical and literary resources of scientific investigation, they create the impression that the objects or relations they represent are *inherently* mathematical" (Lynch, 1988, p. 217; Roth & McGinn, 1998, p. 402). As Roth and McGinn go on to demonstrate, the assumed mathematical nature of *inscriptions* has serious implications in educational environments for perceptions of fairness and objectivity in evaluating students. Since "Inscriptions gain in power as the information they summarize grows and the work it takes to deconstruct them increases," grades are a prime example of a powerful inscription in educational actor-networks (Latour, 1987).

Boundary objects are an extension of the concept of *inscriptions. Inscriptions* are mobile and immutable as they travel through actor-networks, "[drawing] power from their superposable, combinable, presentable, mobile, and immutable character. These properties allow them to be moved unaltered across long distances, collected, processed, and compiled" (Roth & McGinn, 1998, p. 402). The movement of *inscriptions* across long distances can also be seen in terms of movement across and between different actor-networks as *boundary objects. Boundary objects* are members of multiple actor-networks and social worlds that mediate understanding across these different groups. A canonical example of a *boundary object* is an engineering drawing: produced by engineers, these are used by manufacturers, accountants, marketers, and more, crossing disciplinary boundaries and utilized by each group differently. Roth & McGinn explain how grades are *boundary objects* produced by high school actor-networks and transferred to college admissions officers, again used by both groups in different ways. Furthermore, "Standardized examinations and the scores they produce are also boundary objects that allow articulation of science education in different counties, states, and countries" (Roth & McGinn, 1998, p. 404).

The concepts of *inscription* and *boundary objects* thus scaffold understanding of Roth & McGinn's argument:

> Students are in large part constructed by means of grades, a particular form of inscription. To translate students into grades, tests and examinations are used. Here, students are isolated from the contexts and relationships in which they typically function: Examinees cannot use any of the resources that allow them to function under ordinary conditions. The relational values such as cooperation, working with people, and helping others… are disrupted in the production of grades (1998, p. 408).

Tests and examinations translate students into the durable *inscription* of grades, which can be circulated among local actor-networks at schools and transported to the global actor-networks of universities and aggregate statistics. Roth & McGinn trace the history of grading back to the end of the 18th century, originating in record-keeping practices of military academies designed to maintain discipline within hierarchical organizations. The authors demonstrate that this archaic system was initially designed to keep soldiers in line, to monitor their activities and control them through stratification, and that alternates to this militaristic grading system should exist today – apprenticeships and the process of becoming a midwife are given as examples.

The importance of exams and grades in educational actor-networks is further explained in the context of the political (and powerful) construction of knowledge:

> Through the exams, knowledge is not simply tested, but produced; this new knowledge is clearly political. Schools become uninterruptedly functioning examination machineries that make possible continuous comparisons of each student

> with everyone else. In this way, exams do not even ascertain learning, but become a permanent aspect of the learning process so that new knowledge can be produced destined for, and at the sole disposition of, the teacher (Roth & McGinn, 1998, p. 408).

The metaphor of schools as a mechanistic factory is compounded by the monetary and economic factors surrounding the completion of a degree:

> Many students and their parents view education as an investment (an accumulation of inscriptions). One spends money, gets grades and a diploma in return, and trades in the diploma for acceptance letters to good colleges or universities – translations through a cascade of inscriptions… Information, distributed by teachers, takes the character of a commodity which is traded for symbolic capital that assures future success. Schooling becomes a retail product (Roth & McGinn, 1998, p. 410).

In higher education, the concept of schooling as a 'retail product' is ever more evident as increasing costs of tuition and fees reinforce the concept of education as an investment made by students and families. As Roth & McGinn illustrate, the chain of translations in which a student obtains a diploma or a degree is largely dependent on *inscriptions* like grades and scores on standardized tests. To apply terminology from Nespor, this is an example of a 'compression of space-time,' as "the heterogeneity and complexity of people and their contexts are reduced to the homogeneity and simplicity of grades and report cards" (Roth & McGinn, 1998, p. 410). Grades and report cards are mobile *inscriptions* – they travel where people cannot, they inscribe years of student experiences into a tidy number or piece of paper that is institutionally recognized as a faithful representation of the efforts, intelligence, or worthiness of students. Clearly, grades are powerful and can seriously affect student trajectories through educational actor-networks.

Roth & McGinn next connect grades to the dynamic processes that maintain actor-networks themselves, stating: “Grades stabilize educational networks. These networks are stable because the interests of some actors are successfully translated into the interests of others, in a process of interessement. Students learn it is in their own interest to do well, to study to get high grades” (1998, pp. 412–413). In this view, the desire of students to get high grades is a manifestation of the successful interessement of students in educational actor-networks. If students were not interested or motivated by the promise of a grade, the educational landscape would shift dramatically, in ways we can barely imagine. “If grades were taken out of the system, they could no longer be used to discipline, punish, and reward useless tricks such as memorizing facts for a specific test” (Roth & McGinn, 1998, p. 414). Alternate models for education are put forward, including the apprenticeship model and midwife training as examples. However, as Roth & McGinn point out, many of the actors currently embedded in educational actor-networks have no interest in changing the status quo, in challenging the powerful position that grades currently inhabit. Students who achieve high marks are the ones who would lose out if the system were changed; similarly teachers of “hard” sciences including science and mathematics have no reason to disrupt the academic hierarchy in which they occupy the top level.

Part of the power of grades as *inscriptions* stabilizing actor-networks is that they are also *boundary objects* that move among different actor-networks, impacting each uniquely. As Roth & McGinn explain:

> Grades constitute the most important circulating boundary object in schooling, and define the relationship between, for example, teachers and students. Teachers hold and distribute grades, and students want to get those grades at the highest possible value.

> Actors accrue power if they can constitute themselves as gatekeepers at obligatory passage points for other actors. That is, power derives from the actors' special positioning within actor-networks… Relative to students, teachers are therefore in positions of power (with respect to students) because it is in the interest of students to get high marks (p.413).

Here we see another level in which grades serve as *boundary objects*, moving between the actor-networks of students to the actor-networks of teachers. Seeing grades in this way, as a dominant type of *inscription* that serves to interest students, enroll them into educational actor-networks, and define relationships between entities in the network, allows for consideration of power dynamics in a unique way. Roth & McGinn's definition of accruing power above focuses on the positioning of actors around *obligatory passage points* – we keep this in mind as we analyze the engineering sophomore year, examining how actors are positioned and to what effect.

Finally, we learn from Roth & McGinn that "taking the view of a nonhuman actor makes the familiar strange, disrupts common sense, and therefore can provide new insights to the phenomena of interest" (1998, p. 415). In taking the view of grades, the authors are able to trace how students, teachers, administrators, and researchers differentially develop connections to grades and under what conditions. Their study takes a truly novel view of a conventional and ubiquitous practice throughout modern educational systems, calling into question what has been assumed for centuries. We take away from Roth & McGinn this method of shifting our focus and viewpoints away from solely human actors, considering alternate non-human perspectives with potential to change the way we look at even the most common and stable habits of the actor-networks under study.

3.2.5.3 Fenwick 2011

Jumping forward a decade or so, we find ourselves at a new frontier of actor-network scholarship as applied to educational studies in particular. In addition to authoring the text *Actor-Network Theory in Education* with Edwards (Fenwick & Edwards, 2010), Fenwick has published several articles highlighting the potential of Actor-Network approaches for studying educational systems. Here, a short review of the article "Reading Educational Reform with Actor Network Theory: Fluid spaces, otherings, and ambivalences" is provided to illuminate critical aspects of ANT that have not yet been discussed here, particularly the concept of minding the gaps within networks (Fenwick, 2011). This article also discusses the theoretical shift from traditional *Actor-Network Theory* approaches to *After-ANT* or *ANT-ish* methods, signaling a shift in focus from the formulaic imposition of definitions to allow more fluid interpretations and applications of ANT.

Fenwick (2011) reviews a decade of scholarship of ANT applied to education, highlighting the pushback against early ANT approaches for their predominant focus on powerful central actors – similar to the analysis of Star (1990) but with the support of two decades of ANT-ish and After-ANT studies (e.g., S. Fox, 2005; Law & Hassard, 1999; Law, 1999, 2004; Nespor, 2002). She proposes a simple research question along traditional ANT lines: "What does a network analysis contribute to understanding educational reform efforts?" and then flips the question on its head, asking from an *After-ANT* perspective: "What can be understood about educational reform by stepping *outside* a network analysis, which while important for illuminating certain dynamics, can become a singular and totalizing representation that obscures others?" (2011, p. 115). In proposing both questions, Fenwick makes explicit the difference between *ANT* and *After-ANT* investigations, and the intention to purposely look beyond the obvious or prominent representations for the quieter, less outspoken actors and events. This is vital for education research, as students frequently appear on the margins of educational studies that primarily focus on the actions of powerful administrators and teachers. *After-ANT* approaches also advocate for looser use of the *four moments of translation* "as a heuristic or 'sensitizing' concept adapted to make sense of complex observations," not to "slavishly impose four steps and expect a linear process, but appreciate that translation is ongoing, iterative, and disorderly" (Fenwick, 2011, p. 122).

To create imagery of ANT scholarship that 'steps *outside* a network analysis,' Fenwick suggests:

> …Networks can be envisioned as… ephemeral and rhizomatic in nature. Networks are simply webs that grow through connections. The connections can be thick and thin, rigid and limp, close and distant, dyadic and multiple, material and immaterial. And the connections have spaces between them…The word [network] also serves as a useful reminder both of the precariousness and unpredictability of any network's formation and continuity, as well as the multiple shapes and lengths it can assume—from a large open fishing net to a tightly clasped net bag, from a sticky and multi-netted local web to a far-reaching network gathering global industries in some standardized practice. (2011, p. 119)

These metaphorical images reinforce the interpretation of actor-networks as fluid entities with tremendous diversity and dynamism, in which the things that slip through the gaps in the net are as important to identify as the elements that constitute it.

To demonstrate the value of looking both at and outside of a network, Fenwick reads an exemplar study in two ways: traditional ANT and *After-ANT*. This study by Luck (2008) examines the uptake of a new videoconferencing system at an Australian university in line with Callon's *four moments of translation* in a traditional ANT approach (1986a). Fenwick's first reading of the study highlights the effect of certain circulating administrative documents (*inscriptions)* regarding the videoconferencing system, tracing the impact of sending letters to students and parents advertising the distance learning enabled by the videoconferencing technology, and the demonstrations of the technology's feasibility, quality, and convenience for teachers and students involved. The conclusion overall is that "insufficient attention is often granted to the active role of objects and technology" (Fenwick, 2011, p. 121), recalling the suggestion from Roth and McGinn (1998) to take the viewpoint of non-human actors in order to enrich analyses.

Next, Fenwick reads the same study but with attention towards what was included and excluded in the original analysis. The purpose in doing so is "to suggest the potential for ANT-ish approaches to not only analyse how powerful networks become set in motion through educational reform but also to gesture towards gaps and more fluid spaces within and among these networks" (Fenwick, 2011, p. 123). For instance, while Luck's study focuses on a successful implementation of a technological reform, a complementary study could examine a reform effort that was not successful. While the *four moments of translation* can be used to explain how a network becomes *durable*, or ordered through time, and *mobile*, or ordered through space, they can also be used to explain why some reform efforts are never taken up, never made durable or mobile. Local examples of unsuccessful interventions to increase the representation of women in engineering, for instance, are one example of reform efforts that were not made durable or mobile. Fenwick advocates for examining these unsuccessful interventions as well as the successful ones, to be reflexive about what any study is including and excluding. Furthermore, the absence of "educational research reflecting post-structuralist, feminist, post-colonialist, or any number of contemporary and increasingly widespread orientations in university-based educational research" is named here and called for in future studies (Fenwick, 2011, p. 128).

In addition to the need for reflexivity and awareness around the elements included and excluded in an analysis, Fenwick brings attention to the idea of "partial translations – when and why do they occur, and how do the resulting ambivalent belongings affect the overall network?"

(Fenwick, 2011, p. 126). While Nespor (1994) briefly touches on students who were only partially enrolled in the disciplinary actor-network of undergraduate physics, Fenwick suggests that these marginal characters should in fact be at the center of *After-ANT* studies. Generally, Fenwick argues for educational studies that acknowledge the 'messiness' of social science, of cultures, and of sociotechnical investigations. Partial translations or 'ambivalent belongings' remain important for study as sites of struggle, where identities and connections are formed and broken.

The article closes with a cautionary warning regarding the degree of fluidity that is actually present within university and other educational systems. As "…universities consist of highly durable actor-networks held in place by linkages among vast networks of equipment, architectures, other institutions, and historical relational patterns," they may not be as fluid and ephemeral as non-academic actor-networks (Busch, 1997; Fenwick, 2011, p. 120). This is corroborated by Nespor's suggestion that "it would be a mistake to emphasize the fluidity of the world without noting that it flows at times in very deeply worn channels" (1994, p. 15). As a result, we take away from Fenwick's article the imagery of actor-networks that calls attention to the spaces and gaps in-between the net, as well as caution to explore how some university systems become durable and others disappear. Fenwick offers terminology and metaphors for *After-ANT* studies, to look at actors on the margins of the network, elements of the network that are only partially enrolled or ambivalently belong, in addition to seeing the powerful actors that shape the network around them. These ideas inform our understanding and analysis of sophomore engineering, encouraging the examination of all items along the spectrum of inclusion and exclusion, both human and non-human.

3.2.6 Actor-Network Theory in JEE & ASEE Publications

Now that both classical and contemporary exemplars of ANT scholarship have been reviewed, we turn our attention to the field of engineering education research and consider its readiness for this type of sociocultural/sociotechnical research. We find positive indicators from recent issues of the *Journal of Engineering Education* (e.g., Adams et al., 2011; Johri, Roth, & Olds, 2013) and the first-ever *Cambridge Handbook of Engineering Education* (Johri & Olds, 2014) which introduce elements of Actor-Network Theory as applied to engineering undergraduate schooling. The following paragraphs briefly summarize the evidence of ANT and ANT-ish concepts already published in engineering education journals, books, and conference proceedings.

3.2.6.1 Journal of Engineering Education & Conference Proceedings, 2011

Engineering education authors have described concepts and theories from Science and Technology Studies (STS) and the importance of mixing social and technical worlds in published works since at least 2011. Two articles published in the January 2011 issue of JEE are relevant as they initially introduced Actor-Network concepts to a broad engineering education audience (Adams et al., 2011; Johri & Olds, 2011). First, the article "Multiple Perspectives on Engaging Future Engineers" incorporated short essays from 11 different leading researchers in fields related to engineering education, to broaden readers' perception of interdisciplinary and cross disciplinary scholarship in the field and to argue for re-conceptualizing how we see engineering, innovation, and engaging engineering students (Adams et al., 2011).

One of these essays, written by Stevens, introduces readers to the concept that engineering "ought to be reimagined as something more—as *socio-technical* work" instead of purely *technical* (Adams et al., 2011, p. 58). Recognizing the social element of engineering is one of the lessons learned from Science and Technology Studies that Stevens brings to the engineering education audience. Citing Latour (1987), Stevens explains the process of "follow[ing] scientists and engineers through society" to study how the "practices of the professionals line up with the images that textbook pedagogies and philosophers espouse" (Adams et al., 2011, p. 58). Stevens offers three potential ways that engineering education could move towards socio-technical education, two of which reference tenets of Actor-Network Theory without actually saying the words. For instance, the second suggestion Steven gives for educators is to incorporate " 'Follow the object' Fieldwork" to see "how the object is shaped and deflected (*translated)* by the many humans with whom it comes in contact "(Adams et al., 2011, p. 60, empahsis added). This concept of 'following the actors' was initially stated by Latour (1987) and revised by Czarniawska (2007) to 'follow the object'; Stevens is borrowing from this actor-network history here. Stevens' third suggestion to "Design experiences that multiply the relevant actors," discussing how even senior capstone projects could go further in acknowledging the myriad humans and non-humans involved in the project, is another way of suggesting that engineering educators teach their students to be aware not just of the technical linkages and dependencies in their work, but also the people involved. Stevens argues that increased recognition of the social side of engineering in engineering education may help engineering's image and reputation, providing a "welcoming home for the 'people person' " (Adams et al., 2011, p. 60). It's almost ironic that ANT scholars including Latour fought theoretical battles in order to have non-humans included in sociological analyses of knowledge and power while Stevens is arguing for the opposite in engineering, to re-imagine engineering education to include the role of humans. In the context of our current study, we keep both ideas in mind as we investigate interactions between and among humans and non-humans.

The same issue of JEE features an article authored by Johri & Olds (2011), which introduces the Learning Sciences field and how it can contribute to engineering education, and includes a series of vignettes on the theme of *situativity*. Here *situativity* is defined as viewing knowledge "as distributed among people and their environments, including objects, artifacts, tools, books, and the communities of which they are a part" (Greeno, Collins, & Resnick, 1996, p. 15; as cited in Johri & Olds, 2011, p. 155). Part of this definition includes an acknowledgement and awareness of the importance of non-human elements in learning, a foundational concept from Actor-Network Theory. Connections to ANT are further developed by the authors in saying "a central aim of the situated perspective is to understand learning as situated in a complex web of social organization rather than as a shift in mental structures of a learner" (Johri & Olds, 2011, p. 160). Another way of describing the "complex webs of social organization" is as a network - either way Johri & Olds are talking about the same ideas that we are in this study. In this way, this article helps prepare the engineering education audience to be introduced to Actor-Network Theory.

One of the vignettes in the article is written by Sørensen, who formally introduces Actor-Network Theory explicitly in the context of the "Materiality of Learning", building off of the introduction by Johri & Olds to describe particular applications of *situativity* and "webs of social organization." Sørensen introduces ANT via a canonical example from Latour, of hotel keys (Latour, 1992b). The story goes that there is a hotel manager who tries all manners of signage and messaging to encourage hotel guests to leave their keys at the front desk whenever they leave the hotel; finally the manager attaches a heavy weight to each key and consequently induces the desired behavior in the hotel guests (Latour, 1992b). In doing so the hotel manager "delegates the agency involved … to the weights," illustrating how humans and non-humans combine to generate *hybrid* effects, and how the desires of a human (the hotel manager) can be materially translated into a physical object (Johri & Olds, 2011, p. 161).

Sørensen continues, connecting this concept of *hybrids* to engineering education, point out that engineering is one of the most materially saturated disciplines. Sørensen describes how different forms of knowledge emerge when different materials are involved, contrasting the learning that results from blackboards, textbooks, and traditional classroom layouts, to virtual learning environments, blogs, and the Internet. Similar to Stevens' desire to include non-human artifacts in the analysis of engineering learning, Sørensen questions, "How much would there be left of learning engineering if all nonhuman things were left out?" (Johri & Olds, 2011, p. 161). Sørensen concludes that learning must be understood as a socio-material process, reinforcing the earlier message from Stevens that we must keep both people and things in mind as we examine engineering learning.

The next illustrative vignette in the article is provided by Roth, who introduces the concept of *inscriptions* to an engineering education audience. Also citing Latour (1987), Roth introduces the distinction between representations and *inscriptions,* explaining how *inscriptions* have a critical purpose in engineering education. Roth chooses to illustrate the importance of *inscriptions* using the example of a professor writing on a chalkboard during a lecture instead of the more controversial and sacred *inscription* of grades as explicated in the previous section (Roth & McGinn, 1998). Roth explains:

> …rather than trying to get into the mind of the professor, we study what he makes available to his students, which is precisely what to think and how to think with the diagram he is presenting to them in the lecture…students watching and listening to the professor learn how to use and talk about the graph not by going into his mind or by trying to guess what is going on inside, but by carefully attending to what the professor makes public in and through his communication. They further learn to use inscriptions while doing assignments, a form of communication with the professor, or by communicating with others over and about inscriptions. (Johri & Olds, 2011, pp. 164–165)

This passage by Roth interprets a common occurrence in engineering education, a professor's lecture at the board, and serves as a foundational introduction to the concept of *inscriptions* and how they circulate through engineering undergraduate actor-networks. Roth's explanations of assignments as an *inscriptional* form of communication with the professors, as well as pointing out the role of *inscriptions* in student conversations about homework, for example, contribute to our understanding and interpretation of how *inscriptions* circulate and affect the actors in our study of sophomore engineering. We can thus build off of Roth's introduction to *inscriptions* and Sørensen's introduction to Actor-Network Theory in communicating our study to an engineering education audience.

Also in 2011, a paper on the subject of *boundary objects* was presented at the American Society for Engineering Education (ASEE) Annual Conference & Exposition in Vancouver, British Columbia, explaining how this concept from STS and partially ANT is useful for investigating interdisciplinary and multidisciplinary teams in engineering. The authors explain their novel approach to studying the artifacts produced during interdisciplinary team projects, instead of the attitudes and opinions of the student team members themselves, to see from a different perspective how teams use *boundary negotiating artifacts* to navigate their work. Ontology of this particular type of *boundary objects* is introduced, detailing specific categories of *inclusion artifacts* and *compilation artifacts* as relevant to the analysis of the interdisciplinary team's practices. Overall, the article provides an introduction to these concepts, proposing that *boundary negotiating artifacts* offer a valuable framework for interpreting the inner workings of teams and suggests a research agenda going forward to further examine their use. The concept of *boundary negotiating artifacts* is in itself positioned as a *boundary object* connecting the fields of engineering education, STS, and Engineering Studies.

3.2.6.2 Special Issue of the Journal of Engineering Education, 2013

Moving forward to January 2013, a special issue of the *Journal of Engineering Education* (JEE) was organized around the central theme of "Representations in Engineering Practice", spearheaded by an guest editorial suggesting that engineering education researchers purposely shift towards the study of representations in addition to continuing to examine cognitive factors in learning (Johri et al., 2013). In doing so, the authors are taking up the suggestions from the variety of articles in 2011 discussed above, as representations are non-human elements, frequently *boundary objects* and *inscriptions,* that have a central place in engineering education (Adams et al., 2011; e.g., Beddoes, Borrego, & Jesiek, 2011; Johri & Olds, 2011). For instance, chalkboards, equations, and software programs incorporate *representations* in the name of learning engineering. Roth collaborates with Johri & Olds here to expand what was started in the description of *inscriptions* in 2011, to further describe and offer an example of a representational (inscriptional) chain:

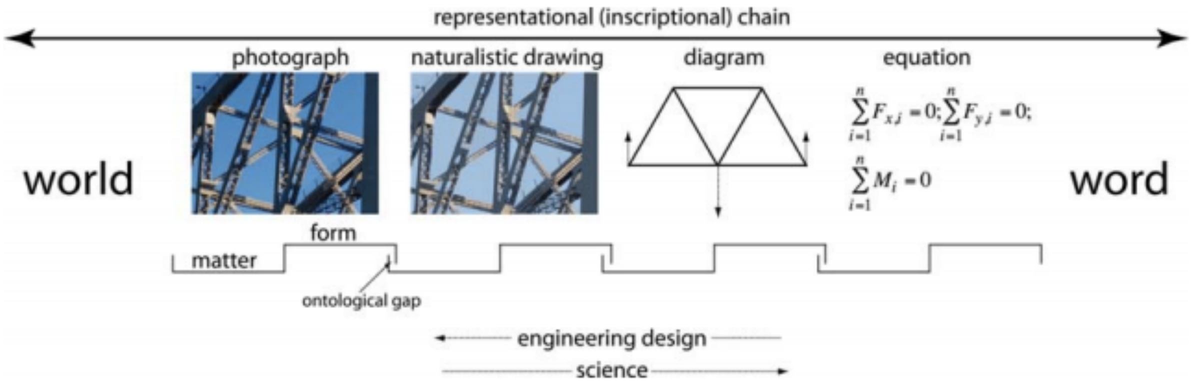


Figure 5: Roth's illustration of a representational chain, which "establishes the relation between the things in a material world and the word" (Johri et al., 2013, p. 9).

Roth, Johri & Olds suggest that "In this situation, abstract and concrete are only relative notions, for in the hands of an engineer, the equations to the right are as palpable entities with which one can work as are the photographs to the left" (2013, p. 10). The authors further explain that:

> In the natural sciences, the movement in this chain (Figure 5) tends to be from left to right, through progressive translations into inscriptions that have decreasing resemblance to the world until scientists arrive at verbal representation and the corresponding forms of verbal thought. In contrast, in engineering, the movement tends to be from right to left as ideas are translated into sketches, formal designs, prototypes, and objects in the material world. Although the movement appears unidirectional in these fields, there is in fact a continuous circulation…think about the chain as constituting all the pair-wise references between inscriptions that make possible the back-and-forth movement between material world and language…this cyclical movement along the chain of inscription becomes an important factor in

> bringing about conceptual cohesion and integration to STEM learners…engineering students develop fluent practices within and across inscriptions. (Johri et al., 2013, p. 10)

The distinction between how scientists and engineers move along this inscriptional chain is instructive for our study as we examine in the context of a mathematics course how students develop fluency, or not, in moving along the chain from the physical world to abstract representations and back again. We consider student assignments, exams, and projects in the context of this chain, charting their movement and the resulting implications for what constitutes knowledge in the courses under study. Generally, this article and accompanying figure demonstrate the greater level of detail afforded to ANT concepts of representations and *inscriptions* in 2013 found in this flagship journal for the field of engineering education.

The remainder of this special issue includes a variety of articles that study representations in specific engineering contexts from a variety of theoretical perspectives. One of the studies explains the importance of applying theories from STS to study engineers-in-the-making, suggesting that "STS…offers a range of questions that guide engineering education research by focusing on the important heterogeneous and complex relationships between humans and things in engineering to better understand its practices" (Juhl & Lindegaard, 2013, p. 22). This reasoning is reminiscent of the arguments made by Stevens and Sørensen in 2011, summarized above, again communicating to the engineering education audience the usefulness of examining heterogeneous (humans and non-humans) connections and complex relationships when researching engineering.

3.2.6.3 Cambridge Handbook of Engineering Education Research (CHEER), 2014

In 2014, this thread is taken up yet again in the publication of the first-ever *Cambridge Handbook of Engineering Education Research (CHEER)* (Johri & Olds, 2014). Many of the authors who introduced ANT and STS concepts to engineering education audiences in 2011 and 2013 also authored or co-authored chapters published in the handbook, thus communicating the concepts of *situativity*, *inscriptions*, *representations, heterogeneity, boundary objects, actors*, and more to an engineering education audience in the format of a bound reference handbook instead of a journal article or conference proceeding. Here a few related chapters from CHEER are reviewed to illustrate the apparent trend towards accepting and understanding STS and ANT concepts in engineering education research.

Building on the work started by Johri & Olds (2011), these authors collaborate with O'Connor to write a chapter describing "Situative Frameworks for Engineering Learning Research" (Johri, Olds, & O'Connor, 2014). In this article, the concept of *situativity* is re-introduced, refining the 2011 article that presented *situativity* in the context of the Learning Sciences. Updated in 2014, the chapter includes discussion of *situated learning theory* from Lave & Wenger (1991) and how it has been applied in engineering education research. The authors point out that unfortunately, *situated learning theory* has been only simplistically understood and implemented in studies of educational systems in engineering, with insufficient nuance and attention to the original critical intent of the theory. They conclude that "research on learning must centrally involve attention to processes of the organizing of processes through which people move along trajectories into their futures, including the conditions in which people become recognized, or not, as valued participants in social worlds" (Johri et al., 2014, p. 61). We consider this critique of the current literature in moving forward with our study, keeping in mind the importance of the "processes of organizing" students along trajectories "into their futures", or into professional actor-networks of engineering.

The next chapter in CHEER, authored by Roth, continues the discussion from the special issue of the *Journal of Engineering Education* (2013) on the topic of representations in engineering education but with an added meta-analytical approach to further illustrate the point that representational engineering knowledge is inherently social as well as technical and cognitive (2014).

Roth begins by explaining the "sociocultural and cultural-historical perspective" taken in the chapter, explicitly not a cognitive approach, to studying *inscriptions* in engineering. The distinction between representations and *inscriptions* remains important here, as Roth samples journals in the fields of engineering, physics, social sciences, and the learning sciences, counting the number of inscriptions per article. Inscriptions are a sub-category of representations, as representations can refer to mental images or thoughts while inscriptions are written tangibly and visible either literally or virtually (e.g. on a computer screen). Roth's data is further categorized into the type of inscription common for each field, finding that engineering tends to be heavy on the equations, line graphs, and scatter plots with a greater number of inscriptions per page than any of the other fields except for physics. Roth reports:

> …there is an order of magnitude difference between the per page frequency of visual representation in engineering and those social science journals reporting about the psychological and social aspects of learning in the areas of science, technology, engineering, and mathematics… we may conclude that representations constitute a large part of what counts as knowing in engineering. At the same time, these representations do not go by themselves, but rather they come with a large amount of language-based presentation. (2014, p. 70)

The chapter goes on to build on this concept of representations and inscriptions constituting a large part of "what counts as knowing in engineering," explaining that one view of the process of learning engineering is as a novice becoming familiar with multiple representations and developing the ability to move between them along the representational/inscriptional chain shown above in Figure 5 (Johri et al., 2013). Roth also explains how inscriptions function as *boundary objects*, building on prior scholarship from Beddoes (2011) and others in describing how inscriptions "coordinate people who have qualitatively different understandings of the situation" (2014, p. 75; from Star, 1989). As boundary objects, inscriptions serve the purpose of coordinating different groups as well as being circulated among them. As immutable artifacts that are transported, scaled, and combined as part of daily engineering practice and education, inscriptions are accessible to engineering education researchers and can be studied in the context of the work they do to coordinate human activity.

Building on the finding that representations and specifically inscriptions are "what counts as knowledge in engineering," Roth contends that the advantage to studying inscriptions in engineering is that they are prevalent and readily available to researchers interested in studying engineers-in-the-making. By studying how engineering students relate to inscriptions and take them up, researchers have a novel route into seeing how knowledge is developed before it is internalized into private thoughts and 'common sense' assumptions. Roth is convincing in describing the advantages of this inscriptional approach to engineering education research, yet stops short of naming this approach and connecting it to Actor-Network Theory. We study inscriptions in engineering with a similar perspective and approach, but explicitly contextualize our study as inspired by Actor-Network Theory to examine the work of inscriptions, which also serve as boundary objects coordinating the activities of students, instructors, TAs, administrators, and more. In doing so we build off the scholarship of Roth and others who have ably introduced the concepts of representation, inscription, and boundary objects to engineering education audiences.

3.3 Research Need & Questions

3.3.1 Gap in Engineering Education Knowledge Base

Looking over the prior socio-cultural research in engineering education, we see an apparent gap in the engineering education knowledge base that we seek to illuminate through the lens of Actor-Network Theory. The critical nature of the sophomore year for engineering students as well as the lack of prior studies that explore sociocultural aspects of second year gateway courses encourages our focus on engineering sophomores. Especially compared to the extensive engineering education literature related to first-year experiences, it is clear we have more work to do in studying the next year of engineering school. While the heavily-studied first year is characterized by the transition from high school to college environments, the understudied second year remains a pivotal time as passing or failing grades determine which disciplinary networks, or majors, students come to call their own. The second year features gateway courses that eventually lead to the practice of engineering, courses that initiate students into greater levels of abstraction and analytical engineering problem solving like Calculus 3 and Differential Equations. These two courses, chosen as initial sites for our network study, also serve as prerequisite requirements for subsequent technical courses in engineering degree programs.

The field of engineering education has long emphasized survey research and factor analysis to identify individual characteristics that predict success or failure in engineering. This study breaks from this cognitive, individual tradition rooted in statistical analysis to instead take a novel view at what constitutes engineering and how. Our attention to how cultures, systems, and networks of engineering are created and maintained is in some ways related to the work of McIlwee & Robinson (1992), Fletcher (1999), Tonso (1996b), and Seymour & Hewitt (1997), but distinct in our theoretical orientation. Examining sophomore engineering through Actor-Network Theory allows us to analyze the educational trajectories of undergraduate engineering, highlighting how human and non-human actors interact to maintain and organize undergraduate pathways through engineering. We trace out connections made between different types of elements along a student's journey, including other students, TAs, professors, tests, concepts, projects, textbooks, overall courses, cognitive constructs, and more. We adopt Actor-Network Theory to investigate the core engineering sophomore year – not in isolation, but in connection with the elements that flow in, out, and around this transitional time in engineering education.

Actor-Network Theory was introduced in the Conceptual Framework section, as the background of ANT was described as well as how ANT can be applied to a wide variety of social and cultural contexts including the canonical examples of the domestication of scallops in France and the internationally durable actor-network of McDonalds (Callon, 1986a; Star, 1990). Once introduced, the fundamental concepts and criticisms of ANT were applied to the engineering example of the failed *Aramis* transportation project (Latour, 1992a), and then in educational settings including the actor-network of undergraduate physics programs (Nespor, 1994), the prominent inscription of grades and grading practices in schools (Roth & McGinn, 1998), and traces of a novel videoconferencing reform in higher education from both ANT and after-ANT perspectives (Fenwick, 2011). We believe the engineering education community is prepared for an in-depth ANT analysis of sophomore engineering as authors including Stevens (Adams et al., 2011), Sørensen (Johri & Olds, 2011), Roth (Johri & Olds, 2011), and Beddoes (2011) have already introduced aspects of the theory in journal articles and conference publications. The recent publication of the Cambridge Handbook of Engineering Education Research and the inclusion of chapters authored by O'Connor et al. (2014) and Roth (2014) on the subjects of situated engineering education research and representational knowledge, respectively, further reflects the readiness of the field in understanding this novel approach and its benefits.

While buzzwords like "chilly climate" or the "leaky engineering pipeline" have dominated the discourse in engineering education, we wish to add a completely different type of metaphor about the social organization of engineering cultures in education. We feel that our exploratory qualitative study identifying actors and network connections in engineering gateway courses will identify salient consequences for different student actor-networks and the power relationships which structure student progress through achievement of an undergraduate degree. By initiating this novel work in this sociocultural arena, we seek to escape the deficit paradigm and lay a framework for future engineering education researchers to use.

3.3.2 Research Questions

In the language of Actor-Network Theory (ANT), we ask how students become enrolled in the actor-networks of engineering sophomore year and to what consequence. Inspired by Fenwick (2011) we also wish to ask the complementary question in the language of After-ANT scholarship, pondering what else can be gleaned from a network perspective that includes attention to those on the margins of the networks under study, not just those at the center.

The ultimate goal of this research is to identify network connections between engineering cultures, students, and teachers, and how this network travels through the space and time of an undergraduate engineering program. As such, our main research questions are:

1. How are students *problematized, interessed, enrolled, mobilized, and translated* in the actor-networks of engineering sophomore year and to what consequence?
2. What can we learn about engineering sophomore year by stepping outside of the network metaphor, or by shifting the focus away from central actors towards those at the margins?

Chapter 4 – Methodology

To address the proposed research questions, we adopt a qualitative, ethnographic approach. This section defines qualitative research and ethnography for unfamiliar audiences, and explains our specific research design and analysis processes.

4.1 Why Qualitative?

Qualitative research has steadily gained traction in education research since the early 1980s due to its ability to answer fundamentally different kinds of questions than can be answered through quantitative research. Where quantitative educational research looks to measure, or quantify something in a student population of interest, qualitative research seeks to understand the "how" and "why" behind the lived experiences of students. Qualitative research is particularly important in understudied areas, as it enables exploration of unknown cultural and social phenomena. Open-ended questions are the standard in qualitative research whereas closed-ended questions typify quantitative research. Where quantitative studies require testable hypotheses, qualitative research encourages an open mind that can react to emergent themes and phenomena, as they are uncovered. We choose a qualitative approach as fitting for an exploratory study into the under-researched culture of gateway courses in the engineering sophomore year.

4.2 What is Ethnography?

Ethnography is one methodology for qualitative research frequently employed by education researchers. With a strong tradition rooted in the disciplines of anthropology and sociology, ethnography has come to be known among contemporary researchers as:

> … a particular method or set of methods… (which) involves the ethnographer participating, overtly or covertly, in people's daily lives for a extended period of time, watching what happens, listening to what is said, asking questions-in fact, collecting whatever data are available to throw light on the issues that are the focus of the research. (Hammersley & Atkinson, 2007, p. 1 as quoted in Case & Light, 2011, p. 195)

We choose to employ ethnography in this study because it allows for close investigation of engineering culture as enacted in public spaces of lecture halls and study rooms and as experienced by engineering students privately. Our ethnographic approach to studying sophomore engineering encourages the research team to gather data in multiple forms: classroom observations, informal conversations with students around campus, semi-structured interviews with students, graduate teaching assistants, and teachers, and artifacts related to our focal courses of Calc 3 and Diff Eq.

It is important to note that ethnography is a distinctive qualitative method with traditions and a rich history; it is not "just" the collection of observations and interviews. Well-known ethnographers include anthropologists Bronisław Malinowski and Margaret Mead, who traveled to foreign cultures and lived for years among the people and cultures they were studying. This model of the western, educated researcher fully immersing themselves in the exotic cultures of "savages" was once what typified ethnography, and established the ethnographic tradition (Malinowski, 1929; Mead, 1928). Sociologists including C. Wright Mills applied ethnographic methods to the study of local cultures like 1950s America, "making the familiar strange" through reflective consideration and analysis of everyday events (Mills, 1959). Ethnography has been used to study an immense variety of cultures, and is our chosen approach for understanding the lived experiences of students in engineering.

4.3 Research Design

As is customary in qualitative research, data collection and analysis occur in overlapping iterations, as emergent themes from early analysis have enabled the research team to adjust the parameters of data collection to better suit the evolving study's focus. The data collection and analysis process is presented here in a linear fashion for readability, but in reality the process is simultaneous and iterative. The CU Boulder Institutional Review Board (IRB) has approved these methods of data collection and analysis in Protocol #13-0459: Sophomore Engineering Students' Constructions of Status and Hierarchy.

4.3.1 Data Sources and Collection Methods

Data collection for this study began ethnographically in a fall semester with the targeted observation of two lecture sections of APPM2350: Calculus 3 for Engineers (Calc 3) consistently throughout the duration of the semester. Fieldnotes documenting classroom events, interactions, and student behaviors were taken electronically in real-time by a member of the research team to establish a baseline primary record of each class meeting. Particular attention was paid to the public discourse heard in the classroom, as questions and statements made by students were recorded verbatim in the fieldnotes. Key phrases from instructors regarding student attitudes and recommendations for studying or conceptualizing the course material were also recorded verbatim in the fieldnotes to the best of the observer's ability during each class. For the larger lecture sections, the researcher moved around the lecture hall during the semester to vary the context of the observations, noting the habits of the students around each different seating location and striking up informal conversations before the lecture periods with the students proximal. For the smaller lecture sections and recitations of less than 30 students, the researcher stayed in the middle or back of the room to afford a view of student activity around the room.

The fall semester course activities including recitations, review sessions before each midterm, and a midterm exam were also observed by a member of the research team with accompanying fieldnote record. Artifacts, including course syllabi, homework assignments and solutions, exams and exam solutions, projects, worksheets, textbooks, etc. were collected for later analysis. In totality, over 95 hours of course activities were observed during the first semester of data collection. At the end of the fall semester, semi-structured interviews were conducted with eight students enrolled in the course and one course instructor. The eight students were chosen strategically to represent both lecture sections under observation and a spectrum of seating locations and perceived attentiveness during lectures, as students who took notes diligently and students who browsed Facebook and other online networks were interviewed. These interviews were approximately 60 minutes long, audio-recorded, and later transcribed to text with personal identifiers removed for further analysis.

In the following spring semester, data collection continued with targeted ethnographic observation of three lecture sections of APPM2360: Differential Equations & Linear Algebra (Diff Eq). Each of the lecture sections was attended once a week by a researcher during the 16-week semester. Similar to the prior semester, observational fieldnotes were taken in each class meeting a researcher was present for, with 48 total hours of observations completed. Artifacts specific to this course were collected as well. We performed follow-up interviews with the six students still enrolled in engineering at the end of the spring semester, adding one additional student interview subject to supplement student perspectives on these gateway mathematics courses. Interviews were conducted with only one of the three instructors under observation as the other two instructors declined to participate following the conclusion of the semester. All interviews are semi-structured, audio-recorded, and cleaned of personal identifiers in the resulting transcripts.

Four graduate Teaching Assistants (TAs) from the gateway mathematics courses under study were interviewed during the subsequent fall semester, and follow-up interviews were conducted with the two instructors who were willing to participate in the research. Questions for these follow-up instructor interviews and TA interviews arose from in-process analysis of the data, centered on major themes from prior interviews and observations. Focus groups with engineering students were convened during this third semester of data collection, with a total of eight student participants discussing contentious issues related to their experiences in the gateway math courses. Contentious issues included what students thought of the midterm and final exams in these courses, what students believed to constitute cheating on homework, how students used diverse resources to assist in completion of homework and course assignments, what unofficial activities students did during lecture periods, and general student opinions of and reflections on their mathematics experiences. Semi-structured interview protocols are included in Appendix C for reference.

Table 2: Data Collection Activities Over Three Semesters

Semester	Focus	Data Collection Activities	Hours of Researcher Observation	Artifacts Collected
1 - Fall	APPM 2350: Calculus 3	Intensive observation of 2 lecture sections (2 instructors); 1 recitation section; 8 student interviews; 1 instructor interview	95	Syllabus, homework assignments, exams, projects, textbook
2 - Spring	APPM 2360: Differential Equations & Linear Algebra	Weekly observation of 3 lecture sections (3 instructors); 7 student interviews; 1 instructor interview	48	Syllabus, homework assignments, exams, projects, textbook
3 - Fall	Follow-Ups	3 focus groups with students; 4 interviews with graduate TAs; 2 follow-up instructor interviews	N/A	Grade distributions from past years, FCQ scores, TA coordination documentation

Overall, the ethnographic method of qualitative data collection adopted for this study is well suited for ANT analysis. We recall a slogan of ANT, to “follow the actors themselves” as they establish varied and dynamic connections in the social terrain under investigation (Latour, 1987). We examine human and non-human actors symmetrically, seeing how objects like curricula and textbooks can be connected as meaningfully to other elements in a network as a student to an instructor. Following the heterogeneous actors means tracing the associations made between all actors and artifacts in a given system, adding new elements as new connections are made and letting go of elements whose connections fade. By starting with the students, teaching assistants, instructors, and artifacts involved in sophomore-level required mathematics courses, we have a foundational set of elements from which to expand the network and analyze which conditions are conducive to network formation vs. dissolution. We record observations of course events both official and informal; conduct semi-structured interviews with human actors that can speak for themselves; and gather artifacts and documentation that assist in tracing the connections made by non-human objects. This method is intended to trace out connections and map student actor-networks in the university setting.

4.3.2 Context and Participants

Studying the sophomore year of engineering is not an altogether straightforward task. Students entering the university with advanced preparation in the form of Advanced Placement (AP) or International Baccalaureate (IB) test scores are given college credits, thus inflating their college standing regardless of how many semesters they have actually been in undergraduate school. For our study, we chose two mathematics courses that are generally taken in the second year of engineering school, though first-year, third-year, transfer, and non-traditional students are enrolled as well. These diverse student demographics add to the interesting cultural landscape of these courses, as a precocious freshman that is unafraid to dominate a sophomore-level course can affect how other students in the course perceive it and themselves. Generally, the majority of students in the courses we observed are considered sophomores, but not all.

In the first two semesters of data collection, we observed one small "honors" lecture section of less than 30 students and the rest were large lecture sections of over 100 students. Students in the honors sections had the same recitations, homework, exams, and projects as the rest of the sections, with a smaller classroom instead of a large lecture hall. During the course of the semester, some students would find out about the honors lecture sections or alternate large lecture sections and choose to switch to better suit their schedules or preferred lecturers. There was no method to track which students were actually enrolled in each section, with students switching among sections and lecturers further adding variability to the formation of classroom cultures. Individual interviews with students highlighted this flexibility, as some explained their choices to attend different lectures while others had never considered the possibility of attending a class they were not officially enrolled in. Interview subjects were chosen from both honors and larger lecture sections, from a variety of majors (see Table 3).

Table 3: Student Interviewee Details

Student Pseudonym	Sex	Semester 1: Calc 3 Section	Semester 2: Diff Eq Section	Major at start of Semester 3
Aurora	F	Honors	Honors	Computer Science
Dylan	M	Honors	Honors	Mechanical
Elizabeth	F	Large	Large	Aerospace
Eric	M	Large	Large	Mechanical
Ethan	M	Honors	Honors	Applied Math and Engineering Physics
Jason	M	Honors	N/A	Biochemistry
Leigh	F	N/A	Large	Civil
Nate	M	Large	Large	Aerospace
Susan	F	Large	N/A	?

The instructors of the courses under study were all experienced in that they had each taught the courses at least once before, and in some cases many times before. The research team informed the instructors under observation early on during the semester with a short description of the study and its purpose. Instructors generally ignored the presence of the research team in the classes, enabling surreptitious participant observation in the classroom.

Table 4: Details of Instructors Observed

Instructor Pseudonym	Course Observed	# Interviews
Dr. Hayes	Calc 3	2
Dr. Oliver	Calc 3	0
Dr. Lewis	Diff Eq	2
Dr. Greene	Diff Eq	0
Dr. Perry	Diff Eq	0

TAs were chosen for interviews based on a variety of criteria: one conducted the Calc 3 recitation observed by the research team during the first semester of data collection, one was in charge of an optional course offered to supplement Calc 3, and two were in a leadership position for the department during the academic year and thus uniquely positioned to discuss the administration and logistical organizing of the TA system. All of the TAs interviewed were at least in their second year of graduate school, and serving as TAs for at least the third full semester in the Applied Math department at CU.

Table 5: TA Interviewee Details

TA Pseudonym	Sex	Courses TA'd	# Interviews
Roger	M	Calc 3	1
Sylvie	F	Diff Eq, Calc 3, Calc 2, Calc 1	1
Sam	M	Calc 1, Calc 2	1
Carol	F	Calc 1, Calc 2, Calc 3	1

4.3.3 Qualitative Analysis Methods/Process

Analysis and collection of data occurred in overlapping cycles, with all data collected by the end of three semesters. Interviews and focus groups were transcribed into text and then input into the qualitative analysis software package NVivo, along with the fieldnote observations and salient artifacts from the courses under study. Analytic memos were written and discussed by the research team during the data collection period and afterward, based on emergent topics from the data. Additional artifacts were procured from research participants based on interview and focus group transcripts, to further illustrate aspects of participant stories and experiences in these sophomore level mathematics courses.

Multiple iterations of coding schemes were developed based on the research paradigm at the time. A descriptive codebook was created initially to categorize the data by major course events and actors including professors, exams, projects, homework, lecture, recitation, and more. Later an actor-network codebook was constructed in-line with the conceptual framework in order to categorize the different relationships and network connections made between the various actors under study, including person-to-person connections like students relating to their peers, person-to-material spatial connections like TAs connecting to their classrooms and office hour spaces, and person-to-representational/inscriptional connections like instructors connecting to the mathematical concepts and content of their courses. Categorizing the data by type of actor-network relationship was intended to highlight the different organizations of actor-networks evident for the various actors under study, mapping out the actor-networks of sophomore year and their movement through time and space. Attention was also paid to the strength of the various network connections, as loosely connected items were contrasted with strongly connected relationships among all types of actors. The final actor-network codebook is included in Appendix D for reference.

4.3.4 Threats to Validity

Social science researchers have developed extensive standards, frameworks and literature on the topic of quality and rigor in qualitative research (e.g., Lincoln & Guba, 1985; Miles, Huberman, & Saldaña, 2013), yet engineering education researchers have chosen to create their own framework for quality in interpretive research called “Qualifying Qualitative Research Quality” or “Q3” (Walther, Sochacka, & Kellam, 2013). The engineering education community has seemingly taken up this framework and is advocating its use in engineering education qualitative research, so we chose to use the Q3 framework instead of others in discussing the validity of our study (A. Pawley, personal communication, June 16, 2014). The creators of the Q3 framework believe that its format is uniquely suited for engineering education researchers and that it is justified by our community's specific needs and traditions (J. Walther, personal communication, June 12, 2012). Consequently this section of the dissertation explains the Q3 Quality Framework and details how our research has considered each aspect of this framework throughout our data collection, analysis, and subsequent writing.

The Q3 Framework was introduced to the engineering education community around 2012 with a conference paper and accompanying workshop at the American Society for Engineering Education (ASEE) Annual Conference & Exposition by Walther, Sochacka, & Kellam (2012). The framework was refined through various conference proceedings and journal publications (2013), with another workshop offered at the 2014 Frontiers in Education (FIE) Conference attended by two members of the research team (2014). A handout from this workshop session titled "Questions of Quality in Interpretive Research" is reproduced in Appendix E, as it provides a visual flowchart journey through the talking points of the Q3 framework that are addressed in this section. The authors suggest that the categories are overlapping and not sequential, yet for explanatory purposes we proceed through them one by one before summarizing at the end.

The first category posted by the Q3 framework involves "Theoretical Validation" and "concerns the fit between the social reality under investigation and the theory generated" (Walther & Sochacka, 2014). As discussed in the Data Sources and Collection Methods section, we feel that Actor-Network Theory is an ideal fit for studying the social reality of sophomore engineers. ANT theorists actually suggest that there is no such thing as a preconceived "social reality;" instead of assuming the nature of prior relationships and social structures, researchers must themselves look for the specific connections between local actors that have relevant consequences and effects (Latour, 2005). The symmetry between human and non-human actors espoused by ANT helps to level the playing field between people and the artifacts they encounter, helping to keep the familiar strange and prevent biases and assumptions from directing the analysis. Thus, the Q3 idea of theoretical validation, the fit between theory and social reality, is addressed by the tenets of ANT itself.

"Procedural Validation," which "concerns features of the research design that inherently improve the fit between the reality studied and the theory generated" comprises the next category of the Q3 framework (Walther & Sochacka, 2014). This category asks if the methods and procedures of the data collection and analysis are sufficient to ensure an "authentic view" of the participant's social reality, with triangulation given as one example strategy for addressing procedural validation. In our study, we have triangulated in accordance with ANT, comparing in-class observations with the notes, memories, and opinions of students and teachers; student feelings regarding homework assignments and exams as expressed in interviews with the actual homework assignments, solutions, exams, and exam solutions; and more. FCQ data, course grade distributions, and archival data from historical resources have also been part of the data collection to further illuminate aspects of the actor-networks under study. While a non-traditional type of triangulation, we believe that our study has sufficient diversity of data from both humans and non-humans to support our findings. Furthermore, our research design included follow-up interviews with instructors in order to check researcher interpretations of the data, as well as focus group sessions with students in order to clarify contentious issues, which emerged from the data. In these ways we have attempted to address the category of procedural validation through our research design, data collection, and data analysis processes.

The third category from the Q3 framework is "Communicative Validation," which "concerns the integrity of the interlocking processes of social construction with the relevant communication communities" (Walther & Sochacka, 2014). In other words, this category asks if the participants' meanings are captured in their own terms appropriately, and if these meanings can be translated to research audiences and other audiences without losing the original intent and sense of the participants. For our study, this category encourages us to see how we make meaning from participant interviews and artifacts, and if during the process of analysis or writing any of the meanings are lost. For instance, we examine what it means for the different communication communities of teachers and students to have opposite opinions on the fairness of exams in Applied Math. The teachers believe and state that the tests are fair, while the students maintain throughout interviews and focus groups that the tests are unfair. Our analysis and writing process must honor both perspectives, the meanings from both communities, without taking away either one. In bringing the findings and our study to an engineering education audience, another communication community, we must also be cognizant of not losing anything in the translation and compression process of writing. Overall, instead of smoothing over differences in opinion in our data, we seek instead to show the mismatches and explain all sides of the argument in the language of ANT. In lieu of forcing a consensus in our data, we examine the tensions between accounts and are informed by the disagreements that highlight the different actor-network perspectives of those under study. In this way, ANT is conducive to illustrating differences in the organization of actor-networks, types and strengths of network connections, and consequences to the actors involved. Thus it is a sign of communicative validity that we honor our participant's voices even when they fundamentally disagree.

"Pragmatic Validation" is next, a category that "concerns the compatibility of theoretical constructs with empirical reality" (Walther & Sochacka, 2014). Generally, this category can be conceptualized as asking if the research study is practical and grounded in reality, if the findings will resonate with the stakeholders involved, and if the recommendations generated by the study will actually be taken up by those in a position to act on them. No one wants to do a study that has no bearing on reality or that generates findings that no one is interested in or cares to listen to. Since we have chosen gateway courses of engineering sophomore year as the starting point for our analysis, a topic that many are interested in both globally in the engineering education community and locally with the administration at CU Boulder, we feel that our study is relevant and will resonate with multiple audiences. By maintaining close contact with the administration at CU Boulder that is currently interested in improving the mathematics experience of engineering undergraduates, we feel that this study is indeed pragmatic and important for those looking to change policies related to these required math courses (J. Sullivan & D. Sieber, personal communication, December 4, 2014). Additionally, the research team has been in close contact with instructors and administrators of the Applied Math department under study, so that they will be familiar with the research design, the researchers, and the findings from our work. In keeping these different groups involved in the research, we believe that our study will have pragmatic validity and could even make a positive impact on the undergraduate experience.

The last category related to validation is "Ethical Validation," which "concerns aspects of integrity and responsibility throughout the research process" (Walther & Sochacka, 2014). This category deals with potential research biases, preconceptions, and intentions of the research team, questioning what type of effect these would have on the research. For our study, we believe we are in an advantageous position for investigating the experiences of sophomores in mathematics courses. As the research team is affiliated with Mechanical Engineering, not Applied Math, we have a degree of separation from the inner workings of the department and have no agenda related to how we portray the instructional system in our study. Similarly, since we are not affiliated with the Dean's office or the administration of the College of Engineering and Applied Science, we are not bound by institutional priorities like improving our retention rates with regards to how we interpret our data and make our recommendations. We acknowledge and are intimately aware of the sensitive nature of our study, and tread carefully in our analysis realizing that stakeholders on all sides (teachers, students, TAs, administration) may see our study as a threat or challenge to their current interpretation of the educational system. Our priority is to maintain our integrity and honestly represent the research participants who offered their honest opinions and reflections during our interviews and focus groups – we wish to "do justice to the lived realities of our participants" (Walther & Sochacka, 2014) and are sensitive to making the voices of our participants heard, even when they disagree. Our three-person qualitative research team that includes one instructor, one research faculty, and one graduate student has been helpful in checking each other's biases and discussing assumptions and preconceptions from each of our official roles. Research meetings have involved honest discussion of our reactions to data from both students and teachers, commenting on our different perspectives and how the same events (i.e., a midterm) can be interpreted very differently by the various parties involved. Our research requires withholding judgment, instead looking to map out the consequences that arise from different interpretations and experiences of events, examining how connections are formed or dissolved as a response to various stimuli (like doing poorly on a midterm). As the research involves attention to power dynamics and the interests of diverse populations, we remain neutral by not promising any outcomes and by not allying ourselves with administrators, teachers, or students. We protect our position as researchers interested in knowledge, not political agendas, to maintain our ethical responsibility to accurately portray the sociocultural environments under study.

The final category of the Q3 framework relates to "Process Reliability," which "concerns the mitigation of random influences on the research process" (Walther & Sochacka, 2014). We recognize that our three-semester long study may be influenced by variations in the specific cohort studied. Similarly, as the total count of student interview and focus group participants in the study was around 20, it is possible that we missed some students who would offer different answers to the interview and focus group questions we posed. All students who attended classes were observed, however, during participant observations of lecture and recitation sections of Calc 3 and Diff Eq. Generally despite these limitations, we feel that we have obtained a sufficient sample size for this exploratory study into an understudied time in an engineering undergraduate's trajectory. As we are looking to explain how actor-network connections are formed and severed dynamically during sophomore gateway courses, this is a good starting point for illustrating these actor-networks and the conditions that affect their development and in-line with the scope of similar ANT studies (Busch, 1997; Fenwick & Edwards, 2010; S. Fox, 2005; Nespor, 1994). Follow-up studies will have no shortage of additional populations and environments to study, but as our work is novel and based on prolonged observation and exposure to these focal classes, students, and instructors, it offers a unique empirical view into the experiences of sophomore engineering undergraduates. The multiple interviews with instructors and student research participants also helps to mitigate the possibility of undue random influences in the data, as spurious questions were asked and clarifications were sought on contentious issues. The continued involvement of instructors and administrators also speaks to the reliability of the study, as their opinions have been sought where appropriate to check researcher interpretations of the data.

Overall, we take away from the Q3 framework an acceptance of the validity and reliability of our work. While we recognize the limitations to our analysis, we see that the work has immense potential for describing the understudied phenomena occurring during this critical transition time in engineering undergraduate.

Interlude: Actor-Network Durability in the College of Engineering Mathematics Sequence

While the Background chapter covered both canonical and contemporary usages of ANT in a variety of settings, we now choose to explain ANT by describing the activities and efforts which led to the initial creation of the main Engineering Center building that has housed and organized engineering activities on this campus since 1965. The largest building on campus at the time of its construction, this concrete behemoth has garnered both criticism and acclaim throughout the last fifty years. Informed by ANT, we trace out the influential actors, educational movements, and artifacts that played a large part in instituting this building that we still use. We also identify how the physical spaces and ideologies built into the Engineering Center have affected the movement and shape of student actor-networks to the present day. This interlude illustrates through application the usefulness of ANT concepts in local environments.

Do Artifacts Have Politics? This story starts with a simple comment from Winner (1986): "Histories of architecture, city planning, and public works contain many examples of physical arrangements that contain explicit or implicit political purposes" (1986, p. 23). The context of this declaration is the story of Robert Moses as told by R. Caro (1975); an influential biography which painted Moses as a progressive dreamer who was eventually corrupted by the enormous power he wielded as the de facto Master Builder of Long Island and New York City, New York. From 1924-1968 Moses built parks, roads, bridges, beaches, and more in accordance with his vision of the world, with his values and desires built-in (Caro, 1975; Powell, 2007). Described as a bigot and racist by colleagues, Moses designed the overpass bridges over the Long Island Expressway to hang very low, prohibitively low to public buses but passable for passenger vehicles owned by the white middle and upper classes (Caro, 1975; Powell, 2007). In doing so, Moses effectively cast his intentions in stone, the physical artifacts of the expressway and the low overpasses, which restricted access of poorer populations to the public beaches he designed (Bleyer, 2004; Caro, 1975).

From an ANT perspective, these bridges are political artifacts, designed by Moses to purposefully keep poor, non-white city residents from accessing the lavish state parks. In line with Winner's statement, these overpasses exemplify the biased nature of artifacts as well as the shifting nature of their politics. As cars became more widespread, the overpasses became less of a constraint; people of all races now use the beaches Moses attempted to preserve for whites. Today the Long Island Expressway is considered outdated as it is too twisty, small, and narrow to accommodate the growing needs for mass transit (Rumsey, 2013). This once-political artifact no longer serves its initial purpose, yet still organizes human activity for those who suffer through traffic on the expressway. ANT encourages investigation of the consequences both intentional and unintentional of political artifacts like Moses's Long Island Expressway, including how these consequences can change drastically over time.

Winner (1986) continues, suggesting a locally relevant type of political artifact designed expressly for social purposes: "One can visit any number of grotesque concrete buildings and huge plazas constructed on American university campuses during the late 1960s and early 1970s to defuse student demonstrations" (p. 24). As the Engineering Center building is easily the most "grotesque concrete" structure on the University of Colorado Boulder's campus, Winner's statement stuck out as something worth investigating: Was the building really designed with a specific political purpose? In line with the lessons learned from Moses's expressways, how has technology shifted to change the consequences stemming from a building of this type? And, how have the educational activities in the building changed in the intervening fifty years?

Motivated by the desire to investigate these questions and uncover the motivation and reasoning behind the building's design, we researched the history of the building, the university, the architects, the curriculum, and more, tracing out connections between designers, artifacts, administrators, consequences, and users. What we found was unexpected, and unexpectedly relevant to Actor-Network Theory and our project as a whole. In this chapter, we discuss the history and design of the Engineering Center and analyze from an Actor-Network perspective the significance of the building's construction and organization on contemporary students, faculty, staff, and visitors who pass through the building every day.

The American Turn Towards "Engineering Science"

To explicate the Engineering Center, we first examine the social and cultural climate of America and American engineering during the decades prior to the building's construction. This section highlights the influential actors of the post-WWII era in the United States, making connections from nationwide trends to engineering at CU and in Boulder.

The balance between engineering, science, and engineering science in undergraduate engineering education has shifted twice in the last century. Seely (1999) discusses the "re-engineering of engineering education," referring to the late twentieth century reform efforts in engineering undergraduate programs as a second wave of engineering education transformation which re-incorporates design experiences and practical engineering knowledge. Under this paradigm, the first wave of engineering education reforms occurred between 1920 and 1950, spurred by prestigious engineering professors from Europe and Russia whose preference for engineering science and advanced theoretical knowledge spread widely throughout undergraduate engineering programs, dramatically altering America's conception of appropriate training for engineering students (Estrin & Van Houten, 1963). The burgeoning Cold War and space race of the late 1950s and 1960s further encouraged engineering educators towards increasingly rigorous technical and fundamental scientific training for undergraduates, even reaching the University of Colorado Boulder. As *Colorado Alumnus* magazine reported:

> One of the ingredients necessary to accomplish the proper chemistry for the stimulating engineering education is the spicy "why" mixed with the more solid and traditional staples – for engineers – "what" and "how"… [Dean] Peters hastens to add that he does not advocate divorce from "how" for a new, monogamous union with "why." Rather, he is saying that **the demands on engineers in our day require an increasing scientific content in the engineering curriculum: the "why."** ("Dean Peters Declares: Students Should Be Excited to Become Engineers," 1962, emphasis added)

This excerpt sums up the prevailing trend of engineering education in the early 1960s, condensing prior engineering training into "what" and "how," and looking toward future engineers as needing "increased scientific content," or more of the "why" behind how things work.

Professor Stephen Timoshenko, originally from Russia, was one of the hugely influential foreign scholars who transformed engineering education in the United States between the 1920s and his eventual death in 1972. Upon his arrival to the United States in 1922 to work at Westinghouse Electric in Pittsburgh, Timoshenko promptly found fault in the poor education of American engineers:

> I was amazed at the complete divorce of strength-of-materials theory from experimental research. Most of my students had done no work whatsoever in mechanical testing of materials with measurements of their elastic properties. The newer methods of calculating beam deflection and investigating flexure in statically indeterminate cases had not been taught them at all… In the face of so feeble a

> background [I offered a course given for sophomores in Russia]. (Timoshenko, 1968, pp. 253, 280; quoted in Seely, 1999, p. 289)

Today, Timoshenko is known as the "father of engineering mechanics" (Hartog, 1968) who "transformed the teaching of engineering mechanics in our universities" (Weingardt, 2007). The reach of Timoshenko as he moved from Westinghouse into academia at the University of Michigan (1927-1936) and finally Stanford University (1936-1946) is still vast, as evident in the required undergraduate coursework for nearly all engineering majors today. Several of the twelve engineering textbooks Timoshenko authored or co-authored have been reissued and revised by coauthors as recently as 2012, while his first published textbook in 1925 remains a classic (Timoshenko & Lessells, 1925). Notably, the Mechanics of Materials textbook by Timoshenko (and later, Gere) has served as the foundational text for undergraduate Solid Mechanics from the first edition (Timoshenko & Gere, 1972) to the present (Gere & Goodno, 2012).

Timoshenko immigrated to the United States when he was 44, educated in the Russian engineering and research traditions. He was equally as critical of the organization of American universities as he was of the undergraduate engineering content material. In the *Journal of Engineering Education* in 1959, he explained how Russian institutions were administered and organized:

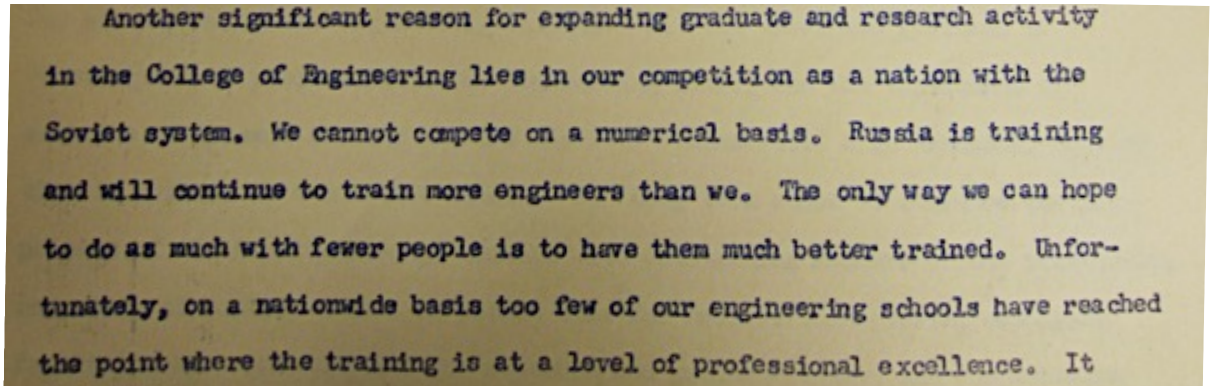
> The Russian engineering schools are considered to be not only teaching institutions, but also centers of research in engineering sciences. One can deduce from the quantity and quality of Russian technical publications that a considerable volume of scientific work is going on in engineering sciences, and that a substantial portion of it is contributed by the teaching staff of the engineering schools. (Timoshenko, 1963, p. 48)

This description of Russian engineering schools producing “a considerable volume of scientific work”, as “centers of research in engineering sciences” offered a new view of engineering institutions, tied to research and science (the “why”) instead of the “how” and “what” of tradition. As described in the subsequent sections, this turn towards the “spicy why” of engineering science influenced the construction and design of the Engineering Center and CU’s curriculum in far-reaching ways.

In line with Actor-Network Theory, we see this national turn towards engineering science as one level of *problematization.* Engineering’s identity is being redefined, transformed away from its experiential roots to include a greater focus on scientific and mathematical content. The United States is becoming *interested* (or *interessed),* in order to “win” the Cold War and re-establish rigor and prestige in our engineering training programs. Thus we see the effects of situating human actors within powerful academic networks – Timoshenko and the other émigré engineers and scientists who found fault with the quality of U.S. engineering education and were in positions for their complaints to be heard, Dean Max Peters and other engineering deans whose best interests resided in increasing the theoretical content of the engineering curriculum while simultaneously expanding their research programs and national reputations – and we also hear, at a much quieter volume, the protests of those who preferred the original, applied definition and conceptualization of engineering. Yet with the advancement of electronics, the innovations in computing, and the space race, those advocating for modernization through engineering science had additional powerful allies. Thus the revised definition of engineering to include a greater emphasis on the sciences became widespread, the new identity of engineering forged in part by these powerful actors. While some say ‘history is written by the victors’, in line with Actor-Network Theory we see that history starts from *problematization*: the defining of allowable identities by influential actors in the actor-network.

“Engineering Science” at CU

Timoshenko’s perspective was particularly influential because domestic engineering educators were simultaneously concerned about competing versus the Russians, even at CU:



Another significant reason for expanding graduate and research activity in the College of Engineering lies in our competition as a nation with the Soviet system. We cannot compete on a numerical basis. Russia is training and will continue to train more engineers than we. The only way we can hope to do as much with fewer people is to have them much better trained. Unfortunately, on a nationwide basis too few of our engineering schools have reached the point where the training is at a level of professional excellence. It

Figure 6: Report of the Sub-Committee on Curricula, 1959

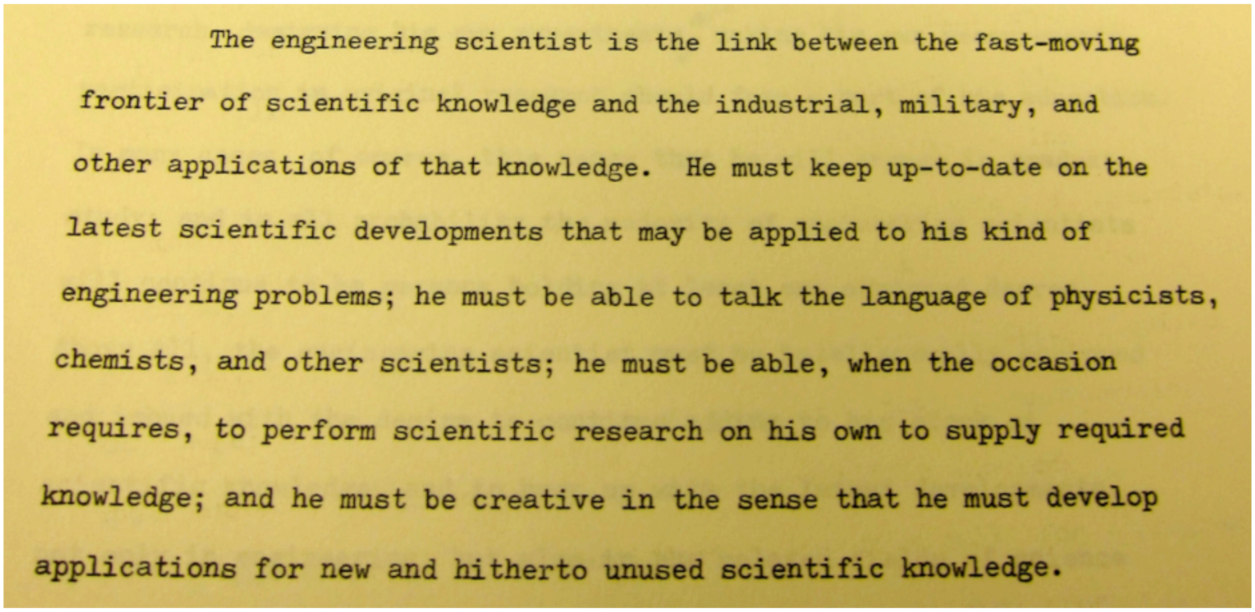
This excerpt, found within the official College of Engineering records in the University of Colorado Archives, demonstrates how the faculty serving on the “Sub-Committee on Curricula” were aware of the Soviet threat and the subsequent need to “better train” our engineers to stay competitive as a nation. This argument – the need to stay competitive with the Soviets – was one of the main justifications behind “expanding graduate and research activity in the College of Engineering”, a shift in the academic system and engineering education as a whole that has endured. Similar rhetoric about maintaining our “global competitiveness” through the proper training of engineers exists today, though the focus of our competition has turned towards China and India instead of Soviet Russia (Augustine, 2011).

The turn towards "engineering science" was acknowledged explicitly in a variety of noteworthy publications in the late 1950s and early 1960s, reaching Boulder to influence the opinions of administrators and faculty here (Alexander, 1959; Estrin & Van Houten, 1963; Grinter, 1959). As summarized in the official account of the college's history:

> At the hub of what was fast becoming the science center that Boulder is today, the College of Engineering was acutely aware, in 1959, of its shortcomings. It needed a distinguished faculty. It needed space. It needed a research program ten times its present scope. In short, it needed to become a center for engineering education comparable in stature to those at Stanford, the University of California, and the University of Illinois. (Mandel & Shipley, 1966, p. 194)

As explained here, the college was "acutely aware" of its shortcomings and was taking action, in fact, to address the college's perceived limitations. Our college was *interested* in addressing these "shortcomings" to reach the "distinguished" level of Stanford. The excerpt above illustrates the local devices of *interessement*; our official history contextualizes the institutional belief that greater focus on engineering science was necessary, thanks in part to the efforts of the surrounding actors (including Timoshenko) to encourage this buy-in, this *interest* or *investment*.

Committees were formed to study the needs of the College of Engineering, including the appointment of various faculty and consultants to form the "Engineering Building Committee". Among their findings related to the needs for space and a new engineering building, this committee reported in 1960:

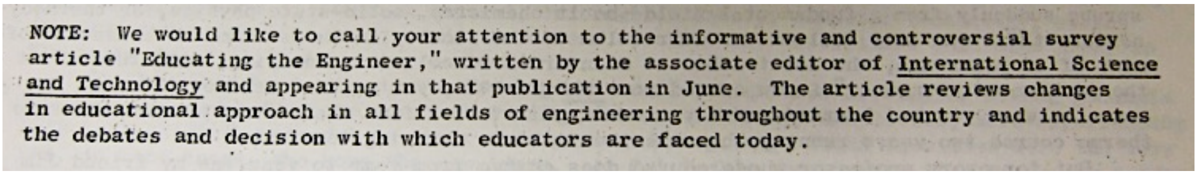


The engineering scientist is the link between the fast-moving frontier of scientific knowledge and the industrial, military, and other applications of that knowledge. He must keep up-to-date on the latest scientific developments that may be applied to his kind of engineering problems; he must be able to talk the language of physicists, chemists, and other scientists; he must be able, when the occasion requires, to perform scientific research on his own to supply required knowledge; and he must be creative in the sense that he must develop applications for new and hitherto unused scientific knowledge.

Figure 7: Report of the Engineering Building Committee April 1, 1960

The members of the committee understood the importance of the turn towards engineering science, and described the "engineering scientist" as an important "link" between the "frontier of scientific knowledge" and the "other applications of that knowledge". The committee utilized this concept of the "engineering scientist" in designing the building, believing that engineering science and an expanded research program was needed for future survival. Under the ideology of becoming "the leading college of engineering in the Rocky Mountain Region", the committee convinced the administration that a new building was desperately needed (Mandel & Shipley, 1966, p. 196).

Max Peters, who became Dean of the college in 1962, was an advocate of these arguments and a proponent for the new center. Dean Peters hailed from the University of Illinois, one of the institutions CU looked to as a model of engineering science and leadership in engineering education. In his messages to the faculty, in the form of printed Faculty Newsletters, Dean Peters often called attention to recent scholarship in the field of engineering education. In September 1963, for instance, Dean Peters republished an influential article about "Educating the Engineer" in the Faculty Newsletter, with the following foreword:



NOTE: We would like to call your attention to the informative and controversial survey article "Educating the Engineer," written by the associate editor of International Science and Technology and appearing in that publication in June. The article reviews changes in educational approach in all fields of engineering throughout the country and indicates the debates and decision with which educators are faced today.

Figure 8: Dean Peters's foreword, September 1963 Faculty Newsletter

Written by David Allison, the "Educating the Engineer" article covered a wide range of topics, institutions, and opinions related to the changing landscape of engineering education. On one hand was the powerful and prestigious engineering science contingent represented by MIT, Stanford, and Caltech and their leaders, notably Dean Gordon Brown of MIT. Dr. Brown first initiated reforms as Department Head of Electrical Engineering at MIT, eliminating traditional courses relating to machinery and power plant design much to the chagrin of power engineers in industry and the AIEE (American Institute of Electrical Engineers). While the professional engineers once threatened to withhold accreditation for Dr. Brown's new curriculum, they eventually "came around" and thus MIT established a model of engineering science education for the rest of the nation to follow:

> There had to be a close association between faculty and students in research, a strong program for teaching advanced concepts in graduate courses, and a faculty that is enthusiastic about integrating these ideas into new meaningful forms and teaching them in a coherent and stimulating manner to undergraduates… During his early training, the engineering student has no alternative but to gain essentially the same mastery of the basic sciences as is required of a scientist. (Allison, 1963, pp. 28–29)

In transforming electrical engineering and winning the battle versus the legacy and traditions of engineering education, Dr. Gordon paved the way for other departments to dramatically adjust their undergraduate curricula. In this way, Dr. Gordon and MIT were powerful actors in this network who recruited Dean Peters into their fold. They *interested* him in seeing their point of view that there was "no alternative" to gaining "mastery of the basic sciences" in educating modern engineers.

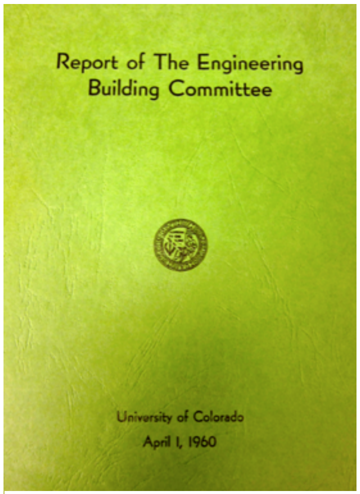
On the other hand, institutions including UCLA and Dartmouth and their leaders remained vocal about the "dangerous" trend towards engineering science, explaining that this trend was detrimental in confusing the public image of engineering and taking the focus away from design. UCLA's educational model included common training for the single "engineering" degree, with Dean L.M.K. Boelter believing "that specialization in engineering can be postponed until after the completion of the undergraduate curriculum" (Allison, 1963, p. 29). Arguments against this system were primarily that without departments, it would be difficult to do the cutting-edge research that supposedly accompanies a strong undergraduate program.

In any case, Allison's article explained that engineers on both sides of the divide between science and design in engineering agreed "that the engineer, as presently taught in most schools, is insufficiently equipped to *do* engineering" (Allison, 1963, p. 31). Seemingly clear to engineers and administrators at these institutions of higher learning were the limitations of the current approach and personnel for effectively teaching students contemporary knowledge. Suggestions for improving included developing more teachers of engineering, focusing on the recruitment of promising students into doctoral programs and the academy instead of industry and defense agencies. Tempered with the actual numbers of students in engineering degree programs, Allison's article concluded that "the situation has many of the elements of a dog chasing its tail", as to graduate more PhDs to suit the needs of industry and academia, schools would require more PhD advisors and professors, etc. The shortage of qualified engineers was seen then as a threat to our nation's survival, another device of *interessement* to convince the US to grow more engineers. This theme has reemerged in the twenty-first century, now accompanied by government initiatives to address our shortage of STEM-trained workers (Engler, 2012).

Dean Max Peters at CU was aware of the growing debate regarding the philosophy and method of teaching engineering and the need to grow more engineers nationwide, publicizing the controversy and discussion via the CU Faculty Newsletter. Coming from Illinois, Dean Peters was privy to the Caltech-MIT-Stanford model of engineering education, bringing an increased awareness of and emphasis on engineering science to CU in the early 1960s. Viewed through the dual lenses of hindsight and Actor-Network Theory, we see the devices of *interessement* acting on Dean Peters – he had personally experienced the turn towards engineering science and was hired in part to bring that prestigious model of engineering research and education to CU. In presenting the debate to the CU faculty, he was beginning the process of *interesting* (*interessing*) them as well.

Mapping the Needs of CU's Engineering Departments

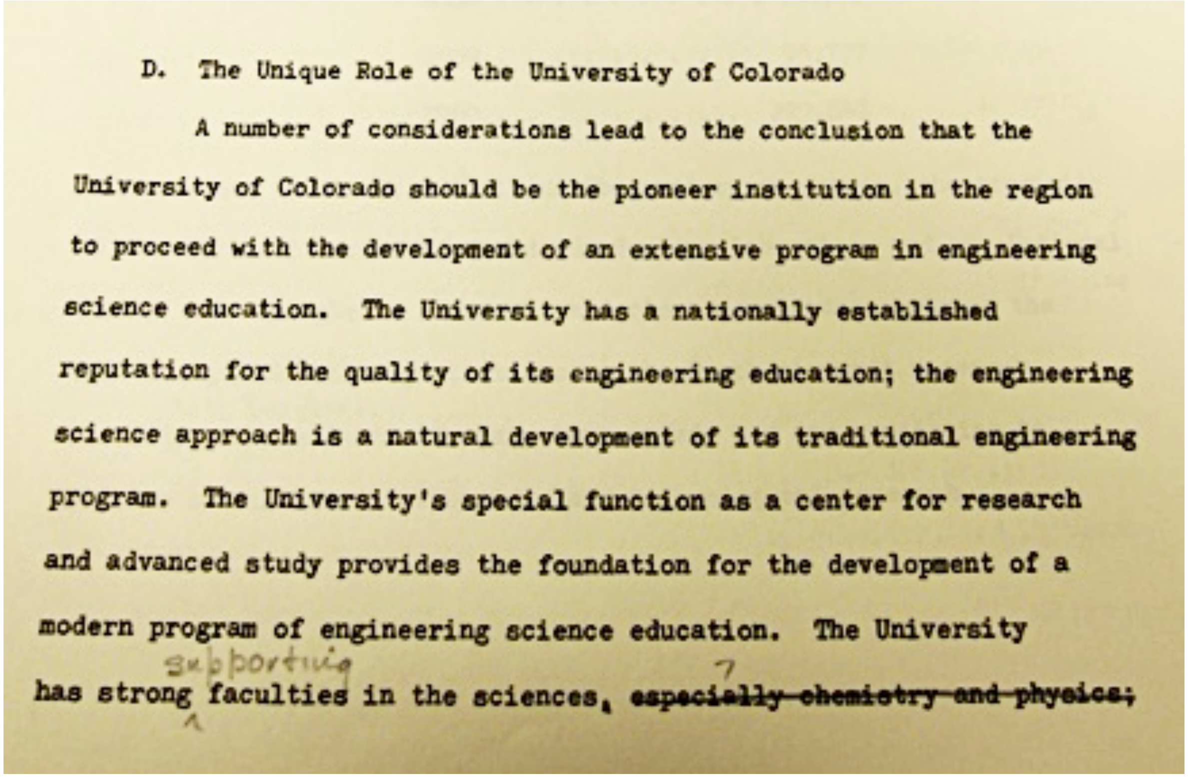
Around the same time the nation, Dean Peters and CU were debating and turning towards engineering science, the College of Engineering was faced with a pressing need to design, fund, and build a new engineering complex. By 1955, the College of Engineering Planning Committee, led by Associate Professor Robert Rathburn of architectural engineering, submitted a report regarding the new "Building Program," describing the overall vision and general need for a new building with laboratories, classrooms, offices, and an auditorium. With institutional support and resources, this committee was able to refine and expand the report by 1960, detailing the number of classrooms and square footage needed for the new center, and the offices and laboratory space that each department would require. This "Report of the Engineering Building Committee", drafted by 1960, also included rhetoric and justification for CU's unique and necessary role in training engineers:



Report of The Engineering
Building Committee

University of Colorado
April 1, 1960

Figure 9: Committee Report, 1960



D. The Unique Role of the University of Colorado

A number of considerations lead to the conclusion that the University of Colorado should be the pioneer institution in the region to proceed with the development of an extensive program in engineering science education. The University has a nationally established reputation for the quality of its engineering education; the engineering science approach is a natural development of its traditional engineering program. The University's special function as a center for research and advanced study provides the foundation for the development of a modern program of engineering science education. The University has strong supporting faculties in the sciences, ~~especially chemistry and physics;~~

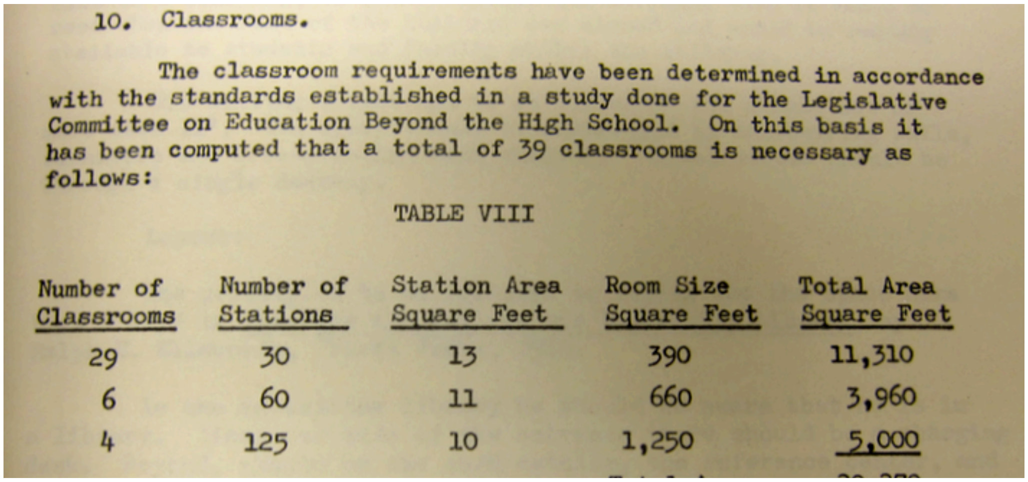
Figure 10: Excerpt from Committee Report, 1960

Once revised, this report became the foundation for a printed booklet about "the Engineering Sciences Center at the University of Colorado" which was subsequently distributed to legislators, lobbyists, and policy-makers by 1961. By this point, the specifications for the center had been identified and combined as "the Program Requirements for the Engineering Sciences Center", which was disseminated to architectural consultants and architects bidding on the project in October 1961. The requirements were listed in tabular form and in circulation diagrams, which indicated the relative square footage for various offices and laboratories from each department. The circulation diagrams for two exemplar departments are included below for reference, as is the overall circulation diagram for the entire building. The overall circulation diagram includes a representation of the percentage of each department's space allotted to research: ranging from 11% in the Engineering Graphics Department to 49.9% for Aerospace Engineering.

Demonstrated by the percentage of space designated for engineering research in the plans for the new building, the College of Engineering was clearly *interested* and *invested* (*interessed*) in a greater focus on engineering science and research, just as advocated by Timoshenko. As the building plans began to take shape, the intent to increase our research activities in engineering became fundamentally integrated into these tables and circulation diagrams, and eventually in the blueprints, specifications, and requirements. Cast first on paper, we will see how these intentions eventually became tangible and enmeshed into the building, a process of *enrollment* confirming the institution's *interessement* in the engineering sciences.

The circulation diagram for the overall "Engineering Sciences Building" indicates the relative size and relationship of rooms to one another, and dictated the amount of space that each engineering department thought they would need in 1961. From the overall circulation diagram, reproduced as Figure 12 on the next page, we see a few items of interest:

- Faculty offices were twice the square footage of classroom space: 40,500 vs. 20,270 sq. ft.
- Lecture halls were separate from Classrooms for the purposes of planning, and represented 4,200 sq. ft. See inset below for detail on Classrooms.



10. Classrooms.

The classroom requirements have been determined in accordance with the standards established in a study done for the Legislative Committee on Education Beyond the High School. On this basis it has been computed that a total of 39 classrooms is necessary as follows:

TABLE VIII

Number of Classrooms	Number of Stations	Station Area Square Feet	Room Size Square Feet	Total Area Square Feet
29	30	13	390	11,310
6	60	11	660	3,960
4	125	10	1,250	5,000

Figure 11: Details for Classroom Sizes, Engineering Sciences Center, Oct 1961

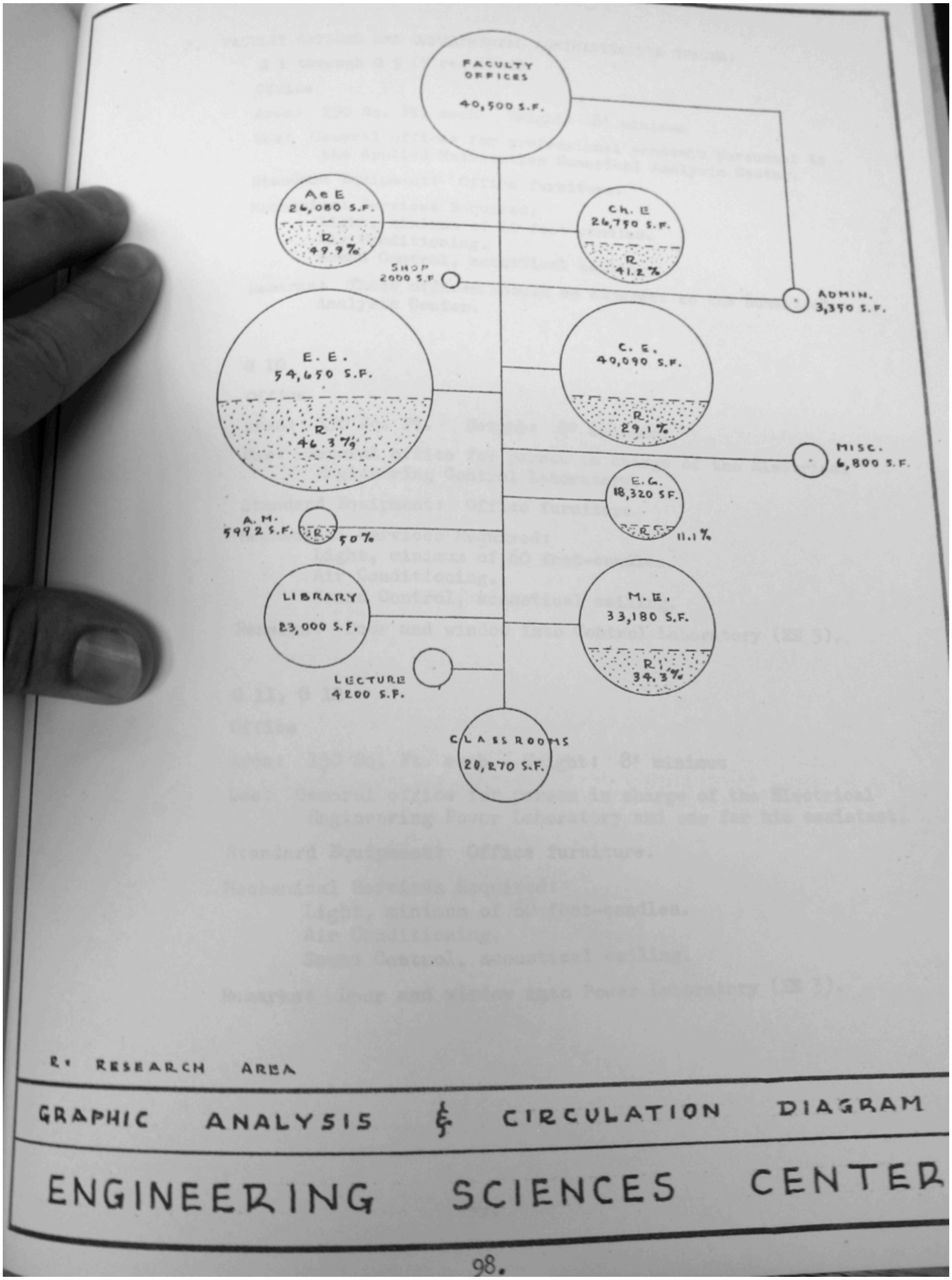


Figure 12: Circulation Diagram for the Engineering Sciences Center, Oct 1961

Tallying up the information displayed in graphical form on the Circulation Diagram for the overall building, we also see the relative sizes of each department and the administration, and the percentage of each department's space allocated from the outset for research:

- Administration was separate from Faculty offices, and required 3,350 sq. ft.
- Shop was separate from individual departments, and required 2,000 sq. ft.
- The departments of this era included:

Table 6: Size in Square Feet of Departmental Spaces, with Percentage Devoted to Research

Department	Allotted Sq. Ft.	Research Percentage
Aerospace	26,080	49.9
Chemical	26,750	41.2
Civil	40,090	29.1
Electrical	54,650	46.1
Engineering Graphics	18,320	11.1
Applied Math	5,992	50
Mechanical Engineering	33,180	34.3

We take a detailed look at Mechanical Engineering's planned spaces and circulation on the following page.

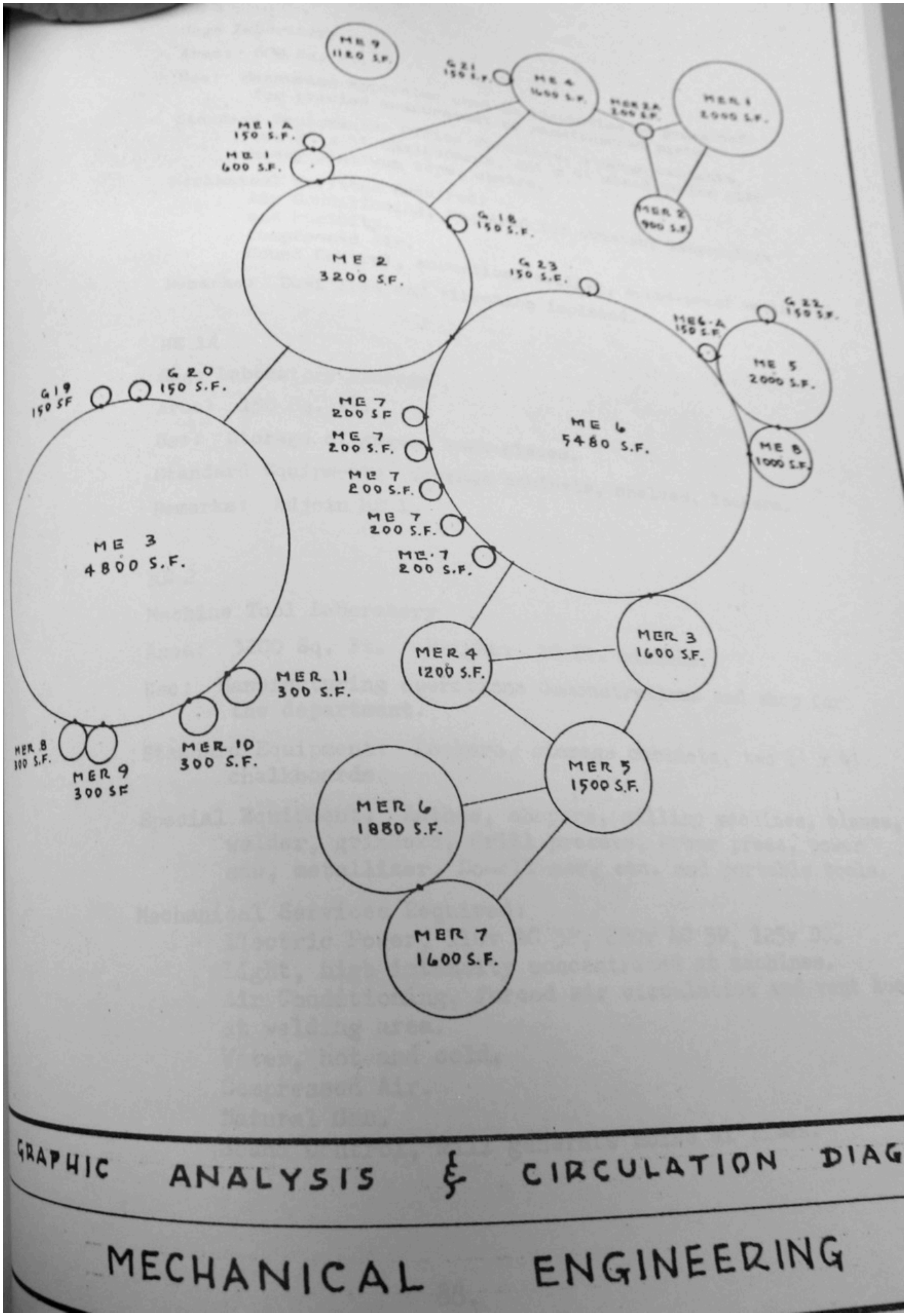


Figure 13: Circulation Diagram, Mechanical Engineering, Oct 1961

Looking over this diagram, we see the general blocks of space the department requested in the new building. The details of each circle, aside from the square footage, were listed in pages following the circulation diagrams, specified for the architect. For instance, ME1 was the Gage Laboratory, while ME2 was to be the Machine Tool Laboratory. The image explains what the architects had to work with, how the requirements were transferred from individual departments to university committees to designers who ultimately made the center what it is today. In comparison with the Applied Math circulation diagram, below, salient differences in spatial organization and requirements are apparent:

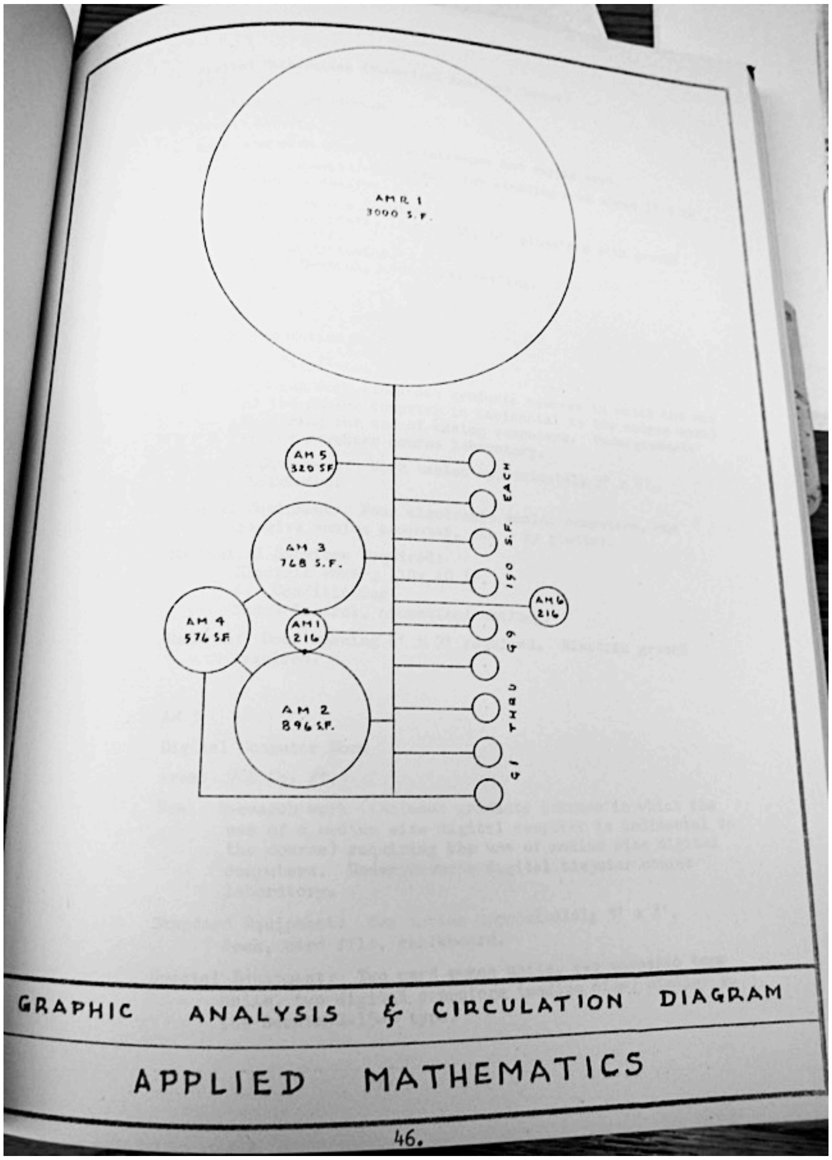
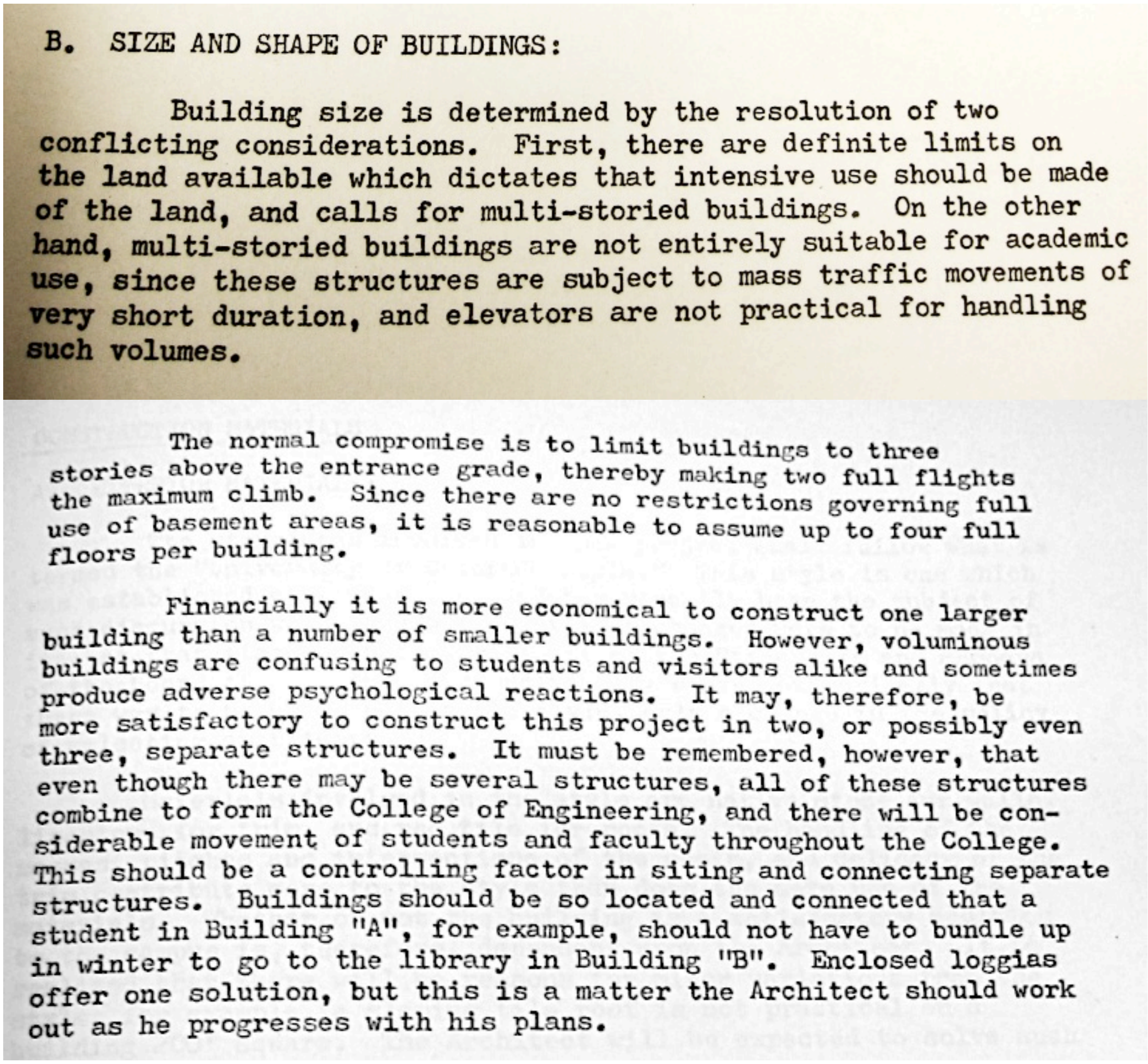


Figure 14: Circulation Diagram, Applied Mathematics, Oct 1961

Whereas the Mechanical Engineering department required several large blocks of space, connected in turn to rooms of various sizes, the Applied Math department appears much more linear – a central line connecting one very large room of 3,000 sq. ft. to smaller rooms, including nine identical 150 sq. ft. spaces. AM1 was a Maintenance and Storage room to support computer equipment, AM2 was the Analog Computation Room to house the analog computer, and AM3 was the Digital Computer room. In the specifications for the Digital Computer Room, two medium-size digital computers were requested to be similar to the Bendix G-15-D type. Allocating space to house these large computers was necessary for CU to remain on the cutting edge of contemporary technology, an important selling point for the institution and another demonstration of our *interest* and *enrollment* in moving forward with engineering technology, research, and applied science.

Clearly, the activity occurring in these rooms has shifted through the decades, as computers have become smaller and analog computation obsolete. As the newer practices of holding "office hours" and providing a math "help room" emerged, they occurred in spaces originally designed for something else – perhaps a room initially meant to store magnetic tape or punch cards. What is the impact of these spaces, originally designed for technology of the 1960s, on modern-day activities and practices? We continue investigating to find out.

In addition to these circulation diagrams and department-specific requirements, the Program Requirements for the Engineering Sciences Center booklet included description of the physical site designated for the new building. The University of Colorado campus employed the notable firm of Sasaki, Walker, and Associates, to be responsible for site development and long-term planning. These consultants had already identified that the Engineering Sciences Center project would be located just east of 24th Street and south of Pennsylvania Avenue, creating a constraint on the form factor of the building. The Program Requirements also discussed the "Size and Shape of Buildings" for the project:



B. SIZE AND SHAPE OF BUILDINGS:

Building size is determined by the resolution of two conflicting considerations. First, there are definite limits on the land available which dictates that intensive use should be made of the land, and calls for multi-storied buildings. On the other hand, multi-storied buildings are not entirely suitable for academic use, since these structures are subject to mass traffic movements of very short duration, and elevators are not practical for handling such volumes.

The normal compromise is to limit buildings to three stories above the entrance grade, thereby making two full flights the maximum climb. Since there are no restrictions governing full use of basement areas, it is reasonable to assume up to four full floors per building.

Financially it is more economical to construct one larger building than a number of smaller buildings. However, voluminous buildings are confusing to students and visitors alike and sometimes produce adverse psychological reactions. It may, therefore, be more satisfactory to construct this project in two, or possibly even three, separate structures. It must be remembered, however, that even though there may be several structures, all of these structures combine to form the College of Engineering, and there will be considerable movement of students and faculty throughout the College. This should be a controlling factor in siting and connecting separate structures. Buildings should be so located and connected that a student in Building "A", for example, should not have to bundle up in winter to go to the library in Building "B". Enclosed loggias offer one solution, but this is a matter the Architect should work out as he progresses with his plans.

Figure 15: Size and Shape of Buildings in Program Requirements, Oct 1961

Thus it was part of the project's architectural challenge to balance the limited size of the site with the given requirements for the spaces. A multi-story building was called for, but was coupled with the desire to avoid "adverse psychological reactions" associated with "voluminous buildings", a difficult task indeed. The consultants further specified "the considerable movement of students and faculty throughout the College", encouraging the architects to pay careful attention to this "controlling factor in siting and connecting separate structures". Furthermore, as these structures were to be "subject to mass movements of very short duration", a multi-story design dependent on elevators would not work to get all of the students and faculty where they needed to be, on time. As the building site was on the easternmost side of campus, connecting the building to the rest of the university, to the west, was also an important factor.

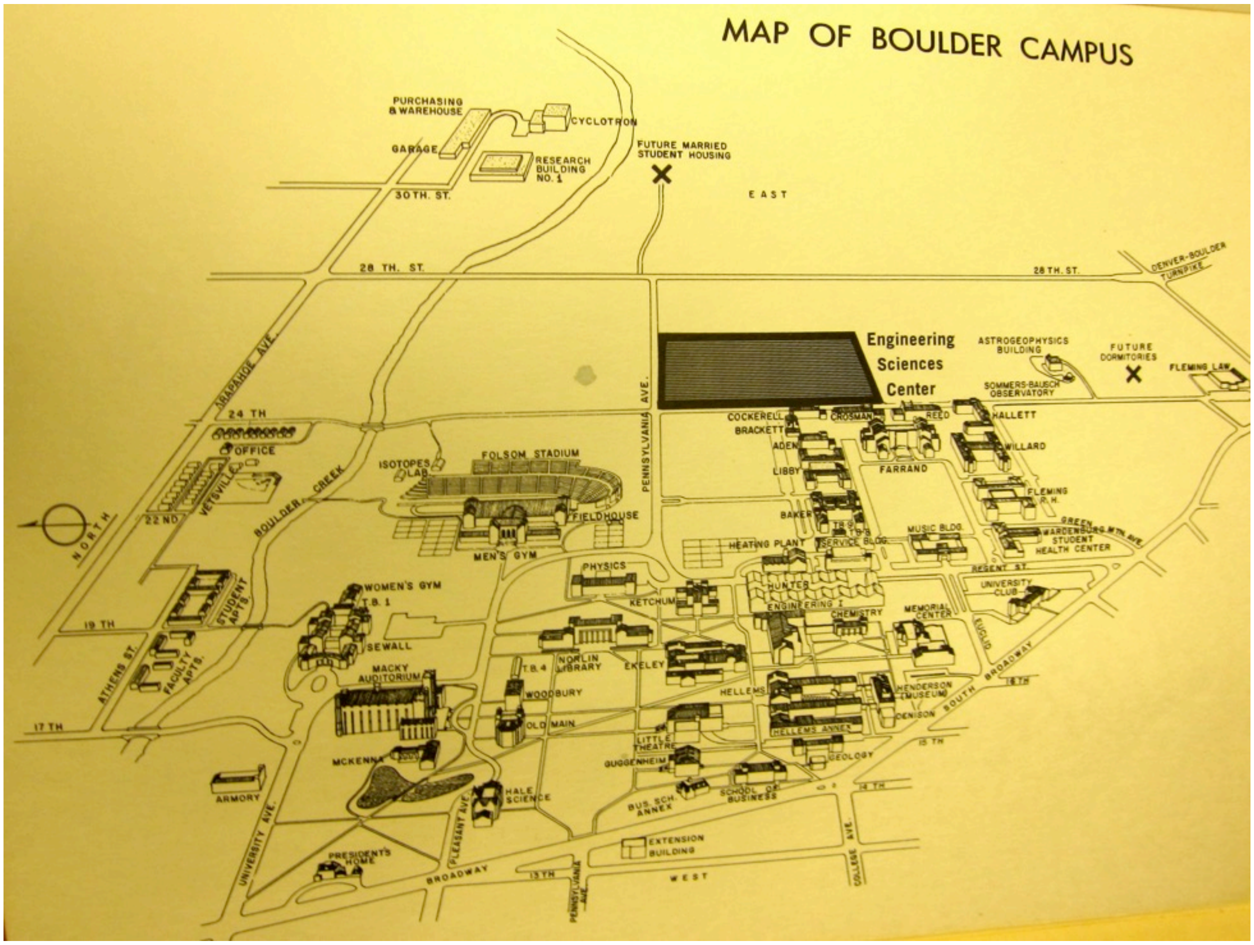


Figure 16: University of Colorado Boulder Campus with designated site for Engineering Sciences Center, Oct 1961

A local architecture firm, Architectural Associates of Colorado (AAC), took up the unique challenge of the Engineering Sciences Center building project. The partner-in-charge, William Muchow, was already well established in Colorado, with a proven track record of designing buildings for educational purposes. Muchow began drawing and thinking of ideas immediately, and by March of 1962 the building's design was largely finalized. Through sketches and trials, the shape of the building was determined and shared with consulting architects, local administrators and faculty, and architectural magazines and review boards nationwide.

The consulting architects, Sasaki, Walker & Associates, analyzed Muchow's design and created a master circulation diagram for the building, seen below.

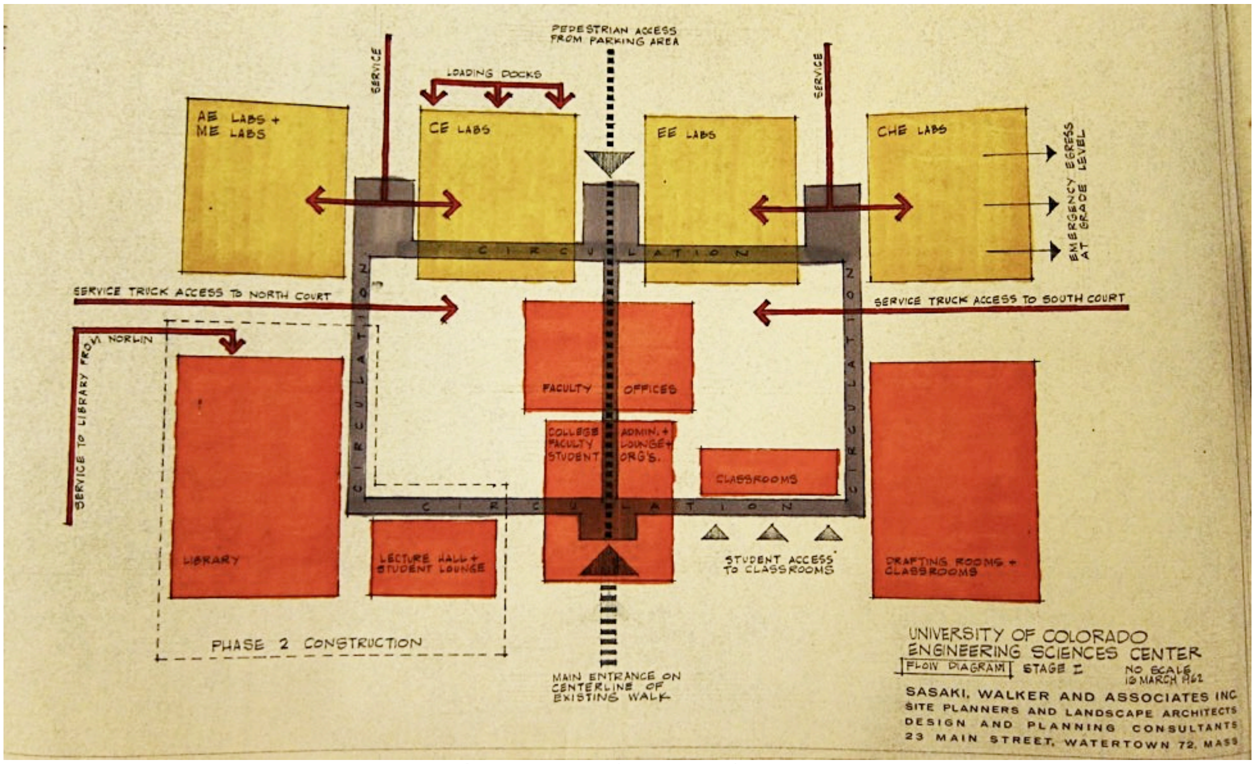


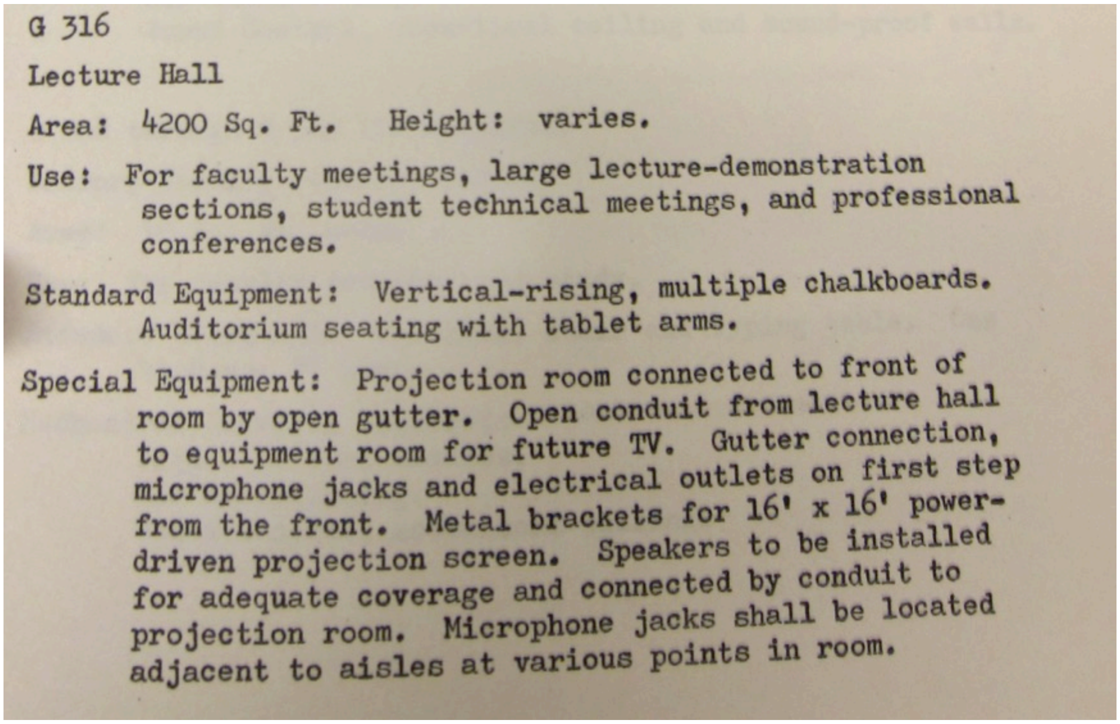
Figure 17: Flow Diagram from Consulting Architects, March 1962

Similar to the previous circulation diagrams, this image depicts the connections of each space with one another and the relative importance of certain objects and passageways in comparison to the others. Across the top, in yellow, are the departmental laboratories for Aerospace, Mechanical, Civil, Electrical, and Chemical Engineering. Connected by hallways for circulation and service access, these labs feature prominently in the building's design and correspondingly in the diagram. The next layer down includes a dotted line demarcating building elements saved for Phase 2 of planned construction for the building, which were subsequently redesigned and included with a different building project, years later. Vertically along the center of the diagram is a prominent dotted black line, indicating at the top, pedestrian access from parking structures, and at the bottom, alignment of the main entrance with the centerline of the existing campus walkway. Also along this axis are the faculty offices, located right in the middle, in close proximity to the laboratories at top, the central campus axis, college administration, faculty lounge, and student organizations. Finally, at the bottom right hand corner of the diagram are the drafting rooms and classrooms, with three small arrows indicating student access to classrooms, and subsequently the building. The diagram makes clear that research laboratories and connecting this building to the rest of campus were priorities, while students appear only in one corner of the diagram and one corner of the building, evidently a less visible and lower priority group.

The diagram also illustrates the overriding focus on engineering research, as the bulk of the building's spaces are dedicated to laboratories (shown in yellow blocks) wherein engineering faculty and graduate students could perform experiments, theorize and develop new technologies, etc. The architects designed a space in which faculty could easily traverse the distance from their research laboratories to their offices and periodically into classrooms, a building where service access to laboratories (as represented by bold red arrows) was critical in order to support the ongoing research efforts. This Circulation Diagram thus signifies *enrollment,* the confirmed *interests* and *investments* of the Engineering Building Committee, the wishes of the faculty and administration bound together in the plans for the new space.

Today, the building has been remodeled many times over to change the internal distribution of laboratories, faculty offices, and classroom spaces. The center lobby which was once just a passageway connecting spaces together, has been expanded several times to allow for more space in which students can congregate, sit, and work. As the "student lounge" designated for Phase 2 construction was not built in conjunction with the Engineering Center or the later Engineering Library, the lobby area of the Engineering Center building has instead become the de facto student lounge. Looking at the diagram it is apparent that much thought was given to ensure that faculty and service people could access all parts of the building equally well. Yet it is also clear that while each department had a voice in the designation of laboratory spaces and interior organization, the students' desires and opinions were not evidently voiced or accommodated. In other words, students were not *enrolled* or *interessed* during the process of designing the building – their opinions compared to the faculty and administration were not nearly as prominently considered.

As the student enrollment has grown in the intervening fifty years, students have permeated the building to a greater degree than illustrated in the 1962 circulation diagram, and the spaces have been adjusted and remodeled to fit the contemporary needs. For instance, the 1961 "Program Requirements for the Engineering Sciences Center" described the form and function of the four planned lecture halls as follows:



G 316

Lecture Hall

Area: 4200 Sq. Ft.   Height: varies.

Use: For faculty meetings, large lecture-demonstration sections, student technical meetings, and professional conferences.

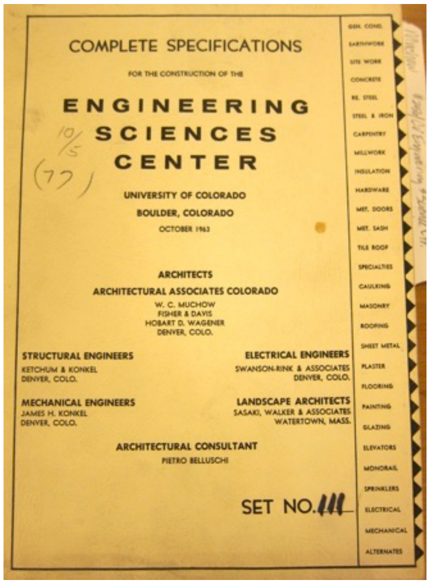
Standard Equipment: Vertical-rising, multiple chalkboards. Auditorium seating with tablet arms.

Special Equipment: Projection room connected to front of room by open gutter. Open conduit from lecture hall to equipment room for future TV. Gutter connection, microphone jacks and electrical outlets on first step from the front. Metal brackets for 16' x 16' power-driven projection screen. Speakers to be installed for adequate coverage and connected by conduit to projection room. Microphone jacks shall be located adjacent to aisles at various points in room.

Figure 18: Lecture Hall Description, Oct 1961

Surprisingly, the first listed use of lecture hall is for faculty meetings, not for a student-oriented or instructional purpose. The second listed use is for "large lecture-demonstration sections", which is partially correct for describing the treatment of these rooms today for large-sized lectures. Demonstrations, unless chalkboard derivations or displays of software and videos count, are used less frequently in engineering today than in physics or chemistry. The third and fourth potential uses of the lecture halls remain appropriate, though by and large the main purpose of these rooms is to deliver mathematical and engineering content via lecture to the students assembled. While the designers were forward thinking with their incorporation of the "special equipment" of projection, TV, speakers, microphone jacks, etc., the "standard equipment" of multiple chalkboards and seats with "tablet arms" have remained ubiquitous and necessary for students learning and instructors teaching in these lecture halls today.

By October of 1963 the design for the Engineering Sciences Center had been finalized to the point of soliciting contractors and subcontractors for executing the design. The faculty were satisfied with the plans for the new facility, with Dean Max Peters expressing that "I can't help but smile with pleasure when I look at these [drawings & blueprints for the new building]" ("Dean Peters Declares: Students Should Be Excited to Become Engineers," 1962). This booklet of specifications represents a 'hardening' or 'solidifying' into reality what had previously been opinion and discussion; the completed set of plans is the result of negotiations among the various actors at play, between the Building Committee, administration, architects, contracting engineers, and the building site itself. The booklet represents the alliances built between these diverse parties of humans and non-humans, the *enrollment* of these various groups in the project that is building the "Engineering Sciences Center".



COMPLETE SPECIFICATIONS

FOR THE CONSTRUCTION OF THE

ENGINEERING
SCIENCES
CENTER

10/5
(77)

UNIVERSITY OF COLORADO
BOULDER, COLORADO
OCTOBER 1963

ARCHITECTS
ARCHITECTURAL ASSOCIATES COLORADO
W. C. MUCHOW
FISHER & DAVIS
HOBART D. WAGENER
DENVER, COLO.

STRUCTURAL ENGINEERS
KETCHUM & KONKEL
DENVER, COLO.

ELECTRICAL ENGINEERS
SWANSON-RINK & ASSOCIATES
DENVER, COLO.

MECHANICAL ENGINEERS
JAMES H. KONKEL
DENVER, COLO.

LANDSCAPE ARCHITECTS
SASAKI, WALKER & ASSOCIATES
WATERTOWN, MASS.

ARCHITECTURAL CONSULTANT
PIETRO BELLUSCHI

SET NO. 111

GEN. COND.
EARTHWORK
SITE WORK
CONCRETE
RE. STEEL
STEEL & IRON
CARPENTRY
MILLWORK
INSULATION
HARDWARE
MET. DOORS
MET. SASH
TILE ROOF
SPECIALTIES
CAULKING
MASONRY
ROOFING
SHEET METAL
PLASTER
FLOORING
PAINTING
GLAZING
ELEVATORS
MONORAIL
SPRINKLERS
ELECTRICAL
MECHANICAL
ALTERNATES

Figure 19: Complete Specifications for the Construction of the Engineering Sciences Center, October 1963

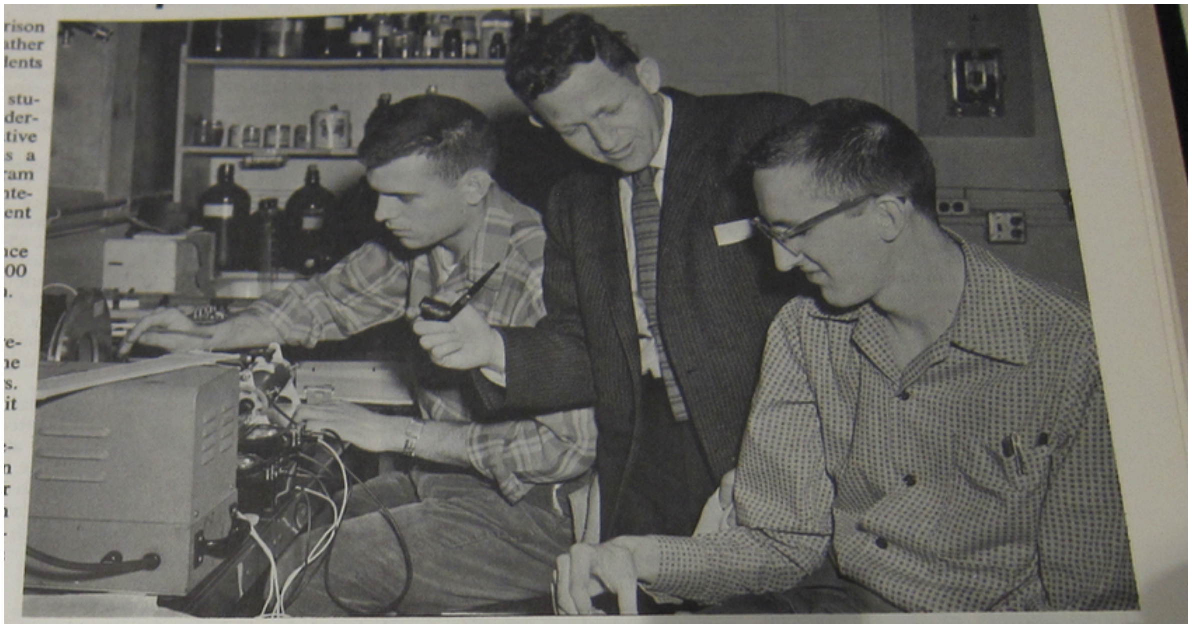
In addition to crafting the architectural plans to satisfy the needs of the current engineering departments, the Building Committee had the additional task of assisting university administration procure funding for the new center. With "Engineering Science" in the name of the new building, the concept of leading the region in the engineering sciences was at the forefront of the university's messaging and marketing campaign to convince legislators and taxpayers that the new building would be worth the cost, and to *interest* them in *enrolling* taxpayer dollars with the project.

Growth of CU Engineering

This era of CU Engineering included dramatic shifts in the enrollment and expansion of the graduate program and undergraduate population. The initiation of the Superior Student Program created a subculture of prestige within CU engineering, while changes to the format and administration of the mathematics courses irrevocably shifted logistics for students, TAs and instructors, classrooms and course catalogs. The mathematics curriculum during this time was also under considerable revision, as algebra and trigonometry became requirements for admittance while differential equations was added to the standard engineering mathematics curriculum. These changes contributed to a shifting organization of the engineering actor-network for undergraduates at CU, creating new influential networks and actors in the form of required courses and institutional structures.

The Superior Student program predates the current Engineering Honors program by approximately fifty years. Founded by Dr. Frank Kreith of Mechanical Engineering in the fall of 1960, the Superior Student program started with twenty-seven freshmen selected based on their entrance and admissions examination performances ("Engineering College Starts Program to Meet Superior Student Needs," 1961). "The program is not one of acceleration, but rather one in which the students are given a more thorough, broader education than ordinarily offered to engineering students," as students in the program took electives in the Arts and Sciences and the Science Honors program as well ("Engineering College Starts Program to Meet Superior Student Needs," 1961).

The program was lauded and highly publicized by its second year, as Superior Students experienced new laboratory courses and specialized environments to support their learning.



Frank Kreith, professor of mechanical engineering and director of the Program for the Superior Student in Engineering, observes work being done in a special laboratory by students enrolled in the program. The CU program is unique in that for at least the first two years, all work is within the program for the superior student. The students are Charles Swanson (l.) of Lakewood and Lawrence James of Denver, sophomores.

Figure 20: The Superior Student Program, 1962

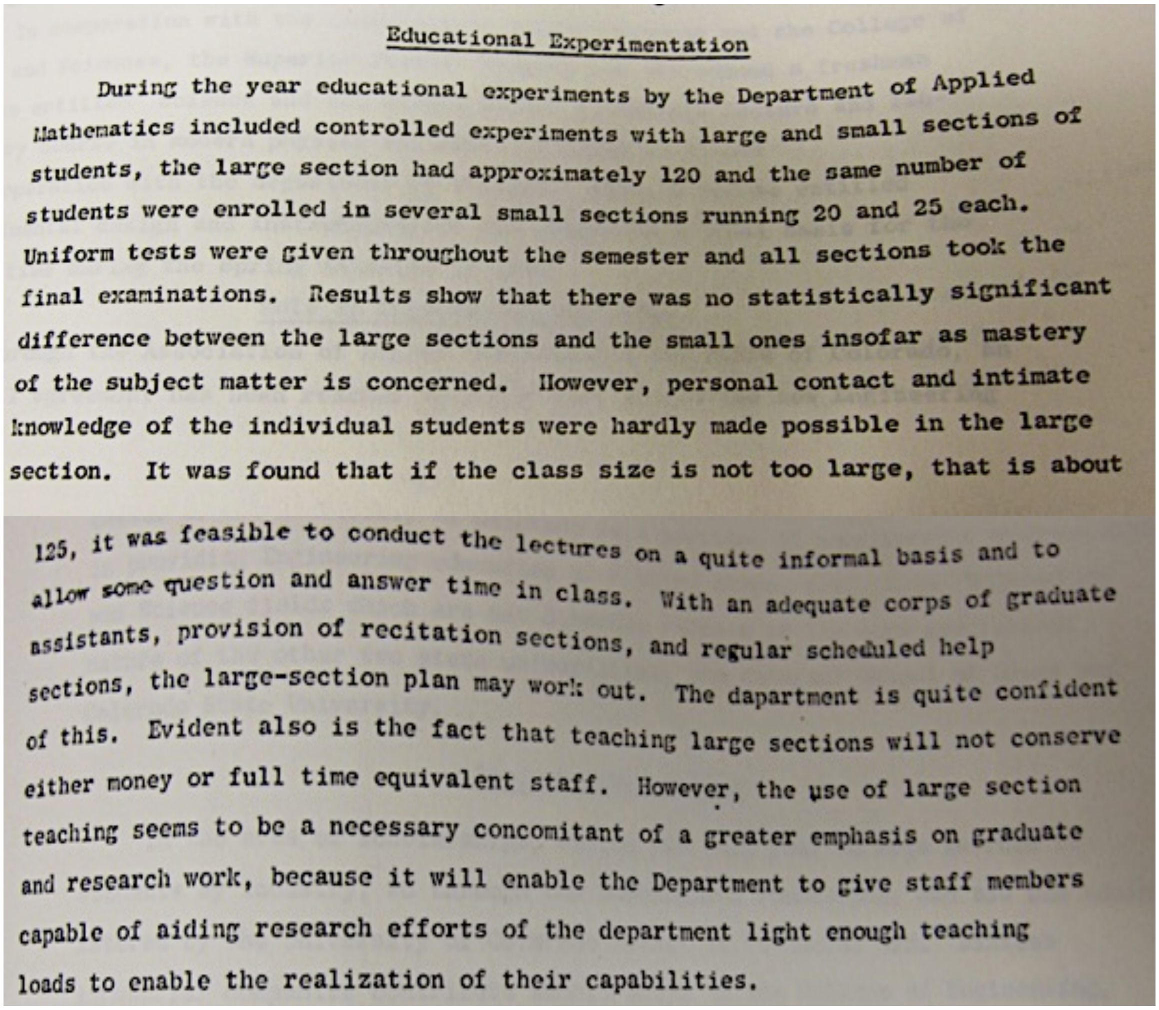
Reportedly designed to "attract exceptional students to the University's College of Engineering and – at least as important – to keep them once they have enrolled," the Superior Student program was cited as "revolutionizing the approach to engineering education for gifted students" ("University Starts Unique Plan: Curricula Started for Superior Engineering Students," 1962). The above photo, taken from a lengthy feature on the program in the *Colorado Alumnus,* depicts Dr. Kreith in a special laboratory for Superior Students working closely with two of these gifted young engineers. Dr. Kreith's pipe, the pocket protector on the male's shirt to the right, and the laboratory equipment shown in the photo are artifacts of the 1960s that are no longer standard in the present-day. Yet the notion of the program has persisted, reincarnated as the Engineering Honors Program. Both the Superior Student program and the Engineering Honors program select students based on entrance examinations and prior performance, featuring special class sections taught by specifically selected faculty to "go into material in greater depth and introduce aspects of a subject that might not interest the student who has no intention of doing graduate-level work" ("University Starts Unique Plan: Curricula Started for Superior Engineering Students," 1962).

The Superior Student Program was also credited for attracting freshman students to the College of Engineering. Between 1960 and 1961, the freshman class increased by 12%, from 376 to 429 freshman students, even when engineering enrollments at other universities in the nation and the state were diminishing ("New Freshmen In Engineering On Increase," 1961). Enrollment increases for new freshmen continued in the 1962-1963 academic year, with an increase of 7%. Dean Peters explained, "We are enrolling higher quality students, many lured by our Engineering Superior Student Program" ("Engineering Enrollment Still Grows," 1962).

Attributed to the Superior Student Program or other factors, the College of Engineering's growth in the early 1960s was undeniable. The designers of the Engineering Center thus had to prepare for realistic increases in the enrollment of both undergraduate and graduate students. By 1965, the projected engineering enrollment included 2,300 undergraduates and 300 graduate students, with additional expansion planned by 1972 to accommodate 4,000 undergraduates and 600-800 graduate students ("Completion Set for '65: Engineering Science Unit Asked," 1962). These projections turned out to be accurate for the number of undergraduates but less so for graduate students, as the enrollment of the College of Engineering and Applied Science in 2013 included 3,657 undergraduates and 1,623 graduate students ("Facts and Figures, College of Engineering and Applied Science," 2014). These numbers indicate both greater *interest* in engineering at CU and a confirmed, demonstrable *enrollment* of students, literally and figuratively into the actor-network of education in the College of Engineering.

The growth of the undergraduate program along with the Superior Student Program was contemporary with the American turn towards engineering science, the arrival of Dean Peters, and the increased emphasis on research locally in the College of Engineering. In order to expand the research program, new methods of administering courses and employing graduate students were tested and subsequently implemented – notably, the innovative concept of recitations came to roost within the Applied Math Department as a means of enabling research for faculty and graduate students.

The Annual Report for the College of Engineering from the 1962-1963 academic year includes the following description of “Educational Experimentation” activities:



Educational Experimentation

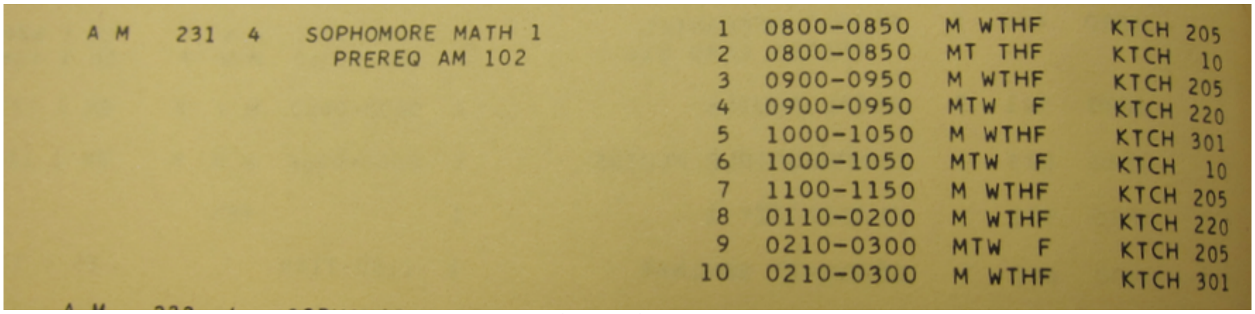
During the year educational experiments by the Department of Applied Mathematics included controlled experiments with large and small sections of students, the large section had approximately 120 and the same number of students were enrolled in several small sections running 20 and 25 each. Uniform tests were given throughout the semester and all sections took the final examinations. Results show that there was no statistically significant difference between the large sections and the small ones insofar as mastery of the subject matter is concerned. However, personal contact and intimate knowledge of the individual students were hardly made possible in the large section. It was found that if the class size is not too large, that is about 125, it was feasible to conduct the lectures on a quite informal basis and to allow some question and answer time in class. With an adequate corps of graduate assistants, provision of recitation sections, and regular scheduled help sections, the large-section plan may work out. The dapartment is quite confident of this. Evident also is the fact that teaching large sections will not conserve either money or full time equivalent staff. However, the use of large section teaching seems to be a necessary concomitant of a greater emphasis on graduate and research work, because it will enable the Department to give staff members capable of aiding research efforts of the department light enough teaching loads to enable the realization of their capabilities.

Figure 21: Educational Experimentation Creating Recitations in Applied Math, 1963

Described as “controlled experiments,” the comparison of student test performances in classes of 120 and 20-25 students showed “no statistically significant difference” (Peters, 1963). On the basis of these experimental results, the Applied Math department of 1963 was “quite confident” that "with an adequate corps of graduate assistants, provision of recitation sections, and regular scheduled help sections, the large-section plan may work out" (Peters, 1963). Though administering classes in this format "[would] not conserve either money or full time equivalent staff… it [seemed] to be a necessary concomitant of a greater emphasis on graduate and research work, because it [enabled] the Department to give staff members capable of aiding research efforts of the department light enough teaching loads to enable the realization of their capabilities" (Peters, 1963).

This large-section trial period over one academic year offered sufficient evidence to the faculty and administration that the large lecture and smaller recitation model was viable and in fact "necessary" given the increased focus on the research program and engineering science that the College of Engineering was shifting towards. Recitations were thus a novel form of technology that enabled a structural shift in the way the Applied Math department delivered the fundamental mathematics courses for engineering students. This shift simultaneously created new positions for graduate students, allowed for increased focus on research and the graduate program, and enabled faculty to have lighter teaching loads with greater time for research as well. The trial period over the 1962-1963 academic year required that faculty, administration, and graduate students were *interessed* in this new opportunity to shift the balance of teaching and research, while the subsequent test scores demonstrating "no statistically significant difference" in performance across large and small sections confirmed that the large section/recitation model was viable. The Annual Report describing the success of this trial illustrates the *enrollment* of Dean Peters and the administration in adopting this model for undergraduate mathematics education. In subsequent academic years, as the large section/ recitation model became widespread across all Applied Math classes, classrooms, teachers, students, graduate students, lecture halls, chalkboards, and other various resources were *mobilized* to support and enable the continued success of this mode of education. What started as a straightforward comparison of test scores between two groups of students, taught under different conditions, became a giant system or actor-network of humans and resources that has existed until the present day.

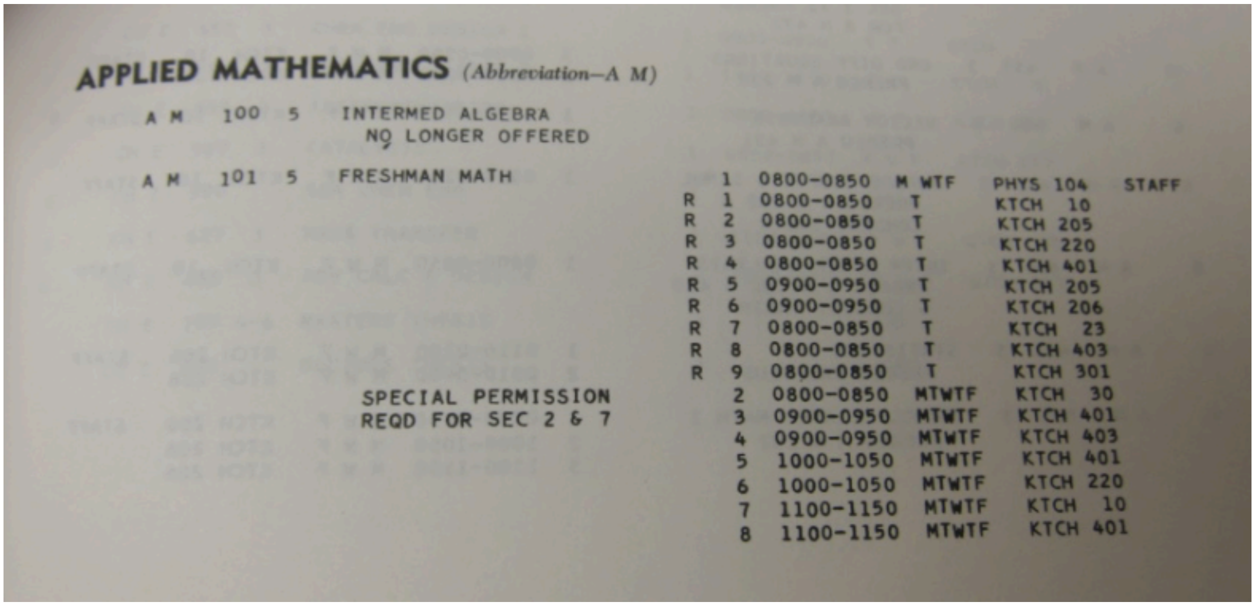
The gradual propagation of the large lecture section / smaller recitation model can be seen in the course catalogs of the years in question. For instance, the Fall 1960 course offerings for Sophomore Math 1 (AM 231) appeared as follows:



```
A M   231  4   SOPHOMORE MATH 1          1  0800-0850  M WTHF    KTCH 205
                 PREREQ AM 102           2  0800-0850  MT THF    KTCH  10
                                         3  0900-0950  M WTHF    KTCH 205
                                         4  0900-0950  MTW  F    KTCH 220
                                         5  1000-1050  M WTHF    KTCH 301
                                         6  1000-1050  MTW  F    KTCH  10
                                         7  1100-1150  M WTHF    KTCH 205
                                         8  0110-0200  M WTHF    KTCH 220
                                         9  0210-0300  MTW  F    KTCH 205
                                        10  0210-0300  M WTHF    KTCH 301
```

Figure 22: Course Catalog, Fall 1960

Ten individual sections meeting four times a week, each taught by one individual instructor, was the norm for these classes until the concept of recitations came along and shifted the entire system. Jumping forward a few academic years to examine the course catalog during the trial period, we see that during the academic year from Fall 1962-Spring 1963, recitations were piloted only for one large lecture section of Freshman Math, with nine recitation sections:



APPLIED MATHEMATICS *(Abbreviation—A M)*

```
A M   100  5   INTERMED ALGEBRA
                 NO LONGER OFFERED

A M   101  5   FRESHMAN MATH                1  0800-0850  M WTF   PHYS 104   STAFF
                                          R 1  0800-0850   T      KTCH  10
                                          R 2  0800-0850   T      KTCH 205
                                          R 3  0800-0850   T      KTCH 220
                                          R 4  0800-0850   T      KTCH 401
                                          R 5  0900-0950   T      KTCH 205
                                          R 6  0900-0950   T      KTCH 206
                                          R 7  0800-0850   T      KTCH  23
                                          R 8  0800-0850   T      KTCH 403
                                          R 9  0800-0850   T      KTCH 301
               SPECIAL PERMISSION           2  0800-0850  MTWTF   KTCH  30
               REQD FOR SEC 2 & 7           3  0900-0950  MTWTF   KTCH 401
                                            4  0900-0950  MTWTF   KTCH 403
                                            5  1000-1050  MTWTF   KTCH 401
                                            6  1000-1050  MTWTF   KTCH 220
                                            7  1100-1150  MTWTF   KTCH  10
                                            8  1100-1150  MTWTF   KTCH 401
```

Figure 23: Course Catalog, Fall 1962-Spring 1963

The image also illustrates the "special permission" required for the Superior Student Program sections, segregated from the rest of the student population taking freshman math. Also apparent in the Fall 1962- Spring 1963 Course Catalog is the discontinuation of "Intermediate Algebra," as prior knowledge of algebra and trigonometry became requirements for admittance into the college instead of courses offered at the college level for engineers. Taking these subjects out of the college level and expecting them to be completed in high school created space for differential equations to be added into the required mathematics curriculum. The inclusion of differential equations in undergraduate engineering was an important marker that CU's College of Engineering had reached a level of engineering science and theoretical content on par with peer institutions in at least the required math topics and course titles.

Dean Charles Hutchinson, or "Hutch", became Acting Head of Engineering Mathematics in 1921 and remained involved with Applied Math (as it was later renamed) through 1966. He also served as interim Dean between the retirement of Dean Clarence Eckel in 1960 and the arrival of Dean Max Peters in 1962 (Mandel & Shipley, 1966). During the span of his years at CU, he saw the department grow from offering a few classes for undergraduates to creating full undergraduate and graduate programs accredited to grant bachelors and doctoral degrees in Applied Math. In his farewell address, he reflected on how he "started it [the graduate program] with Differential Equations – now a standard sophomore course" (Hutchinson, 1966). Dean Hutch also reflected, "This is the most prominent memory of almost half a century—the tremendous change in engineering education from a 'how to do it,' largely empirical, discipline, to a profession with a sound basis in mathematics and the theoretical physical sciences" (Hutchinson, 1966). His interpretation of the "tremendous change" in engineering education resonates with the turn towards engineering science at CU and nationwide, and demonstrates Dean Hutch as one of the influential actors who *mobilized* resources to change the content of the required mathematics courses as well as the format in which these courses were taught.

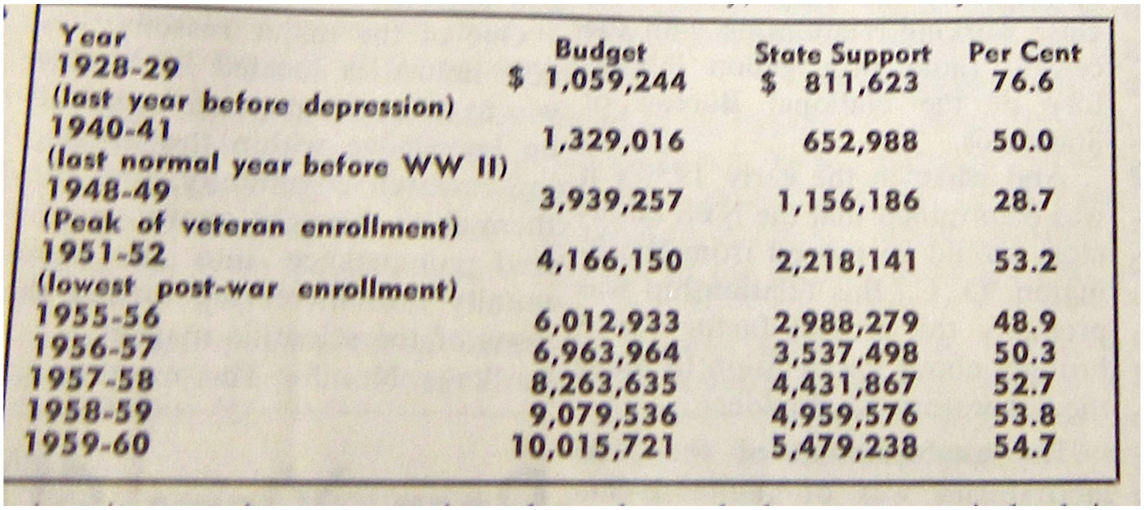
The changes Dean Hutch witnessed and put in place, adding differential equations and removing courses on algebra and trigonometry, have largely remained until the present day. The innovation of subdividing a large lecture section into smaller recitation sections meeting once a week, administered by graduate teaching assistants, is another idea of the 1960s that has persisted through the decades to affect current students, TAs, and faculty. Finally, the Superior Student Program, though renamed and re-initiated as the Engineering Honors Program, has retained several key features including specialized class sections and facilities. The durability of differential equations, recitations, and the Honors/Superior Student Program over fifty years is not by chance, but by the efforts of innumerable actors who are sufficiently *interessed* and *enrolled* in maintaining these structural artifacts instead of changing them. The construction of the Engineering Sciences Center, or Engineering Center, further cemented these curricular artifacts in place as the large lecture halls and smaller recitation rooms *mobilized* the large lecture / recitation model into concrete spaces for students to inhabit semester after semester. We investigate how these structures were made durable through actor-network connections, to understand the impact of these 1960s era technologies on our students and educational system today.

Funding the Construction of the Engineering Sciences Center

At the time of its construction, the Engineering Sciences Center was the largest building on campus with a planned cost of $10 million dollars in 1965 – adjusted for inflation, $74.5 million in 2015 (Bower, 1966; "Inflation Calculator," 2015). To fund the new building, CU looked to both state and national funding agencies for opportunities.

In 1961, the University of Colorado administration met with the Colorado State Legislature's Joint Budget Committee to request an approval of operating budget for the 1961-1962 academic year and an increase in the amount appropriated from the state. Editorials for the *Colorado Alumnus* championed this effort, pointing out the history of Colorado's government on the low end of supporting higher education, particularly compared to other states and institutions ("State Support to CU Not High," 1961, "University Needs Full Amount Asked, Newton Informs Legislative Committee," 1961). The relatively low salaries of faculty were one of the main arguments from Provost Tippo and President Newton regarding the need for greater state funding, as CU was "96th on the list of comparative faculty salary schedules among American universities" ("University Needs Full Amount Asked, Newton Informs Legislative Committee," 1961).

The Colorado State Legislature of that era had supported CU financially for many years, reportedly providing 76.6% of the overall operating budget in 1928-29 and 56.7% in 1959-60 (See Figure 24 below for detail on intervening years). Support from the state has since diminished significantly, dipping to 4.4% of the overall operating budget in 2013 ("Where Does the Money Come From?," 2013). Thus the request for greater state funding was not misplaced, though viewed through contemporary expectations seems surprising:



Year	Budget	State Support	Per Cent
1928-29 (last year before depression)	$ 1,059,244	$ 811,623	76.6
1940-41 (last normal year before WW II)	1,329,016	652,988	50.0
1948-49 (Peak of veteran enrollment)	3,939,257	1,156,186	28.7
1951-52 (lowest post-war enrollment)	4,166,150	2,218,141	53.2
1955-56	6,012,933	2,988,279	48.9
1956-57	6,963,964	3,537,498	50.3
1957-58	8,263,635	4,431,867	52.7
1958-59	9,079,536	4,959,576	53.8
1959-60	10,015,721	5,479,238	54.7

Figure 24: Selected Budget Years at CU with Per Cent from State ("State Support to CU Not High," 1961)

Having successfully convinced the lawmakers in 1961, the CU administration returned to the state legislature the following year with a follow-up request: $5.4 million in capital appropriations to be spread between 1962-1963 and 1963-1964 academic years for the construction of a new Engineering Sciences Building. In early January 1962, Governor Steve McNichols delivered a speech to the Colorado State Legislature supporting this request, stating:

> The University of Colorado has requested an engineering and science center costing $10-million and has presented a comprehensive study showing the need. If authorization is given right now to go ahead on this project, it will be late in 1965—more than three years from now before it is ready for use. There are needs to attract and retain a superior engineering and scientific faculty—a necessity to train our young people for their own advancement and to aid the national interest. In this space age, an outstanding faculty and a modern facility such as this must be available before certain types of industry will locate in an area. ("Completion Set for '65: Engineering Science Unit Asked," 1962)

With the Governor backing the University's request, the Legislature acquiesced as well. Newspaper editorials supported the center and popular opinion seemed to turn in favor of supporting its construction, even at taxpayer cost (Olin, 1962). The argument that a new building was essential for providing a modern technical education to keep up with changing technology was convincing, particularly given the rapid advancements in computers and electronics of the era and the growth of the engineering college. Taxpayers were in this way *interessed* to support building the new facility and taxpayer dollars were subsequently *enrolled* into the project by the State Legislature's agreement to appropriate $5.4 million to finance the center. The actual transfer of the money from the State into CU's coffers to pay for building supplies and labor was a *mobilization* of resources, with money joining the alliance of actors enmeshed in the network working on the overall building project.

With the State Legislature agreeing to appropriate the funds for the University's budget and additional $1.8 million from the University Mill Levy Fund, $7.2 million of the Engineering Sciences Center's $10 million total budget was in hand (University of Colorado, 1962). For the remainder of the funds, the administration applied for federal grants. The National Science Foundation (NSF) acquiesced with CU's request, and granted $1.3 million toward construction of the new engineering center ("Engine Center Accepts Big Construction Grant," 1964). Among the largest grant ever made by the NSF to any university for building facilities, the federal support enabled completion of the building as the total money raised now reached approximately $8.5 million of the original $10 million budget ("Engine Center Accepts Big Construction Grant," 1964). Thus the money was all in place, committed / *enrolled,* and eventually *mobilized* to contribute to the Engineering Sciences Center building project.

With the money, design, architects, specifications, contractors, site, administration, etc. on board to build the Center, construction commenced to erect the unique shapes and façade of the building. It would not have come to life in its surprisingly *Brutalist* form if not for additional allies which became *interested* in purposely deviating from the predominant architectural style at CU. While the "Tuscan vernacular" style used by campus architect C. Z. Klauder had dominated campus construction since 1918, the Engineering Sciences Center brought a significant break from the uniform theme of red sandstone, tile roofs, and limestone arches (University of Colorado Boulder, 2011). This was on purpose, as the site planners for the University of Colorado suggested "continuation of the old style might well be harmful to the old campus in creating an excess of similarity" ("CU to Engage New Architects," 1961). Instead, these consulting architects believed "it would help the present character of the campus if the style were changed in the area east of 24th Street," and the Engineering Sciences Center was the first building created in this area to follow this edict and significantly deviate from the Klauder architectural style ("CU to Engage New Architects," 1961).

The Engineering Sciences Center had enlisted many allies, both human and non-human, in order for its construction to be initiated and completed. The extensive fundraising efforts enlisted the Colorado State legislature, the National Science Foundation, the University Mill Levy fund, and countless individual taxpayers and representatives as well. These sponsors were *interested* in supporting the new construction to maintain CU and Colorado's competitiveness on the national stage, believing that the new building was needed to attract industry and faculty and to aid national interests as well. The donors confirmed their *enrollment* by *mobilizing* millions of dollars in support of the new Engineering Sciences Center, enabling the architects, contractors, consultants, building materials, equipment, etc. to proceed with actual construction of the structure. The Engineering Sciences Center was also allied with the site planners who suggested a new look for the building, enabling a departure from the predominant CU architectural style, and *mobilizing* these suggestions into the creation of a concretely different campus structure than ever seen before in Boulder.

Figure 25: Engineering Sciences Center, 1966

The Engineering Sciences Center, 1966

The building was near completion in the fall of 1965, with laboratory equipment, furniture, office supplies and furnishings moving in throughout the fall of 1965 and spring of 1966. The building was officially dedicated and publicly unveiled during the "Engineering Days" celebration May 5-7, 1966, with much fanfare. See Figure 26 below from the Daily Journal ("Space Age Countdown Plan to Open Engineering Center," 1966):

SPACE AGE COUNTDOWN PLAN TO OPEN ENGINEERING CENTER

Special to The Daily Journal

BOULDER, Colo.—When the University of Colorado dedicates its new 10-acre Engineering Center next Friday a Rube Goldberg chain of events will be unleashed by dignitaries in a ribbon cutting ceremony.

The dedication will take place at 2:15 p.m. at the west entrance of the Engineering Center, 24th st. and Colorado ave.

The ribbon cutting will employ lasers and helium filled balloons. The balloons will hold the ribbon at waist level.

When it is time to cut the ribbon, a dignitary will push a button to activate a continuous helium laser. The laser beam will strike a reflector to be located on top of the Space Science building about four blocks away.

The reflected beam will then pass through a telescopic photo electric cell to activate a machine that will start the space-age "countdown."

The electric impulse from the countdown machine will start a pulsed ruby laser that will fire a beam, in less time than it takes to blink, at a small explosive target on a balloon causing it to burn, the balloon to explode and the ribbon to burn in two pieces to be carried out of the way by other helium filled balloons.

In case the elaborate scheme doesn't work, the engineers, in true space-age fashion, have provided for intermediate and final back-up procedures.

The intermediate step will be that a dignitary will activate the pulsed ruby laser. If that doesn't work, he will resort to one of the oldest engineering tools—an axe and chopping block—to do the job.

Figure 26: Description of Space-Age Countdown Plan to Open the Building, 1966

The newspaper article above describes the "Space-Age Countdown Plan" that was expected to accompany the opening of the building, featuring lasers, balloons, a reflector, dignitaries, ribbons, photo electric cells, machines, backup plans, engineers, etc. ("Space Age Countdown Plan to Open Engineering Center," 1966). This complicated "Rube Goldberg" type plan befit the "Space-Age" design and motivation for constructing the Engineering Center, and recalled the promises of winning the Cold War through redoubled efforts to teach, learn, and research the engineering sciences. The complicated cascade of intermediaries planned to execute the ribbon-cutting ceremony is an example of a group of non-human objects recruited by humans to do specific functions, with success contingent on the performance of variable and potentially inconsistent technologies. In other words, many human and non-human actors were *enrolled* in the "Space-Age Countdown", with proper *mobilization* necessary to achieve the desired cutting of a ceremonial ribbon.

The "Space-Age Countdown" also served as a public marker of the significance of the new building, and a celebration of completing this ambitious and record-setting construction project under budget and largely on-time. Headlines proclaimed that this bold Engineering Center "Transforms Boulder Campus" as its large size and prominence on the east side of campus made it visible from nearly all of Boulder ("New Engineering Center Transforms Boulder Campus," 1966). While the administration, architects, faculty, and others were proud of the new structure, many alumni and residents of Boulder found the building to be hideous and untenable. In response to a preview of the building, several alumni wrote into the *Colorado Alumnus*, complaining about the exterior of the Engineering Center:

> "No doubt the inside of the shed is beautiful and functional but the outside appearance *could be* beautiful too. Instead it is *ug ug ugly*... some chicken coop.
>
> ~Arthur Dalling, '29
>
> "I viewed the picture of the new Engineering Center with horror and disbelief. Who, may I ask, designed this mess – a Kansas wheat farmer? I ask this because the new Center looks exactly like a jumble of old, dilapidated grain elevators – no less ugly.
>
> ~ John R. Olbert, engineering '59
>
> "Maybe some ivy on those Engineering Center walls would make it look less like the old mine building collections in some of the canyons – anything to make them fit into the landscape in a hurry.
>
> ~ Irene Bradley Barrett, MD '34" ("Alumni Dislike Buildings | Letters," 1966).

In line with the suggestion to grow ivy on the exterior of the Engineering Center, an "Ivy fund" was established with the university's Development Foundation, so that interested alumni could call in and donate funds to support the beautification of the building.

Though the alumni were vocal in criticizing the Engineering Center, architecture associations, magazines, and national groups repeatedly awarded the Center and its architects for their innovative design. Before the building's construction was completed it had already been awarded the Progressive Architecture magazine "Design Award" in the category of Education in 1963. In 1966 the American Institute of Architects (AIA) and the U.S. Office of Education gave a "First Honor Award" to the architects designing the building, followed by an "Award of Merit" from the AIA Western Mountain Region in 1967. Yet despite these formal accolades, the public opinion continued to oppose and poke fun at the untraditional appearance of the Engineering Center.

The Denver Post published a relatively neutral article describing the building, calling it a "Controversial Complex" (Thompson, 1966). The Rocky Mountain News, on the other hand, chose to announce the AIA and U.S. Office of Education "First Honor Award" with this headline:

Pretty (Ugly) CU Center Wins Prize

The University of Colorado's new Engineering Center Tuesday was named one of seven first-place winners in the 1966 Design Award Program for college academic buildings.

Figure 27: Ugly CU Center Wins Prize, Rocky Mountain News (1966)

Residents of Boulder also continued to comment on the building for years after its initial opening, as a local restaurateur became vocal in calling the Engineering Center a "mining shack," adding "if they are going to put those mining shacks in there, there will be a lot of protest" ("Restaurateur Labels CU Buildings 'Mining Shacks'," 1968).

In response to some of the complaints about the building's appearance, Dr. Robert Rathburn, original member of the building committee and a hugely influential actor in bringing the center to reality explained, "It says something. The design does not make you think that English or philosophy would be taught in this building. It looks like a building in which engineering would be taught" (Bower, 1966). Dr. Rathburn's response is indicative of the attitude that the building matched the turn towards the engineering sciences, and that it was expected for engineers to be separate from students of English or philosophy, that this new building was meant for engineers only. Dr. Rathburn's opinion also indicates that the actor-network of engineering was entirely separate from the other groups on campus, purposely *mobilized* distinctly from the Arts and Sciences and other campus activities.

Dean Max Peters, Charles Hutchinson, Charles Dedi and Robert Rathburn admire the interior architecture of the new Engineering Center. The Office Towers form the background of the picture (see pages 6-7).

Figure 28: Influential Human Actors in Realizing the Engineering Center, 1966. Dr. Rathburn is the farthest to the right, Dean Peters is on the left.

Further compounding the idea that the Engineering Center was just for engineers and no one else was the geographical isolation of the building from the rest of campus. The designers, including Dr. Rathburn, planned a novel means for keeping the Engineering Center connected – by piping in the sound of the bells rung at Old Main, on the older west side of campus, to keep everyone in campus in sync together ("Old Main Bell Summons Classes in Distant Complex | Live Tie to Old Campus," 1966). Dr. Rathburn explained, "Of course we could simply have recorded the sound of the bell and played it automatically for each class period, but we felt using the actual sound of the bell being rung provided a nice, live tie to the rest of the campus" ("Old Main Bell Summons

Classes in Distant Complex | Live Tie to Old Campus," 1966). While the architects had considered carefully the flow of pedestrian traffic from parking lots to the main axis of campus, the only "live tie" from the Engineering Center to the rest of campus was the sound of the Old Main bells. Aside from the ringing of the bells, there were scarcely any other devices of *interessement* to keep the engineers integrated and connected with the rest of campus life, a trend that has continued to the present.

The initial plans and rhetoric surrounding the building's construction referred to it as the Engineering Sciences Center, to reinforce the connection to engineering science being forged through the construction of the building. By spring of 1966, however, the name had been shortened to simply the Engineering Center, the name by which the concrete building cluster is still known today. To reflect the continued ties to engineering science, however, the faculty and administration voted in 1971 to change the name of the College of Engineering to the College of Engineering and Applied Science, while the Department of Aerospace Engineering was renamed as the Department of Aerospace Engineering Sciences ("CU Engineering Faculty Votes For Name Change," 1971). The name change signified the *enrollment* of the college and faculty in support of the engineering sciences, and the *mobilization* of the sciences into permanent residence with engineering.

The Engineering Center, 2015

Looking through the history surrounding the development and construction of the Engineering Center, we find surprising parallels to our educational system today and a better understanding of the current consequences of decisions made in the 1960s. Inspired by Actor-Network Theory, we have taken the viewpoint of the building, understanding how it came to be *translated* and realized through the actions of various human and non-human actors, including faculty and committee members, building sites, architects, and money. The building is a central artifact for visualizing the *translation* from engineering design to engineering science here at CU. *Translation* in the sense of Actor-Network Theory describes a process wherein "an entity, human or nonhuman, becomes selected, enticed, persuaded and partially or fully changed in ways that mobilize it to join the network's movements" (Fenwick, 2011). By describing the cascading chain of entities that were incrementally convinced to support the construction of the Engineering Center and buy into the ideology of engineering science, we are illustrating the characteristics of the individual actors and how they constitute the overall actor-network at play. We see the power of *translation* and the utility of the Actor-Network Theory in illuminating the underlying power structures that gird the activities of designers, architects, fundraisers, lawmakers, etc. We are able to understand how physical artifacts like the Engineering Center are made durable, and how representational concepts like engineering science are rendered sufficiently stable to persist over decades.

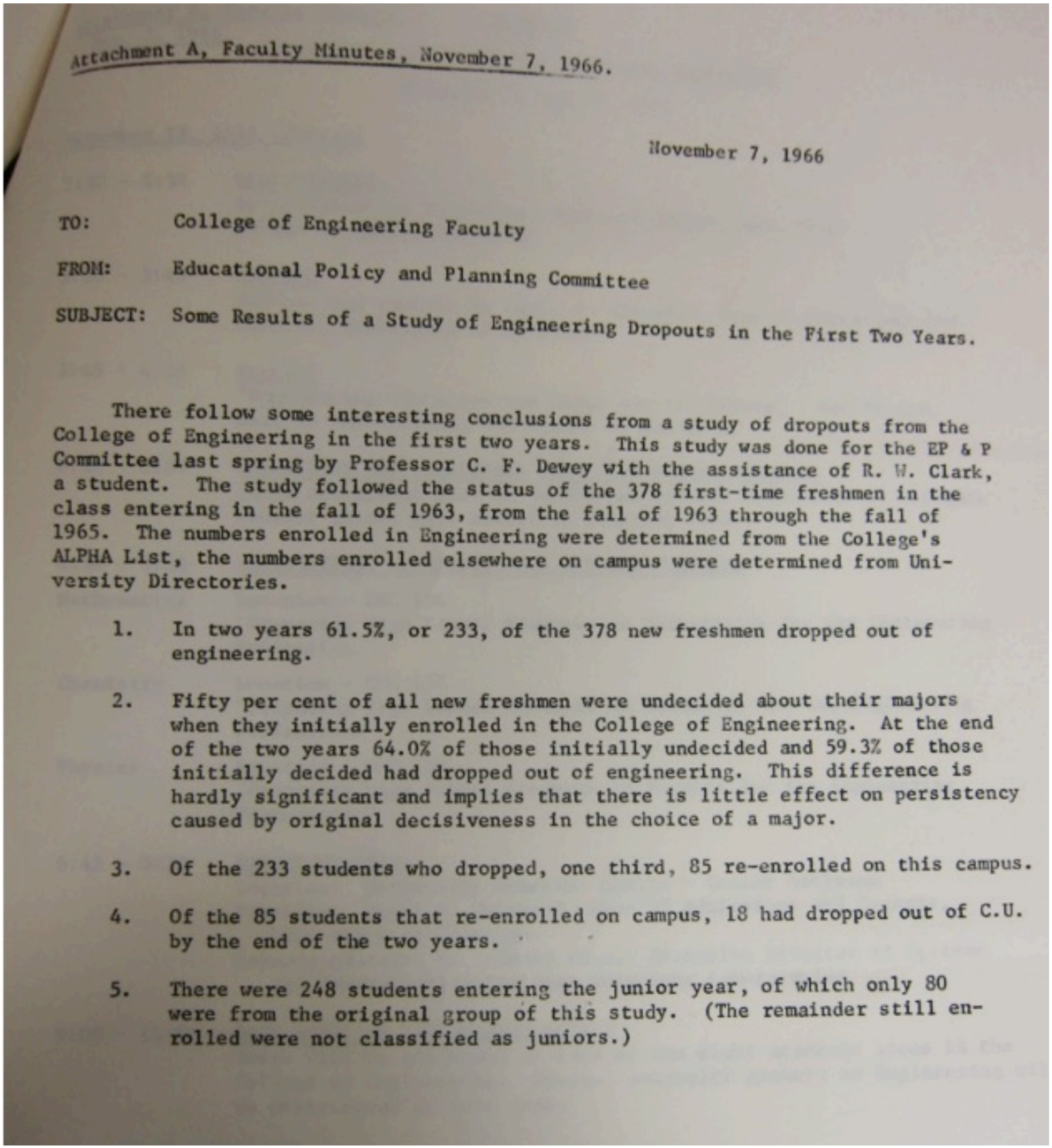
This chapter began with the description of Robert Moses's low-hanging highway overpasses; a physical artifact designed for a social purpose whose effectiveness at restricting access to desired destinations for certain populations drastically decreased with commiserate changes in the ubiquity of cars in American society. We examine the Engineering Center in 2015 to see how changes in technology and society have changed the effectiveness of the building at reinforcing concepts of engineering science and isolation from other topics and populations at the University of Colorado Boulder. Considering the prominent actors which enabled the building to be realized, including the planning committee, architects, administration, faculty, etc., did they anticipate that their designs and perspectives would still influence engineering education 50 years later? We wonder, what has changed and what has remained the same over the last five decades in terms of physical spaces, representational spaces, and artifacts.

First, we look at the durability of the lecture hall as a physical artifact, comparing one brand-new lecture hall when the Engineering Center first opened in 1965 to its appearance in 2015:

Figure 29: Lecture Hall Comparison, 1965 to 2015

Surprisingly robust, the lecture hall has remained relatively unchanged over fifty years. The lone addition of a projector stands out as the main addition to the space, while the tiered format, fixed seats with tablet arms, florescent lighting, and wood-paneled soundproofing have served durably. Consider the history of the lecture hall and recitations; how the administration and faculty of 1963 decided it was desirable for a single lecturer to teach classes of 125 students, to enable more time for research with no apparent negative consequences on student learning. The choice was made more than fifty years ago to include four such lecture halls in the Engineering Center, for the large lecture and smaller recitation model to be dominant in administering engineering courses, particularly in mathematics. Despite the changes in technology and society in the last fifty years, this model for teaching and learning has remained unchanged. This historical interlude has described how this instructional model became the default, and our subsequent Findings chapters lay out the unintended consequences of the large lecture and smaller recitation format that could not have been foreseen by those that put it into place.

Looking back, we also see that retention in the engineering undergraduate program was already a large concern by 1966:



Attachment A, Faculty Minutes, November 7, 1966.

November 7, 1966

TO: College of Engineering Faculty

FROM: Educational Policy and Planning Committee

SUBJECT: Some Results of a Study of Engineering Dropouts in the First Two Years.

There follow some interesting conclusions from a study of dropouts from the College of Engineering in the first two years. This study was done for the EP & P Committee last spring by Professor C. F. Dewey with the assistance of R. W. Clark, a student. The study followed the status of the 378 first-time freshmen in the class entering in the fall of 1963, from the fall of 1963 through the fall of 1965. The numbers enrolled in Engineering were determined from the College's ALPHA List, the numbers enrolled elsewhere on campus were determined from University Directories.

1. In two years 61.5%, or 233, of the 378 new freshmen dropped out of engineering.
2. Fifty per cent of all new freshmen were undecided about their majors when they initially enrolled in the College of Engineering. At the end of the two years 64.0% of those initially undecided and 59.3% of those initially decided had dropped out of engineering. This difference is hardly significant and implies that there is little effect on persistency caused by original decisiveness in the choice of a major.
3. Of the 233 students who dropped, one third, 85 re-enrolled on this campus.
4. Of the 85 students that re-enrolled on campus, 18 had dropped out of C.U. by the end of the two years.
5. There were 248 students entering the junior year, of which only 80 were from the original group of this study. (The remainder still enrolled were not classified as juniors.)

Figure 30: The Study of Engineering Dropouts, 1966

The context of document was a faculty meeting in which the figures above were presented, described as “interesting conclusions” by the Educational Policy and Planning Committee who coordinated the report. The dropout rate of 61.5% after the first two years is about twice the current 31% of students who leave engineering after the first two years, demonstrating that attrition rates have actually changed significantly in the last fifty years. Yet it is interesting that retention numbers and discussion around student persistence in the undergraduate program remains a prominent topic and justification for further research into the climates and attitudes of the first two years of undergraduate (including this study).

The sentiment of "plus ça change, plus c'est la même chose," or "the more things change, the more they stay the same" seemingly applies to the Engineering Center and the system of engineering education as a whole. Actor-Network Theory provides a novel lens for considering how things became this way in the first place and questioning alternate pathways for the system's survival. This chapter began with the comment from Winner (1986) on the purpose of the "grotesque concrete" structures like the Engineering Center found on many college campuses. The process of tracing the history of the building and understanding the actor-networks implicated in its creation have made clear that Winner was incorrect in believing that the *brutalist* buildings were intended to diffuse student demonstrations and prevent community organizing (Campbell, 2013). Instead we find that the building represents a casade of different meanings to all the actors involved: the building marked the turn towards engineering science and signified a commitment to winning the Cold War through training of local engineers and attracting industry, the building was an investment in expanding the research and graduate programs for the College of Engineering, the building was a hideous blight on the otherwise harmonious campus architecture to the alumni of the university, the building was sorely needed in order to sustain the reputation for excellence at the flagship university of the Rocky Mountain Region, etc. The multiple interpretations of the building and what it stands for are evidence of the *translation* process at work.

We proceed to map out actor-networks and identify the *translations* occuring in the modern day environment of sophomore engineering education. This interlude into the history of the Engineering Center provides through application further insight into the meaning of actor-network terminology, and adds nuance to help explain what is meant by our research questions, restated below:

1. How are students *problematized, interessed, enrolled, mobilized, and translated* in the actor-networks of engineering sophomore year and to what consequence?
2. What can we learn about engineering sophomore year by stepping outside of the network metaphor, or by shifting the focus away from central actors towards those at the margins?

As the subsequent Findings chapters build on the concepts of *durability* and *stability* in the system of engineering mathematics, understanding the history of the building and how aspects of the educational system were initially designed is instructive in understanding the state of the system today. Similarly, understanding how *problematization, interessement, enrollment,* and *mobilization* appear in the context of building the Engineering Center assists in applying these concepts to modern actor-networks of sophomore engineering.

Chapter 5 – Findings

This Chapter presents the Findings from the study, parsed into two main sections. The first section describes the durability, or persistence through time, of the engineering mathematics courses under study with special attention to the efforts made by the administration to render the entire system stable. Once the courses are described from a time-based or temporal standpoint, we move onto explaining how students are *translated* through these required math classes into *engineers*, mapping the *four moments of translation* to standard course practices and the movements of notable actors in the network under study. Identifying how the students are *problematized, interessed, enrolled,* and *mobilized* is a classical ANT approach to analyzing the actor-networks of sophomore engineering, so the each section of findings also includes a large component devoted to purposefully examining our data through an after-ANT lens. We specifically look for gaps in the network, for actors who are only partially included or ambivalently belong, giving attention to those at the margins of the sophomore year in addition to those located at the centers. Thus this Findings section maps out the actor-networks of engineering sophomore year with three distinct organizing concepts: time, *translation*, and after-ANT. Building on the preceding historical interlude describing the Engineering Center, we start by understanding what has changed and what hasn't since the building and curriculum were first built in the 1960s.

5.1 Durability in Calculus 3 and Differential Equations

5.1.1 Instructor Perspectives on Stability and Organization

"What else can you do? I mean calculus is calculus, and we have to teach calculus."

~ Dr. Lewis, Interview 2

Dr. Lewis is an experienced instructor in the Department of Applied Mathematics, who describes the potential for change in the Calc 3 and Diff Eq courses above. The attitude of "calculus is calculus" emerged as a dominant theme throughout data collection, as both instructors and TAs used the constancy of mathematics as justification for the durability of the content and administration of these courses. To understand this attitude, we examine the roles and network positioning of the keepers who maintain the revered subject of "calculus": the mathematicians and mathematicians in-training that are the instructors and TAs of the Department of Applied Mathematics.

In line with ANT, we 'follow the actors' and listen to their processes of sense-making. Extended time with Dr. Lewis, in the form of interviews, observations, and informal conversations, allowed opportunities to hear this instructor's opinions firsthand. In line with the opening statement that "calculus is calculus", Dr. Lewis expanded further on the content requirements for the mathematics sequence and why certain subjects must be covered for engineering students:

> I mean, we've been doing the same thing over and over and over again, so I don't think there's a whole lot of room to change things, right now. Because, especially with Calc 1, you have to get up to a certain section of the book, because Calc 2 has a certain amount of material to cover, and then Calc 3 has a certain amount of material to cover. Each semester is packed, and each semester gets progressively harder. So if Calc 1 doesn't cover its material, well they have to cover their material, it's not an option not to. Then that would back up Calc 2 and then Calc 3 wouldn't get anywhere and so, no. There's not supposed to be any changes.
>
> ~ Dr. Lewis, Interview 2

This passage describes the purpose of the immutability of the content in each required math course of the sequence for undergraduate engineering students. Each course “has a certain amount of material” that must be covered, “it’s not an option not to” as each subsequent math class is apparently predicated on the concepts that were covered in the prerequisite. To Dr. Lewis, if the “certain amount” of content is not covered in the first class, Calc 1, the next course would “back up” and Calc 3 “wouldn’t get anywhere”, an undesirable outcome. Furthermore, Dr. Lewis explains that “we've been doing the same thing over and over and over again,” as the math classes of Calc 1, 2, 3 and Diff Eq repeat each semester, every year, “over and over and over again.” Remembering the history unearthed regarding the initiation of recitations and addition of differential equations to the curriculum, the “over and over and over again” referred to by Dr. Lewis indicates the durable repetition of these course cycles over decades, with relatively little change. The next part of the statement, “so I don't think there's a whole lot of room to change things, right now” reinforces this concept of stability, as the cycles of repetition in these courses and their tightly sequential nature has left little opportunity for innovation or transformation. “There’s not supposed to be any changes,” adds Dr. Lewis, as semesters are predetermined and the content cannot deviate from what is prescribed ahead of time.

From the perspective of Dr. Lewis, teaching the same material semester upon semester, the perception of repetition and doing the same thing “over and over and over again” is accurate. Yet from the perspective of a student, these courses are brand-new each semester, with repetition as the punishment for failing a class and needing to retake it. In this way, a wide gulf separates the perception of durability for Dr. Lewis and the experience of most students progressing through the mathematics curriculum, as we will see further in sections 5.2 and 5.3.

The stability of this durable system has recently been challenged due to significant increases in enrollment, jumping from 4,395 students in 2010 to 5,369 enrolled in 2014, 122% growth in five years for the College of Engineering and Applied Science (Planning, Budget and Analysis | University of Colorado Boulder, 2014). This rise in engineering enrollment has strained the system of Applied Mathematics, which has persisted largely unchanged thanks to the diligent efforts of Dr. Lewis and the instructional staff. Upon being questioned about the growth in the college and the resulting impact on the Applied Math Department, Dr. Lewis responded:

> *Dr. Lewis:* Oh, our Calculus classes and Differential Equations classes, are full, everything is fuller, there's just more students in everything, yes. It feels a little bit different.
>
> *Interviewer:* And so does that mean more logistics for TAs, and homeworks, and grading?
>
> *Dr. Lewis:* Yes, yes, yes. It's more logistics all over the place, yes.
>
> *Interviewer:* So has that changed the way anything works?
>
> *Dr. Lewis:* No. We all work harder.
>
> *Interviewer:* Really?
>
> *Dr. Lewis:* Mhm-hmm (affirmative).
>
> ~ Dr. Lewis, Interview 1

The above passage illustrates how the actor-network of Applied Mathematics responds to the external stimuli of hundreds more students per year traversing their way through the engineering math sequence. The straightforward response from Dr. Lewis explaining "we all work harder" in response to the increased load demonstrates how little room for flexibility exists in the system. No revolutionary changes are possible under the current actor-network organization, so the only apparent means to address the rapid growth in the number of students is to "all work harder."

Even when given the hypothetical freedom to envision a different organization of the mathematics classes, Dr. Lewis responds:

> A better way to do the class would be to have the students take a Linear Algebra class separately and before they do the Differential Equations. But that's not feasible given the constraints of the engineering curriculum. So this is the best we can do within the constraints that we've got.
>
> ~ Dr. Lewis, Interview 1

Dr. Lewis is intensely familiar with the "constraints of the engineering curriculum," as they restrict, among other things, the number of credit hours the Applied Math classes can occupy. While the corresponding Mathematics classes (Calc 1, 2, 3, and Diff Eq) in the College of Arts and Sciences are five credit hours, the Applied Mathematics classes are only four credits, for arguably more work. Classes taken in the department of Mathematics meet five days a week, while in Applied Mathematics they only meet four times a week, a significant difference in seat time over the course of a semester. Forced by the four-year graduation guarantee and 128-credit hour limit on engineering degrees, the subjects of Differential Equations and Linear Algebra have been amalgamated together into a single, 4-credit hour class, condensing the material significantly. Dr. Lewis knows "a better way to do the class" is to split the disparate content of Linear Algebra and Differential Equations into two individual courses, but also knows "it's not feasible given the constraints." Engineering credit-hour requirements compress these courses, reducing the time in which content can be presented. Yet the content itself remains formidable and unchanging, the monolithic "calculus is calculus," the "certain amount of material" to be covered in each course. These are the multiple constraints Dr. Lewis is referring to, which so severely restrict the format of the courses as well as the potential for change and possible innovation in administering the course.

Our second instructor interviewee, Dr. Hayes, is similarly experienced in teaching in the Applied Mathematics department, and for the most part echoes Dr. Lewis in believing the content of these required math classes is immutable. Dr. Hayes, however, sees the pressing need for reorganization instead of aligning with Dr. Lewis's sentiment to "all work harder" in the face of changing enrollments. In our second interview, Dr. Hayes explains:

> I haven't seen anything change in what's required in engineering courses that would lead to a change in the content of the math classes…I don't see the content of those courses changing, I think what's going to have to change is the way we deliver the material, the structure of the courses, and frankly I think at this point they need to be simplified.
>
> ~ Dr. Hayes, Interview 2

Dr. Hayes connects the content of the engineering courses to the content of the math courses, and points to the lack of change in "what's required in engineering courses" as justification for the lack of change in the supporting and prerequisite mathematics classes. Dr. Hayes's belief that the mathematical content should be directly linked to engineering coursework is different than the "calculus is calculus" explanation given by Dr. Lewis, but is in agreement with the fundamental concept that the content of the courses is not changing. Dr. Hayes remarks on the need for the math classes to be "simplified" from their current format, a comment explained further in the context of our interviews.

5.1.2 Incremental Translations to Create the Current System

In addition to the growth in engineering enrollment, Dr. Hayes identifies other aspects of specific engineering mathematics courses that have changed. These descriptions of how things have changed highlight the processes of *translation* at work within the actor-networks of engineering mathematics:

> I think our system has changed over the years. In the old days it was a whole lot simpler. In some ways, less is more. The good fairy goes around, 'hey wouldn't it be great if we do this, and this, and this?' and yeah they're all great ideas, but when you

> implement them all you're just overworking the students. They have to hit this target and this target and this target. And for example, in Calc 3, I actually agree with the students on this, there's too much work in it. And I can't undo that, but over the years, little good idea fairy comes around, 'We need to do this, we need to do that,' and pretty soon, you add things to the list but you never take anything off. And, that's something that's changed on our part, that's not students have changed, and I don't think that's helpful to the students. Just adding to the burden, at some point they're just too busy doing and not learning.
>
> We've got 3 projects, we've got a lab class, we've got online homework, we've got homework from the textbook, we've got the 'nasty-ass problems', we call them standard problems. And they have to go to lecture, and they have to go to recitation, and they have quizzes, and it's just, the list gets so long. I'm not in a position to say, 'we're going to cut this and this and this.' I mean, there's this whole machine within the department that it has to be cleared with to make structural change. Given the number of students coming in and the amount of work, I think it's a bad combination.
>
> ~ Dr. Hayes, Interview 2

Dr. Hayes introduces the image of a "good fairy" that brings "great ideas" for classes like Calc 3 that once implemented cannot be undone. This good fairy, a metaphorical actor in the network, has *translated* positive intentions for student learning into powerful non-human course features and supporting infrastructures including three projects, a lab class to support the projects, three different types of homework, lecture, recitation, quizzes, and of course exams, all "adding to the burden" that students bear. Dr. Hayes cannot undo "this whole machine" that's been set in motion and durably *mobilized*, a machine that causes students to be "too busy doing and not learning."

The process Dr. Hayes is describing is gradual, wherein multiple incremental *translations* each with some margin of negotiation slowly shift the overall organization of an actor-network, eventually rendering the initial intent nearly unrecognizable in the final product. The curriculum fifty years ago had the same content material and course titles, but existed without online homework, standard problems, quizzes, software, and projects. As we saw previously, recitations were a novel technology that *translated* graduate students, undergraduates, and instructors into fundamentally new classroom formats, in the interest of enabling research growth. Consider the other additive course features as each *translating* some initial institutional desire into a suite of actions with attendant consequences. We will address each of these in turn, but taken as a whole, as Dr. Hayes explains, "you add things to the list but you never take anything off."

Projects are a particularly contentious and resource intensive non-human actor added into the Calc 3 and Diff Eq courses approximately fifteen to twenty years ago. Dr. Hayes describes the process in which the idea of projects balloons into a giant infrastructure or actor-network of humans and supporting non-humans:

> Projects are an old idea, it's all about having the students see a larger problem and address it. What would a mini-research project look like, right? You start from nothing, you come up with a physical model, turn it into math, solve the math, and then say something intelligent about the physical system. That was the intent of it. But, at some point, the actual calculations are so complicated that you can't do it by hand. Well now all of a sudden the students have to start learning software, and they have to learn how to write reports, and they have to learn to write the reports in the proper software so that you can upload it, so we can grade it, and then you need to start creating a course, an optional course to help them learn the software.

> And it's just, stuff grows, and at the end of the day, I don't know that what the students get out of it is worthwhile… Sounds good, but then this big thing grows and you have to create all this infrastructure…I don't know that they know Calc 3 any better because they're doing projects. It's a good idea. I in principle agree with it. And if that's all that was added to the course that would be fine. But there's all these other decorations hanging off of a course, and pretty soon it's too much.
>
> ~ Dr. Hayes, Interview 2

Dr. Hayes is an impassioned speaker on the topic of projects, questioning if "what the students get out of it is worthwhile" given "all this infrastructure" that has been created to enable them. The original intention to "see a larger problem and address it" has been transformed into a "big thing", an actor-network encompassing TA lab coordinators, computers, software, reports, grading, and an entire additional course. These resources are willingly *mobilized* because those in charge, the instructors and administrators, were *interested* and became *enrolled* in the necessity of adding projects to Calc 3 and Diff Eq. Yet those who were initially *interessed* in the idea could not have foreseen the infrastructure or vast web of actors required for the whole process. Dr. Hayes doubts, "I don't know that they know Calc 3 any better because they're doing projects," despite the fact that "I [Dr. Hayes] in principle agree with it," further demonstrating the distance between the original intention and the current consequences. This space between what was initially targeted and what has followed further illustrates *translation* at work. We will describe the impact of projects on students and their learning in subsequent sections.

The last word on projects from Dr. Hayes states, "And if that's all that was added to the course that would be fine," restating support for the idea of projects, but not given the multitude of other tasks and resources marshaled by the class. From Dr. Hayes we get the sense that there is a limit on what is reasonable as far as "infrastructure", and Calc 3 is currently exceeding that, "it's too much." In the prior quote Dr. Hayes admits to "actually agreeing with the students on this, there's too much work in it," the class Calc 3. "Too much work" here takes the form of student effort on homework, exams, and projects, as well as the numerous tasks the instructional staff must complete to sufficiently assess and support student learning. As described, despite both Dr. Hayes and popular student opinion agreeing, "it's too much," the system remains unchanged. The "machine" within the department continues churning along, stable in spite of the individual humans who voice complaints on official course feedback and to one another, informally.

Dr. Hayes explained how projects were incrementally *translated* into their current state, and we now look to Dr. Lewis to understand how projects are combined with other course elements including exams and homework into a final course grade. This is another process of *translation,* wherein student effort and performance (or lack thereof) becomes a single letter at the conclusion of a semester. Dr. Lewis explains more about the point breakdowns for each category of student work, how exams, homework, and projects came to represent different fractions of the final grade as described in the syllabus. Sample syllabi for Calc 3 and Diff Eq are reproduced in Appendix F. Dr. Lewis describes:

> Oh, that's [the point breakdown] evolved over the years. We've done it that way for years and years and years. Sometimes it's 800 points, and exams are worth 100 points. And then, a couple semesters ago one of the faculty members said, 'Well if we count them all at 150 points, and the final at 250 points, it all scales to 1000 points and it's going to be easier.' But that kind of thing, where there's homeworks, labs, exams and then the final, we've been doing that in all of our large classes for years and years and years. And, because we run the course in a coordinated way, with an experienced faculty member being the course coordinator, then that just

> propagates down from one faculty member to another. So it's, it hasn't changed significantly, the structure hasn't changed significantly in years.
>
> ~ Dr. Lewis, Interview 1

The apparent trend of repetition over “years and years and years” emerges again in speaking with Dr. Lewis, this time with specific regards to grades. This description of how the overall point breakdown for the course came about is striking in the weighting of each course element. The change from 800 to 1000 total points was not motivated by a clear consideration of how the different allocations of points to exams and homeworks would affect students, but by a faculty member expressing “it’s going to be easier” that way. Left unstated is who exactly it is “easier” for, the faculty in charge of assigning grades and scaling each assignment or the students who are subject to this grading paradigm. Grades hold a distinctly powerful position in determining the trajectories of students, as a passing grade allows students to progress through the engineering curriculum while a non-passing grade causes students to remain at a standstill, needing to retake the course before they can move forward. With such serious consequences accompanying grades, the apparent arbitrariness of the total point distribution seems mismatched. Students are governed by grades, an influential non-human in the actor-network, while faculty govern and assign the grades. Dr. Lewis explains how the intent on the part of the faculty member to make things “easier” becomes *translated* into a point system that shifts the balance for students across the constituent grade elements.

Dr. Lewis also explains how the grading and point system becomes durable across semesters, “in a coordinated way… that just propagates down from one faculty member to another.” Considering Dr. Hayes’ belief that no single faculty member can stop “the machine” of the department, the natural propagation from faculty to faculty Dr. Lewis describes is the apparent mechanism by which the grading system is stabilized through time, remaining constant despite changes in faculty members, teaching assistants, semesters, and years. Again, the statement by Dr.

Lewis explaining how “the structure hasn't changed significantly in years” further emphasizes the stability and durability of “the machine” running through these courses. No events, individuals, or conditions have caused this machine to shift, instead “the structure” of the classes persists regardless of the individuals involved.

Proceeding with this understanding of incremental *translations* and the enduring stability of the Applied Mathematics “machine,” we next examine what has perceptibly changed within this mechanistic system. In addition to the natural propagation of the grading system described above, the instructors interviewed also explained a few ways in which administration of these mathematics classes has been modified thanks to new technology and communication venues. Contrasting what has remained durable with what has shifted highlights how the actor-networks of these mathematics courses have evolved.

5.1.3 Instructor-Recognized Changes in the Actor-Network: Communication Channels

The biggest shift in the execution of Calc 3 and Diff Eq has been the increased channels for communicating information from instructional staff to students. For instance, Dr. Hayes compares how information was formerly communicated to what happens now:

> In the old days it was like what happened in the classroom, that was gospel. I mean there was no e-mail, and there was no web, and all the other things didn't exist. It was like all the business happened in the classroom, it was your obligation to find out if you weren't there. Well now, the expectation is, I'm going to try seven different channels to get it to them and they're going to ask a question, and they're going to get really grumpy if they don't get their answer in 30 minutes. And, I don't think faculty buy into that.
>
> ~ Dr. Hayes, Interview 2

The “gospel” of the classroom has been apparently subsumed by the multitude of communication channels now available and reportedly expected by students. Dr. Hayes describes when “there was no e-mail… no web… all the business happened in the classroom,” a specifically bounded location in both space and time. Before electronic modes of communication existed as alternatives to in-class, face-to-face time between students and instructors, the classroom was the primary scheduled time for interaction. It was “gospel”. As explained above, when students missed class it was “your obligation to find out if you weren’t there;” if any of the “gospel” was missed, students took it upon themselves to understand what messages were lost. Now, according to Dr. Hayes, the expectations have shifted along with the communication venues so that it is the instructor’s duty “to try seven different channels to get it [information] to them [students],” as e-mail, two official course websites, phone/text, and TAs now exist as viable methods of communicating information. Furthermore, Dr. Hayes adds that students are “going to ask a question, and they're going to get really grumpy if they don't get their answer in 30 minutes,” as the new modes of communication have engendered expectations of quick turnarounds and near-instantaneous responses to student queries. Adding, “I don't think faculty buy into that,” Dr. Hayes illustrates the perceived divide between faculty and student expectations in describing a disconnect between what students desire and what faculty can realistically do. The advent of email and course websites including the Desire2Learn platform have significantly changed how faculty communicate with students, splitting the focus from the “gospel” of the classroom into a variety of channels for electronic interaction.

The utility of the course websites and email has also changed how faculty convey specific information like homework and exam solutions to students. Dr. Hayes explains how these solutions were transmitted to students in the days before electronic media became the norm:

> We'd post them on the wall. So, right out here, right now there's kind of a bulletin board and then a white board. We would literally, by hand, write-up solutions and

> they would be posted on the wall…On the day after the final, or the midterms, we would hand out, we would very compactly write solutions. We would work very hard to be able to get them on one page, and we would pass them out in class, with the exam.
>
> ~ Dr. Hayes, Interview 2

Solutions were once written “compactly,” “by hand,” to fit on one page and thus be easily passed out in class to the students present. This is another instance of the “gospel” spread during scheduled classes, the handing-out of papers featuring specific important content from instructors to students. Now with course websites and e-mail, students do not have to be present in class to obtain these precious documents, nor do the documents need to be restricted to one page front-and-back in order to be distributed to students economically. The ability to send information electronically and post solutions on a continuously accessible website has made it significantly more convenient for students to access these forms of content knowledge. Where students once had to stand and examine homework solutions “posted on the wall”, the information is now available via mobile device, laptop, or desktop computer, anywhere a student goes, whenever they want. Technology has changed the communication channels in both time and space, removing the sacred status of the classroom by expanding and allowing students to access homework assignments, homework solutions, syllabi, sample exams, and exam solutions at any moment, from any physical place.

Dr. Hayes explains the consequences of this expanded access to course information on teaching efforts and student actions:

> Homework, we would put on the syllabus, and we worked very hard to get the syllabus on one page so we could save paper, and you'd have the whole course schedule with all the homework assignments and all the agreements, the rules of the game, on the other side. And they would get a hard copy and the students would

> actually save it - here's the road map for the semester and they would hang onto it for the whole semester. Now they read it and they throw it away. And they expect you to be contacting them if there's a change. Now we post changes on the webpage, but that's what it was. If there were reviews, you'd write ‘em on the chalkboard, you'd remind them that the exam is on this day and you'd write it on the board, exam is this Monday, from 5-7 in this room, and all the business was conducted in the classroom. And to be honest with you, I really miss it. I mean, having to deliver things in four different channels, and, another big change is access to online homework. I'm not convinced that that's really good.
>
> ~ Dr. Hayes, Interview 2

Here Dr. Hayes refers to the syllabus of the past, which was revered by faculty and students alike, an important inscriptional artifact for the administration of the class containing “the whole course schedule with all the homework assignments” and “all the agreements, the rules of the game, on the other side”. Dr. Hayes describes how faculty “worked very hard to get the syllabus on one page so we could save paper,” condensing the requirements or “road map” of a semester onto a single front-and-back document easily passed out in a large lecture course and then transported by individual students throughout the duration of the class. “They would hang onto it for the whole semester,” explains Dr. Hayes, as the syllabus once was a powerful mediator in the class actor-network, establishing for students important dates, deadlines, and content, putting forth relative importance of each assignment and exam, “the rules of the game” by which student efforts were assessed by faculty.

“Now they read it and they throw it away,” states Dr. Hayes, as the apparent consequence of having the course materials and other information available online has been a de-valuation of the once mighty syllabus. Though the syllabus is still a one-page front and back source of information and the "rules of the game" for the course, students apparently "throw it away" because they can access it online whenever they want. The paper artifact on which the syllabus information is inscribed is no longer the only means of retrieving the information, so as a result it is easily discarded. Dr. Hayes identifies a corresponding shift in student expectations, explaining "they expect you to be contacting them if there's a change," adding, "we post changes on the webpage" in addition to communicating in-class. Dr. Hayes describes how in the past, "you'd write it on the board… and all the business was conducted in the classroom," instead of needing to post information on the webpage and other faculty efforts to spread information apparently expected now by current students.

Dr. Hayes says, "I really miss it," the past in which the classroom was "gospel" and students held onto the syllabus for the entire semester, explaining that "having to deliver things in four different channels" is not productive for faculty. The other "big change is access to online homework," which Dr. Hayes is "not convinced that that's really good." The proliferation of communication channels has seemingly made it more difficult to get information across to students, as the prevalence of different messaging options aside from "the board" and "the syllabus" has diluted the transmission power of the information from faculty. Dr. Hayes is nostalgic for the time when the classroom and class time were the single communication channel between teachers and students, the way things used to be before the Internet and email became integral to the administration of these courses.

Dr. Lewis agrees with Dr. Hayes that communication is the biggest challenge of teaching and administering the engineering mathematics courses of today:

> I think one of the biggest issues for me, the university brings in thousands of freshmen, and how you do you get them all the information they need, to understand that information? Because I think that's one of our biggest challenges, even in our

> Calc 1 class, how do you get all the information out to all the students, and have them all understand that: yes the workgroups are available, yes they should go to recitation, yes they should go to lecture and pay attention. So how do we get all the students moving, more or less in the same direction? That's the biggest challenge.
>
> ~ Dr. Lewis, Interview 2

Dr. Lewis asks, “how do you get” the “thousands of freshmen” “all the information they need”, and further, “to understand that information?” This is apparently the “biggest challenge” even from the start of the mathematics sequence in Calc 1, extending to the courses under study of Calc 3 and Diff Eq. Getting “all the students moving, more or less in the same direction” is difficult in the current era, as the multitude of communication channels has not improved the effectiveness of communication from instructors to students. Compounding the issue is the increase in information that instructors are trying to impart to students, including the availability of workgroups, attendance at recitation and in lecture, yet there is no surefire way of reaching the students and “[having] them all understand”. This is the fundamental challenge, apparently, of administering these courses, as even if students attend lecture but don’t “pay attention” they will miss some of this information and will not be aware or understanding of the information at hand. This is an age-old question of teaching, yet it seems that new communication avenues including the course website and Desire2Learn have not solved the problem of getting students to listen to all the information being presented.

Dr. Lewis also explains how distractions for students during lecture have shifted over the years:

> When I first started teaching here, the problem was not to get the students to read the newspaper in class. So the problems have shifted a little bit, but they're still allowing themselves to be distracted, and now it's just with a phone instead of with a

> newspaper, but it's the same thing…Newspapers are worse because they always rattled the newspaper when they turned a page. Phones, they're a little more, I don't want to say discreet, but they try and hide it anyway.
>
> ~ Dr. Lewis, Interview 1

Here one difference between newspapers and phones is discussed, from the perspective of Dr. Lewis the only salient difference between these two distractions is the noise generated from them during a lecture period. Dr. Lewis does not delve into the fundamentally different technologies of newspapers and smartphones, as newspapers are a static artifact capturing a single snapshot in time when printed, and smartphones are a dynamic connection to the world constantly refreshing and updating with new content and connections to people via social networks, texting, and email. To Dr. Lewis, newspapers would "rattle… when they turned a page," an audible distraction for students and teachers in the lecture hall, different than the somewhat more discreet smartphone. "They're still allowing themselves to be distracted," explains Dr. Lewis, as the students have remained consistent in their desire for diversions away from the mathematical content at hand. Accompanying the addition of course webpages and email as communication channels for the class is the increased prevalence of smartphones and laptops, these mobile technologies enabling a suite of distractions in turn. Just as Dr. Hayes commented on being unconvinced that these new technologies were good for students or communication, Dr. Lewis points out that regardless of the format of the diversion, students will continue to be distracted and communication remains a challenge.

Finally, we turn to an excerpt from a classroom discussion during observations of Calc 3 class to illustrate one more consequence of the new technology and communication channels in these required mathematics courses:

> Shawn asks, "Is there any way that solutions will be put up for the latest practice finals?" Dr. Oliver explains, "So unfortunately, our servers were hacked over the

> summer, so what we have up is what we have. I don't have solutions for them, if I did I would send them out… but I think there are three if not four practice finals and solutions, somewhere over the past five to eight years, on there…"
>
> ~ Fieldnote excerpt, Calc 3 small section, Dr. Oliver Week 16 Friday

The "servers were hacked over the summer," an additional consequence of making an exam archive of finals and solutions available online. Before there was a course website and exam solutions were printed out on paper and distributed to students in class, there was no potential of the data being lost, of hackers breaking into that paper-based system and disrupting it. Dr. Hayes and Dr. Lewis described above the additional challenges of communicating with students now that there are multiple channels for getting information across, and this excerpt from class adds another dimension to the challenges of communicating in the 21st century. Not only does the instructional staff have to maintain the course website with current messages, assignments, solutions, and other information, they have to stay aware of threats to the online spaces they maintain.

From interviews with Dr. Hayes and Dr. Lewis, and a short snippet into class events, we see that the largest change in the administration of Calc 3 and Diff Eq has been the increase in communication channels available for the instructional staff to attempt at disseminating information to students. Whereas the lecture hall and class time were once the only means for communicating information, now there are class websites, email, online message boards and homework assignments. Where students once treated syllabi as important documents and held onto them for entire semesters, now physical documents have less importance as their content is readily accessible online. "I really miss it," says Dr. Hayes, with regards to the past in which all communication happened during class, when there were no other options for students to hear announcements or learn the material. According to Dr. Lewis, "the biggest challenge" remains getting all students to understand the information, as the increase in communication avenues has not led to an increase in comprehending the material or being aware of the tasks or opportunities at hand. Dr. Lewis also comments on the change from newspapers in the classroom to phones, explaining that they are somewhat quieter distractions without acknowledging the greater individual reach of phones to events outside the classroom, in both time and space. Students on their phones during lecture are different than the students of yesteryear reading newspapers, both in noise generated and in the resources available at one's fingertips. These 21st century communication avenues also bring with them 21st century problems, as hackers affect the content available on the course websites and cause more work for those who maintain the electronic resources for students.

Considering these changes to the communication channels along with the incremental translations of course elements like projects and the overriding durability in the content of these courses, we start to see Calc 3 and Diff Eq as paradoxical amalgams of new and old. While the grading scheme, for instance, was seen to have propagated naturally from one faculty to another, the creation of the course websites and use of email are viewed as cumbersome additions to the once-streamlined communication channels between instructors and students. With these changes in communication avenues discussed by the instructors we interviewed, the constancy of the content of these courses is even more striking in comparison. We continue this section of our findings examining what else has remained the same in the actor-networks of Calc 3 and Diff Eq.

5.1.4 Vestiges of the Past, Lecture Halls and Board Work

Part of the historical interlude included a comparative photo of a lecture hall classroom when the building opened in 1965 and how this classroom appears today, half a century later (see Figure 29). That current mathematics courses still meet in these 1960s era lecture halls three days a week for entire semester-long courses is a hint at the highly durable mode of teaching that is the lecture, along with the highly durable artifacts implicated in this teaching style like the chalkboard, chalk, and tiered seating for students. The prior subsection of our findings featured instructors like

Dr. Hayes expressing nostalgia for the time when the classroom was all there was, and frustration that the additional electronic communication channels available for information transmission do not seem to be helping students understand math any better than they used to. Since the classroom was once "gospel" it makes sense that the classroom still remains a place of central importance, at least to the instructors who lecture within it. The primary activity during the class meetings of Calc 3 and Diff Eq is still the instructor lecturing: the instructor stands at the front of the room, speaking out loud while writing on a chalkboard with chalk for students to see and replicate by taking notes. As we will see, the lecture remains the default mode of instruction and consequently the chalkboard, chalk, and lecture hall remain powerful mediating artifacts for student learning.

The bulk of lectures for Calc 3 and Diff Eq begin with the instructor writing down some mathematical words and symbols on the board for students to begin looking at and copying down before the official start of the lecture. The phrases written on the chalkboard are assumed to be true, as they mark the exchange of knowledge from the teacher to the students. For instance, one day in Diff Eq Dr. Lewis comments on the nature of things written on the board:

> Shawn suggests something in response to instructor's question, and Dr. Lewis agrees "exactly…" and then writes it down on the board. "I wrote it down, do you believe it?" and "yes", joke several students in reply. Dr. Lewis recognizes this joking and adds, "well yes, I wrote it down, but how would you show it?" and Ethan responds to the instructor.
>
> ~ Fieldnote Excerpt, Diff Eq small section, Dr. Lewis Week 13 Monday

This exchange demonstrates what is assumed in the context of this math class when a professor writes something down on the board. First, Dr. Lewis questions if students "believe it" because it is written down on the board. Upon finding out that yes, students do believe it because it is written down, Dr. Lewis confirms, "well yes," when something is written down it is true – Dr. Lewis is not aiming to deceive, nothing false is written down on the board purposely. Next, Dr. Lewis asks "but how would you show it?" further demonstrating that what matters in the class is not just what is true or not true, but how you would "show it", or prove it logically. Thus the bulk of the mathematical tasks assigned to students require them to "show it," or demonstrate through a variety of logical steps that a given statement is true or not true. The math lecture is similarly a process of the instructor "[showing] it," writing representational steps on the chalkboard over and over again to prove a result to be logically true.

The feature of chalkboards that makes them indispensable to the mathematics lecture is both the ease of writing information down and the accompanying ease of erasing the representational writing so that more can be written down, over and over again during the course of a lecture. The fact that chalkboards can be erased quickly, with the simple wave of a small object, enables the math lecture to proceed, for multiple chalkboards of information to be presented in only fifty minutes. Dr. Hayes utilizes the seconds it takes to erase the chalkboard as small mini-breaks from the otherwise constant onslaught of math content during lectures, and encourages students to talk to one another as the chalkboard is reset:

> Dr. Hayes says, "Today is Friday, right? I have to erase. While I erase, introduce yourself to a neighbor…." And conversation ensues. I introduce myself to the male on my left, Peter, who explains that he has 4 classes on Fridays because of experimental physics lab. We chat until Dr. Hayes writes "OK" in large script on the board to bring us all back. Dr. Hayes asks, "How many of you actually got a date out of that?" a student in the back row of the lecture hall responds, and Dr. Hayes says "good luck with that." Students laugh in response.
>
> ~ Fieldnote excerpt, Calc 3 large section, Dr. Hayes Week 2 Friday

This fieldnote excerpt is taken from the second week of class, on a Friday. Dr. Hayes encourages the students to talk to one another while erasing the board, to make use of this unique time during lecture to "introduce yourself to a neighbor." The young man I speak to explains that Fridays are relatively busy with classes, since the experimental physics lab he refers to meets only once a week on Fridays, adding another scheduled class meeting onto the lecture classes like Calc 3 that meet Monday, Wednesday, and Friday. Dr. Hayes is adept at keeping the class interested and attentive, frequently peppering lectures with humor and joking around with students. In the fieldnote above, Dr. Hayes is quick to lightheartedly ask, "How many of you actually got a date out of that?" The one male who audibly replies from the back is adept at bantering with Dr. Hayes, unafraid to speak up and receive the last volley of words from Dr. Hayes exclaiming "Good luck with that." Dr. Hayes and the students who play along with the bantering questions jointly establish the joking tone of the classroom.

Dr. Hayes consistently uses the time it takes to erase the boards to ask the class non-math related questions, to share a personal anecdote about the weekend past or ahead, or to discuss lecture-related inventions that would be useful for teaching these mathematics classes. For instance, during the sixth week of the semester in Calc 3, Dr. Hayes discusses the idea of chalk that disappears on its own:

> "So we want to work it out in general, so let's just try a bunch of problems…" says Dr. Hayes, now erasing the right side of the board. "You know what else would be good? Chalk that fades… like after 10 minutes, it just fades…" this makes some students laugh and generates side conversations among students throughout the room. I see the man on my left laugh, and the woman near the in front who was texting says something to the man on her right.
>
> ~ Fieldnote Excerpt, Calc 3 large section, Dr. Hayes Week 6 Wednesday

Here Dr. Hayes is using the time spent erasing the board as a short break for the students from the otherwise constant math content. Instead of pushing forward with the "bunch of problems" immediately, the board first needs to be cleared so that there is room to write the problems. Dr. Hayes jokes about the usefulness of "chalk that fades" "after 10 minutes," as such self-erasing chalk would not require any action by the instructor to clear off the boards. While it is not about mathematical content, this joke still pertains on a meta-level to the experience of teaching on a chalkboard and learning from the chalk representations made on the board by Dr. Hayes. The comment about chalk that "just fades" is successful in motivating side conversations around the room, ostensibly about the potential for this special chalk while Dr. Hayes erases. The students who are noted in the fieldnote as laughing and speaking to others about this idea are confirming their attention on the lecture, instead of talking about something completely different or remaining stuck on their phones. Dr. Hayes uses this aside as a technique for maintaining the class's attention on the lecture, even if the content is not exactly mathematical, it is still on some level about the class experience.

The cycles of writing on and subsequently erasing the board organize the activity of the lecture. Dr. Hayes utilizes the mandatory pauses in content delivery while erasing the board as opportunities to keep the class engaged in non-mathematical content. The chalkboard is a mediator for the content presented, as instructors must engage with the board to communicate via writing the concepts, facts, and equations that the students are to learn. Students, meanwhile, can take notes in the form of replicating what's written on the board in their own notebooks, in the hopes that this scribing assists in learning the content at hand. As we will see in subsequent sections of these findings, many students of the current generation see writing down notes as a waste of time, preferring the textbook or online content help websites as the only reminders of content they need to succeed in the course.

Lecture activity thus centers on the chalkboard. It follows that the chalk itself is also an important mediator in the chain of representations linking mathematical content, instructor's writing, the chalkboard, and disciplinary knowledge learned by students. The technology of chalk has existed for centuries, used for art and practical purposes alike. Surprisingly, chalk itself is ancient – made up of tiny skeletons of plankton-like organisms, compressed under layers of the earth over geologic time scales to become the solid white substance we use in stick form today (Krulwich, 2012). Each time an instructor wields a stick of chalk on a chalkboard, a smear of the chalk is transferred from the stick to the board as the small skeleton particles adhere with pressure to the flat surface of the chalkboard, at least until wiped away by an eraser. This technology is indispensable to learning in the lecture halls, as chalk on the chalkboard provides ample contrast to be legible even from the back of the lecture hall. Dr. Oliver is vocal in professing a preference for chalkboards over whiteboards, even detailing a specific type of chalk that is superior to the rest:

> "And the stuff that you find now, it's so light. It looks like chalk but… since sometime last spring, now everything in the world causes cancer. They described last spring that this chalk causes cancer… they stopped making this, and there's only a few stashes left… and I'm almost to the end of my stash. Now the thing is that the Physics department here has a bigger stash than everyone else.
>
> "Break in… a heist…" comments Spike from the 3rd row.
>
> Dr. Oliver starts passing a sample piece of chalk out to the students. The chalk gets passed from Erika to Ethan to the right of the second row, down the 3rd row to me, I pass it to Samantha in front of me and she passes it to the left, than to the front, with Simon and Jackie.
>
> "What's the name for it?" asks Erika. "Chalk," replies Dr. Oliver, explaining, "The brand is Alpha… I'll bring the box in on Monday."

~ Fieldnote Excerpt, Calc 3 small section, Dr. Oliver Week 7 Friday

Chalk is precious to Dr. Oliver, specifically the Alpha brand that is being discontinued by the manufacturers since it apparently "causes cancer." Dr. Oliver goes on this aside as the small section of Calc 3 discusses if they prefer whiteboards or chalkboards, and then more specifically the exact brand of chalk that Dr. Oliver prefers. This story from Dr. Oliver reinforces the importance of chalk to the lecture, as it is a vital intermediary for facilitating communication between mathematical content, Dr. Oliver, and the class. There is a limited supply of this desired brand of chalk left, and Dr. Oliver is "almost to the end of my stash," apparently causing some distress. Upon finding out that the Physics department "has a bigger stash than everyone else," students like Spike are encouraged to pull "a heist" to procure the desired chalk for Dr. Oliver. The chalk is so precious that it is handled like a rare specimen, passed around the rows of the classroom so that each student can individually inspect it and observe its special qualities. Dr. Oliver does not let an opportunity for joking slip by, responding to Erika that it is called "chalk" before progressing to tell her the name of the brand for the chalk.

This fieldnote excerpt illustrates the depth of Dr. Oliver's connection to this simple technology, and also highlights the staying power of chalk. Thus chalk is another physical consequence of the durability of the lecture format in teaching mathematics. Chalk is crucial to teaching with a chalkboard, for administering a lecture from the front of the room, for writing down symbols and text quickly and in high contrast, visible to students all the way in the rear. Dr. Oliver's insistence on using Alpha brand chalk is also an insistence on using chalk to lecture, on the overall format of lecturing with a chalkboard to teach. It is the predominant form of instruction in these mathematics classes, it is intensely durable, and striking as chalk is literally a remnant of the past. Both chalk and the lecture hall itself are in this way enduring artifacts, scarcely changed in fifty years, and seemingly critical for teaching even today.

We next examine how students arrange themselves in the lecture hall, as their choice of seat determines the distance between their eyes and the front of the room. As discussed above, the bulk of an instructor's activity during a lecture class is near the board at the front of the room, using chalk on the chalkboard and erasing periodically, speaking aloud to the students and communicating mathematics. The seating in the lecture halls is fixed; there are a limited number of seats in each row (around 16) and there are a finite number of rows (about 9). Students who are arrive late to class are not guaranteed an actual seat, particularly during the first weeks of classes when students are busy optimizing their schedules and deciding which classes they will actually enroll in, and which classes they deem worthy of their attendance. Sitting on the stairs at the far ends of each row is not uncommon during the first few class meetings, as students who drop the classes and/or stop attending leave empty seats up near the middle and back of the room.

The seats in the first two or so rows of the lecture hall are unique resources for students who wish to occupy them. Some students queue in the hallway before class, every class, to ensure that they'll get their spot in the first row. One student interviewee, Elizabeth, always sat in the front of the room even if all of the seats in first row were already taken – she would instead sit on the ground:

> Dr. Hayes pauses and looks at the two students seated on the floor in the front of the room, Elizabeth and a male student. "We really need to have honorary pillows for you. There are seats up there…" Elizabeth responds, "I can't see up there…" and Dr. Hayes asks if she wants to use the table in front or something. Dr. Hayes adds, "I've seen people in this room in different places but I've never seen people sit on the floor!" Dr. Hayes continues with the example discussing what happens at critical points and where extreme values exist…
>
> ~ Fieldnote excerpt, Calc 3 large section, Dr. Hayes Week 7 Wednesday

Being near the front is important to Elizabeth, as she "can't see up there" where there are seats available towards the back. Dr. Hayes is apparently surprised at their desire to "sit on the floor," as it is apparently unprecedented. The suggestion that they deserve "honorary pillows" signifies that Dr. Hayes is impressed by their dedication to being in the front, near the chalkboard. The seats in the front are a prized resource, available only in finite quantity. They also offer the greatest proximity to the instructor. Casual conversations can be held quietly between the professor at the front and nearby students without the audio carrying all the way to the back. Pleasantries can be exchanged without interfering with the flow of class. After class officially ends, students sitting near the front and nearest to the instructor can ask questions quickly and informally. Those from the front rows have the shortest distance to travel and thus tend to get to the instructors first, making their question-asking process convenient without the need to wait in line.

In one of the classes observed, the large section of Calc 3 instructed by Dr. Hayes, one front-row habitant becomes emboldened and about two-thirds of the way into the semester the student begins to write strange vocabulary words on the chalkboard before Dr. Hayes arrives for the lecture:

> As I enter class a man who typically sits in the middle of the front row, next to the blond woman from statics who also always sits in front, is writing on the board. He has written "Pop Quiz/ Zenzizenzizenzic/ rhino tillexomania/ podobromhydrosis" Dr. Hayes looks at it for awhile, then asks a different woman in the front row to take a picture of it and send it via e-mail. The male student that wrote the expression on the board adds, "Professor, I have more if you want some…" and then Dr. Hayes begins to draw on the board cylindrical coordinates.
>
> ~ Fieldnote excerpt, Calc 3 large section, Dr. Hayes Week 10 Wednesday

This male student has easy access to the chalkboard, and for some reason in the tenth week of the semester begins to write these archaic pieces of language on the board, mostly for Dr. Hayes to see and respond to. The three words from this excerpt mean, in order: an outdated way of saying to the eighth power, a clinically obsessive-compulsive nose-picking disorder, and extremely smelly and perspiring feet. He offers to write more "if you want some," an offer that he makes good on in the subsequent meetings of the class. The words he chooses are always obscure, as he initiates Dr. Hayes and any students who care into his realm of hearing and knowing of these words. No one second-guesses this man, it seems that the back rows just ignore it, waiting until Dr. Hayes erases the words from the board to move onto math content. That this student is free to write on the board and interact with Dr. Hayes about the words with no consequence or fear is further evidence of the unique status of those in the front rows.

The back rows of the lecture hall afford a different set of resources than the front rows. Instead of having a direct line to the instructor, the back rows are separated by many rows of seats and students, increasing the distance and volume it requires to communicate back and forth. As the board is further away and the text may be harder to read, the reverse is also true as the instructor at the front of the room may have a harder time seeing what the students in the back are doing, what they are writing or reading during class. For an instructor from the front of the room to speak to a person seated in the rear of the room, they must speak loudly and the rest of the class must be relatively quiet. During the semester of Calc 3 under observation, Dr. Hayes called out a student in the back for texting in class, resulting in the following hilarious exchange:

> Dr. Hayes pauses the lecture upon seeing a male student in the far back texting. Dr. Hayes says, "I just gotta ask, what are you doing back there?"
>
> "Sorry." Says the male student, he's blond and in my recitation section.
>
> "What are you doing back there?" asks Dr. Hayes, again.

"Texting," replies the male student.

"Who?"

"Friend."

"Where?"

"Not here."

"Are they in town?"

"I don't know."

"Invite him, if he's not doing anything Monday, invite them here. Do you know what their major is?"

"I do not."

"How much do you know about them?"

"Met her last night." And the class erupts in laughter at this piece of information.

"It's fitting together," says Dr. Hayes, who turns back to the board and says, "You're not going to tell us her name, are you?"

"No," says the male student.

Dr. Hayes recommences the lecture. The student starts blowing his nose loudly causing everyone to laugh. Then Dr. Hayes pauses and turns around, this makes everyone laugh again. Dr. Hayes draws on the board to demonstrate some math concept and then pauses again, "I just gotta ask, where did you meet her?"

"Party," says the male student.

"Okay, I don't want know," concludes Dr. Hayes, returning to the lecture.

~ Fieldnote excerpt, Calc 3 large section, Dr. Hayes Week 7 Friday

The above excerpt demonstrates how Dr. Hayes and a student seated at the rear of the classroom interact. The class is silent save for laughter and the words exchanged by Dr. Hayes and this young man, who replies to Dr. Hayes's questions with short, one-word answers. Initially motivated by the illicit texting, Dr. Hayes chooses to call attention to the young man and put him at the center of class activity to make an example of what happens in lecture when you are caught using your phone. First, upon finding out that the young man is texting, Dr. Hayes assumes that he is texting another male student. The student clarifies that he "met her last night," causing the class to erupt in laughter as Dr. Hayes's initial assumption is proven incorrect.

This exchange would not happen like this if the student caught texting was at the front of the room, in the first few rows, instead of the back. The student's sizable distance away from Dr. Hayes magnifies the humor in the situation, as their conversation is not private – it is spread over the rows of the lecture hall, from the front of room to the rear. The whole class is privy to this exchange, and finds it much more humorous than the random vocabulary words the man in the front row likes to write on the board. Here, Dr. Hayes is reinforcing to the class that their actions are visible, that texting is obvious even from the front of the room. The young man who is caught with his phone apologizes initially, quickly, before giving up the juicy details of the situation upon being questioned by Dr. Hayes.

This event occurs in the middle of the semester, the seventh week, on a Friday. That this male student was at a "party" on Thursday night and following up with a woman he met the next day is unsurprising, as Dr. Hayes comments "I don't want to know" after finding out the context of these students meeting. This exchange marks the longest conversation Dr. Hayes has about phone usage during class, otherwise the occasions where Dr. Hayes calls out a student on their phone are few and far between. This student's visibility in the back and subsequent humorous conversation with Dr. Hayes serves as a warning for other students who use their phones in lecture at risk of being similarly pointed out publicly. The back rows provide a certain level of anonymity, yes, but not entirely as Dr. Hayes is vigilant and does not hesitate to engage students at a distance in open conversation.

Each seat in the lecture hall comes with a set of resources. The seats towards the middle and back of the room are less contested than the front, offering more space and the ability to save seats for friends or to have more room for personal effects, like backpacks or notebooks. Near the front there is easy access to the instructor and the chalkboard, helpful for those students who utilize those resources in learning. Students who desire front seats go to great lengths to secure them, including getting to class routinely early, clinging tightly to their chosen spot. The front seats are privileged in that it's easy to stand out to the instructor from the front, to create a relationship just by being close to the professor and the board. Students farther back are at a greater distance from the instructor and from the board, but privy to a different set of resources and distractions. From the front, all that is visible is the chalkboard and the instructor. From the back, the entire classroom is visible, including all of the students seated in the rows as well as the instructor and the writing on the chalkboard. Some students are more skilled at focusing ahead on the content, while others choose to let distractions like smartphones and peers dominate the class experience.

Students choose where to sit and how to arrange themselves within the lecture hall, sometimes selecting seats that are non-traditional or non-obvious, including the floor or the stairs. Each location offers different benefits and trade-offs, and a different set of possible relationships to peers, instructors, content via the chalkboard, and distractions via phones or peers. The lecture hall is as powerful in organizing student learning as the chalkboard or chalk, and equally durable in persisting through the decades largely unchanged. The seats in the lecture hall have actually been remodeled over the years, replaced from the original design to fit in more seats, and to make the lap desks stronger as several break each year. The tiered-row design has not changed, however, and neither have the rewards and trade-offs associated with each position in the room. While alternate communication channels exist in addition now to the “gospel” of the lecture hall, it still remains central in student learning and impactful for students navigating their way through these math courses. The lecture hall is a vestige of the past, but nonetheless persists as an important element of the present in engineering undergraduate. The lecture hall is another longstanding element in the overall actor-network of sophomore mathematics, another constituent of the amalgam of old and new.

5.1.5 Disconnects and New Questions

Identifying the mix of old and new elements found in sophomore mathematics and discussed in this findings section begs new questions regarding what has been made durable and what has changed in the last five decades. The content has been preserved and is considered immutable today while the communication channels from instructors to students have shifted considerably, indicating that the next area of shift may be in actually communicating the content in new channels, electronically. Textbooks are an example of tangibly durable artifacts that are starting to go online, existing differently and more ephemerally than the hardbound, weighty tomes of tradition. E-textbooks offer electronic pages identical to the printed text, accessible anytime online with an e-reader or mobile device. While some institutions have embraced e-textbooks for widespread use due to their convenience and modularity, there is some hesitance on the part of Dr. Lewis in recommending the electronic version of the calculus text:

> I always feel that the reason an engineering student is taking Calculus and Differential Equations is because they need it for their upper division classes, so I always encourage them to keep the book, and not to get rid of it. Because, presumably, they will want to look things up. And the, the thing is with the electronic textbook, if you get the electronic textbook you only get it for the semester you're in

> the class, and then it disappears, and then you have nothing to look up. So, I think that's a disadvantage.
>
> ~ Dr. Lewis, Interview 1

"Presumably" students will use the physical textbook to "look things up," explains Dr. Lewis when questioned about physical versus electronic text options. Dr. Lewis "encourages" students to "not get rid of" the book in the promise that it may be useful later in "their upper division classes." While purchasing a textbook is certainly one option for referencing content in subsequent semesters of engineering school, there are a variety of other reference sources now available freely to students, both online and in person in the library. Dr. Lewis does not mention these sources as valuable to students, instead choosing to focus on the textbook as the primary source of useful knowledge. The comment that the electronic textbook "disappears" is partially correct, though students can also choose to purchase an electronic textbook for perpetuity just as they can purchase a hardcopy for permanent use, or rent a hardcopy or an e-textbook for just a semester. Though purchasing a textbook and using it to "look things up" is the traditional method, more and more educational systems and students are choosing to go electronic. As knowledge becomes more and more freely available online, the textbook industry continues to raise prices and enforce their stronghold in higher education. Going forward, will electronic avenues of accessing content be viewed as valid? As we will see in subsequent sections, students use Google as often as they use their textbook if not more while trying to do homework problems. A disconnect is apparent between what has traditionally been the standard - hardcopy textbooks - and what students actually use - the Internet.

Another disconnect is evident given the increased enrollments and near-capacity efforts of the instructional staff. Incremental translations that have led to the creation of large infrastructures are now being questioned in the light of resource constraints. As Dr. Hayes explains:

> I gotta be honest with you, in terms of the structure of the courses, I don't think we can maintain. I mean I love the idea, I think it's great, things like orals, the workgroups. I think the best thing you can do is, because this is a volume operation, you gotta teach them how to do this stuff on their own. And, I think you need to step back and take a serious look at how you're using your resources. You know, are workgroups really a good idea? Are projects, a good idea? Because if you get rid of projects, you can get rid of a whole course, which means a couple of teachers are freed up, and you know, students' time is freed up, and so I think in some sense you need to go back and figure out what's the actual critical information you need from this course, and then start from there. Start considering taking the decorations off, and that means taking a serious look at things like workgroups, how recitations are run...
>
> ~ Dr. Hayes, Interview 2

Dr. Hayes illustrates another disconnect in the making: the current structure of the courses and the resources available. There are concerns about the ability to "maintain" the course elements that require considerable manpower and are to Dr. Hayes "decorations," like the workgroups, orals, and projects. Since "this is a volume operation" and the volume of incoming students continues to increase, a "serious look" at how the resources are being allocated is in order. Dr. Hayes explains, "best thing you can do…is teach them how to do this stuff on their own," an ode to lifelong learning and the need to teach students how to learn independently. Yet, how can that be done given the prescribed nature of the class tasks? Dr. Hayes advocates for someone to "step back and take a serious look" at all of the "decorations" hanging off this course, to understand if course elements like projects are justified or not. Dr. Hayes explains how many resources would be freed up if you "get rid of projects," a tempting idea for both course designers and students alike.

"What's the actual critical information you need from this course?" asks Dr. Hayes, and an immediate answer is not clear. Elsewhere Dr. Hayes explained that since the engineering coursework had not changed significantly, there was no reason for the mathematics prerequisite content to change either. Here, however, there is a different tone of the conversation, expressing the need to "go back" and start over, considering fresh what is really needed from the math sequence. The need to reform the curriculum is apparent especially as enrollment growth stretches the available teaching staff thinner and thinner. New questions about what is "critical" and justified for the course are being asked, here by Dr. Hayes and more broadly by this research project as well.

The constraints on the math curriculum are numerous and are also being questioned because of the increasing strain on the available resources. The four-year guarantee, or the institutional promise that "required or essential courses, or acceptable alternative courses, will be available to allow each student to complete all course work required for a single Bachelor of Science degree from this college no later than the end of eight consecutive semesters of full-time enrollment," has been in place in the College of Engineering and Applied Science since 1995 (University of Colorado Boulder, n.d.-b). Dr. Hayes sees the four-year guarantee as setting up unreasonable expectations in students and unreasonable demands on the curriculum:

> I don't mean to be hard-nosed about it…but for me to tell you that I have a prescription for you, that you can do it in 4 years, that's nonsense. Once you adopt that, that we're going to do it in 4 years, then you start trimming things, and start compressing things. And at some point, you're not doing the students justice. So, the first thing I would do is get rid of this 4-year guarantee - out the window. In fact, probably I would think about it as a 5-year endeavor. Because if you're going to do it, do it right. And that means slow down, think about it a little bit more, quit working the students to the point where they don't sleep. Just back off, and give them time to

> do it the way they should be. And so I would personally up the hours back up into the mid-130 range, maybe 140, I don't care. But get rid of this concept that you can do it in 4 years.
>
> ~ Dr. Hayes, Interview 2

The four-year guarantee and the restriction on credits for an engineering degree are thus highly contentious for Dr. Hayes. The implication of the four-year guarantee as a "prescription" is "nonsense" and does not do the students "justice," as it shortchanges and compresses the content in ways that are untenable for this professor. The curriculum has been trimmed to fit into four years of highly intensive work for students, who sometimes forgo sleep in order to get all the tasks done. Dr. Hayes suggests, "[doing] it right" by expanding the expectation to five years, "[backing] off" and giving more time "to do it the way they should be." This alternate vision of the curriculum is significantly less compressed and does not work the students as hard, with more time for reflection and integration of concepts instead of the eight consecutive semesters of knowledge and training that is the current model.

This concept as advocated by Dr. Hayes sounds appealing, but is in direct contrast to institutional policy and state requirements. In 2004, the Colorado Commission on Higher Education mandated that colleges of engineering in Colorado guarantee students be able to complete the program requirements for a bachelor's degree in four years (O'Donnell, 2004). The compression of the curriculum is a direct consequence of this four-year guarantee, with student and faculty suffering another unfortunate side effect. The opinion of Dr. Hayes, though strongly worded, is ineffective against these immovable organizations that force the curriculum and instructors into the four-year pattern. Dr. Hayes does not have the choice to "back off" and teach the class as desired, because these institutional bodies have issued official decrees and guarantees. This is an unfortunate disconnect between what is perceived to be good for students and what has already been promised to them. What change in these classes is possible when the constraints are rigid and institutionally mandated?

There are numerous reasons for the durability of the mathematics curriculum as seen in the content and the adherence to textbooks and other vestiges of the past. There is little room within the over-constrained curriculum for meaningful change, as the immutable mathematics content is connected to equally immutable engineering content, while the infrastructure in place to support the current course features is mechanistic and ongoing. One small idea is rapidly translated into a large actor-network of supporting individuals and equipment, all invested in survival and maintaining the status quo. New technologies have been quickly integrated into these durable courses with few actual changes in the delivery of content. The explosion in communication avenues from teacher to students has not simplified the interaction; rather the multitude of options for transmitting messages causes frustration and nostalgia for the old days when the classroom was "gospel," the one simplified line of communication. The centrality of the lecture hall, chalkboard, and chalk to teaching these mathematics courses shows that the dominant mode of teaching and learning is still through an instructor lecturing, despite the growing distractions and alternatives to the traditional chalk-talk style lecture. Instead of simply "all [working] harder" it seems that a change is on the horizon. Advocates for reform like Dr. Hayes suggest stepping back and questioning what is actually critical knowledge for students passing through these courses, warranted particularly because growth in enrollment is stretching the available resources thin. Many disconnects are apparent between institutional policy and desired practices, between historical tradition and current reality, bringing up new questions and setting the stage for contentious and negotiated learning. With this backdrop of old and new clashing in the durability of the math curriculum, we continue to investigate what happens to students as they navigate through this amalgamated battlefield of enduring content and modern technologies.

5.2 Four Moments of Translation, Translating Students to Engineers

After looking in-depth at the opinions of faculty on the durability of Calc 3 and Diff Eq, we turn to the students to understand their perspectives. We investigate the processes of *translation* operating through these mandatory classes, going incrementally through the *four moments of translation* and after-ANT perspectives on the *four moments of translation*, to understand how sophomores become juniors and how students become engineers. Note that the relevant ANT vocabulary is defined in Appendix A, and briefly in bold at the start of the sections on *Problematization*, *Interessement, Enrollment*, *Mobilization,* and *Translation.*

5.2.1 Problematization

5.2.1.1 Registration and Class Standing

Recall that *problematization* is the first moment of translation, where allowable identities and interests are defined within an actor-network. In the context of this study, there are many layers to being *problematized*, both official and unofficial. Officially from the institution there are salient identities of freshman, sophomore, junior, and senior, defined quantitatively by the credit hours completed and more casually by the number of semesters attended at college. Countable and classifiable, the scheme of assigning students a class year is helpful for grouping students by cohort, a means of letting them know if they are ahead or behind of the rest of their class. This can be a two-sided process of identification, as the institution identifies students as “sophomores” while the students themselves may recognize their status as no longer freshman, but “sophomore” instead. Registration order is governed by this classification scheme, as graduate students are allowed to register and select classes first, followed by seniors, then juniors, then sophomores, and finally freshmen and transfer students. Greater seniority carries with it greater institutional privilege and earlier pick of desired class sections. Consequently juniors or those retaking these math classes get to choose their classes and instructors prior to those taking the class for the first time, provided they have more credits.

Registration is a catalyzing element of *problematization* in the actor-network of sophomore engineering. Once a card-based system of trading paper with administrators and staff, now registration is an online process in which semester-long identities are defined in minutes. During the designated enrollment window, students can self-navigate the online system to add classes and adjust their schedules. Undergraduate advisors typically meet with the students before registration commences and provide advice and feedback on which classes students want to take during the subsequent semester. These advisors can help students adjust and select classes during registration, though most students do it themselves. These acts of choosing a specific lecture and a recitation section defines student identities for the rest of the semester, as students literally write their recitation section number on every exam blue book to assist TAs in identifying their work for grading. Though scheduling conflicts with other classes may restrict the available options for lecture or recitation, students choose which professor will be officially their teacher, and which graduate student TA will be their recitation instructor for an entire semester. Students are identified based on their choices, as students frequently ask one another "Which prof do you have?" "Who's your TA?" to orient themselves in the course. Students belonging to the Engineering Honors Program or Goldshirt program can register for a special "honors" section of these math classes, further identifying themselves as members of these programs. Honors sections are smaller than the large sections, held in intimate classrooms instead of the large lecture halls. Registering for and attending one of these smaller sections is a confirmation of the special identities that are given access to these special sections.

5.2.1.2 Obligatory Passage Points & Course Identities

From the perspective of an undergraduate engineering student, the classes of Calc 3 and Diff Eq are themselves problems that must be overcome in order to proceed: they are the *obligatory passage points* of the sophomore year. All engineering students must pass through these gateway courses with a certain major-specified minimum grade to reach the subsequent technical course requirements and eventual graduation. These classes are rites of passage along the engineering gauntlet and they carry legends of extreme difficulty and immense workload among engineering student communities. Persisting students who have passed through the requirements of sophomore year, Calc 3, and Diff Eq tell tales of the all-nighters they pulled, the terrifyingly low scores averaged on the final, and the diabolical test questions, as they explain to younger students how they journeyed through these challenging courses and emerged at the other end.

The courses themselves have identities and reputations, Calc 3 of being a lot of work and Diff Eq being somewhat easier, though less visually interesting. In one of the student focus groups, Erika described the perceived divide between these two classes:

> *Erika*: I have heard it is like the whole; you either like Calc 1 and Calc 3 and dislike Calc 2 and Diff Eq or you are the opposite, where you like Calc 2 and you like Diff Eq but you do not like Calc 1 and 3.
>
> *Ralph:* I did not like Calc 2 so-
>
> *Becky:* I liked Calc 2.
>
> *Erika:* So you will probably like Diff Eq [to Becky] and you probably won't [to Ralph]. It is the way your brain is wired. Because I have had some people who were like "Diff Eq is so easy it was the easiest one I took." And for me it is the only math class I have had to retake.
>
> ~ Student Focus Group #2

Erika is a junior speaking to Becky and Ralph, who are both sophomores near the end of their semester of Calc 3, who have not taken Diff Eq yet. Erika has taken it twice, she explains, passing her hindsight onto these younger students in the context of the focus group. She states with certainty, “It is the way your brain is wired,” regarding if you will prefer Diff Eq to Calc 3, spreading a myth that enjoyment of math is predetermined, fixed based on the wiring of the brain. This argument is a short distance from the idea that some people are math people while others are not, that math ability is an inherent trait one either has or doesn’t have. Perceived math ability is a means of classifying oneself, taken a step further within the math-saturated curriculum of engineering to categorize students as Calc 1 & Calc 3 people or Calc 2 & Diff Eq people. Erika contextualizes herself as identifying more with Calc 3 than Diff Eq, and forecasts what type of person Becky and Ralph will be as they enter Diff Eq. These identities are known in advance, passed down from upperclassmen along with their survival stories.

5.2.1.3 Roles of Instructor, Student, and Syllabus

Once in class, the major identities are unmistakably clear: students sit in their designated region of the room, while instructors stand up at the front of the room, near the board. That pattern is replicated in recitation sections, though recitations are somewhat more informal they still feature the graduate student TA at the front of the room, frequently working through problems on the board for the benefit of the seated students. Within the classroom the institutional stature of the students fades away, as it is not apparent from a glance if a student is a freshman, sophomore, junior, or senior. It is immediately evident, however, who is the professor and who is the student, these identities are intuitively expressed in the context of a class meeting.

The first day of class in Calc 3 includes the ritual of passing out the syllabus, the powerful artifact that describes the relative importance of each class task towards summing into the final grade. From the first moment of the first day, expectations are put in place as to what being "behind" is in the context of the class:

> Syllabi get passed out from the left side to the right side of the room (from the student perspective). Syllabus is one double-sided page and is standard for all 4 sections of Calc 3 this semester. About 3 minutes into class the syllabi have been distributed around the room. Dr. Hayes quiets everyone as an introduction, explaining, "We'll start the semester a bit behind because I'll go over the whole syllabus."
>
> ~ Fieldnote Excerpt, Calc 3 large section, Dr. Hayes Week 1 Monday

The first action in class is to pass out the syllabus and then go over it, item by item. Dr. Hayes comments that the class will "start a bit behind" already because of this action, implying that being on time is an important value. Apparently it is easy to fall behind, even at the very start of lecture on the first day. Yet it is critical for the class to understand the syllabus, it is worth the time to go over it in class to make sure that the students are aware of the expectations and tasks at hand for the semester. Dr. Hayes is clearly in the role of the instructor on the first day, providing the syllabi that are distributed to the class and making introductions. Students choose where to sit on the first day, seeking out friends if they know anyone in the class, deciding if they want to go for the front rows or be satisfied with the middle or the back. These are identities-in-the-making, which quickly get stabilized after the first class meeting. Note the Calc 3 and Diff Eq syllabi are still one page, front-and-back, just as they were decades ago, with course information on the front and the homework schedule on the back. The front pages of these syllabi are reproduced in Appendix F for reference.

Once the syllabi are passed out, Dr. Hayes chooses to focus on first the textbook, then the different flavors of homework including Webassign, textbook, and standard problems. Dr. Hayes cautions students to take the homework seriously, giving some insight into the nature of problems in this course:

> "A large part of this class is learning how to build skills. We learn 5 or 6 skills, then put them together to make something, then repeat…Goes fast and deep, very vertical in nature. There are some problems that are brute force… 17 pages deep… but if you really understand it's a 3 liner." Students laugh at this. Dr. Hayes continues, "Keep up with this stuff, and don't let your cohort slip by you when you're not paying attention."
>
> ~ Fieldnote Excerpt, Calc 3 large section, Dr. Hayes Week 1 Monday

This excerpt further highlights the importance Dr. Hayes places on "[keeping] up with this stuff," as the consequence of not understanding or trying hard enough is falling behind "your cohort… when you're not paying attention." Dr. Hayes also cautions students "if you really understand," sometimes "brute force" problems requiring seventeen pages can be simplified into three lines. In doing so, Dr. Hayes is defining allowable identities for students: some students will "keep up," while others will "brute force" their way through problems, and still others will "let your cohort slip by" and fall behind the rest of the class. Some will take seventeen pages while others will only need three lines. Dr. Hayes is also characterizes Calc 3, trying to set the students up with realistic prospects for the class. It builds skills rapidly, then combines "them together to make something, then repeat" as the class "goes fast and deep," "vertical in nature." What does it mean for the class to be vertical in nature? The students do not question, they silently accept this description of the class without protest as Dr. Hayes continues reviewing the syllabus.

The syllabus establishes the rules of the game for the entire semester, including the official objective for the course. It says, "This course extends the ideas of single-variable calculus to functions of several variables… these concepts form the mathematical basis for many areas in the

Sciences and Engineering." Dr. Hayes waits until the middle of the period to comment on the official course objective, the connection between Calc 3 and engineering, even though it is the first item on the syllabus:

> "When you graduate to a full-fledged engineer with a stamp on your forehead, at that point the problems aren't so clearly defined, you don't actually know the answer to them... somewhere between Calc 1, where everything is perfectly defined, and the 4 year end where nothing is defined and you don't know all the answers… it has to start somewhere and that is here. "
>
> ~ Fieldnote Excerpt, Calc 3 large section, Dr. Hayes Week 1 Monday

Dr. Hayes further characterizes Calc 3 in the context of graduation and "full-fledged" engineering. Calc 3 is where things begin to be undefined, partway between Calc 1 and being a freshly minted "engineer with a stamp on your forehead". This quote connects past identities "where everything is perfectly defined," to the current realm of ambiguity where "you don't actually know the answer" in Calc 3. Dr. Hayes connects this to the "four year end" when you graduate as an engineer, where "where nothing is defined and you don't know all the answers". Dr. Hayes is situating Calc 3 as the *obligatory passage point* to ambiguity and engineering, explaining, "it has to start somewhere and that is here." There is a sense of urgency in these words, as becoming comfortable with uncertainty is critical for engineering students, yet is not incorporated into the main curriculum until "here". There are a host of possible questions students could ask, including why ambiguity is not included in the curriculum until now, or how exactly ambiguity and the unknown are taught through Calc 3. Yet the students remain silent, as on the first day the salient identities of professor and student encourage the students to believe the professor and the professor to be correct. The few questions asked on the first day are clarifications on the syllabus, not challenges to the veracity of the instructor's statements about Calc 3 or engineering.

5.2.1.4 Introducing Exams, Historical Trends, and Final Grade Calculations

Calc 3 is further characterized and described via exams, the primary means in which students are assessed for their knowledge in the course. Exams are planned well in advance, with the dates and times listed for the three midterms and the final exam on the syllabus so that students can plan accordingly. Students must take each exam unless they have a serious emergency with a doctor's note explaining the ailment. Exam scores factor hugely into the calculation of the final grade, as Dr. Hayes explains:

> "The way it works at the end of the semester, we look only at exam scores. We look at that, and if you're not passing on your own power, the other stuff doesn't count… If you are passing then you are eligible for a C- or higher. If you're not passing on your own, then you'll get a D or an F. Do not freak out about it. Historically we have exam averages, we are really happy if it's a 55%. We have midterm averages, in the 50s, 60s, 70s, one semester where it was in the 80s. So usually 60-70% range for exam scores and it usually drops over the term. Don't freak out, everyone's in the same boat" as students around the room begin murmuring about these low averages. Dr. Hayes continues, "The mean on the final has been between 40 and 45%. We actually really want you to do well. If you put in the effort, we will put in the effort."
>
> ~ Fieldnote Excerpt, Calc 3 large section, Dr. Hayes Week 1 Monday

Dr. Hayes describes how grades are calculated at the end of the semester, explaining for the benefit of the assembled students how "exam scores" determine "if you are passing on your own." This passage contextualizes exams, explaining how they are a powerful actor in determining final grades and student trajectories leaving the course. The critical feature of exams is that they are done under "your own power," isolated in space and time from peers and other resources including calculators, laptops, phones, etc. Because students take exams alone, without any supporting resources (save a 1-

page crib sheet in Diff Eq) exam grades are elevated above “the other stuff” - homework grades, project scores, and recitation points. In defining the final course grade, Dr. Hayes dispassionately acknowledges, “if you’re not passing on your own, then you’ll get a D or an F,” then instructs students “do not freak out about it.” Emotion and panic is not included in the discussion of how grades are determined, instead Dr. Hayes says twice “do not freak out” to set the expectation that low grades are not worth freaking out over.

This section closes with Dr. Hayes discussing exam averages, which “historically, we are really happy if it’s a 55%.” This reinforces Dr. Hayes’s position as an experienced instructor of Calc 3, who has been around long enough to see historical averages and know what makes the instructional team “happy”, “usually.” Dr. Hayes goes on to describe how averages typically start in the “60-70% range for exam scores and it usually drops over the term,” as a mathematician presenting historical data without emotion, just the trends. This statement is buttressed by another encouragement for students to not “freak out, everyone’s in the same boat.” Dr. Hayes intends to soothe students by reminding them that from the first day, they all have equal standing in the course, they all must do the same tasks, and are all evaluated on the same basis. Students react to the description of the low average exam scores by murmuring around the room, as Dr. Hayes continues with the detail that historical averages on the final are “between 40 and 45%.” These low average grades on the final exam are off-putting for students accustomed to scoring well on exams, and intimidating on the first day to learn that the average student performance on the final is only 40-45% correct. Before students can think otherwise Dr. Hayes insists, “We actually really want you to do well. If you put in the effort, we will put in the effort.” Dr. Hayes is characterizing the instructional staff as “actually” wanting the students to do well in the course, reassuring the students that “we will put in the effort” as long as the students do as well.

There are several contradictions in the explanation by Dr. Hayes of the grading process and historical exam averages, as the instructional staff is described on one hand as "happy" at the same time students are encouraged not to "freak out." This indicates that some emotional reaction from the instructional staff to exam scores is appropriate, though students are told not to react emotionally to the low exam averages. The concept that "everyone's in the same boat" is true from the start, but as the semester progresses and students are graded based on their individual performance they become stratified into different levels, different grades, different boats. The curve is not mentioned here, though is the final adjustment to student grades at the end of the semester to assign grades and categorize students. Overall, Dr. Hayes is setting in motion the actor-network of Calc 3, describing the importance of exams as mediators of the final grade, instructing students how not to react to the anticipated low averages on the exams through the semester, and thus defining the desired identities for students to "put in the effort."

The process of *problematization* occurs quickly in Calc 3, explicated above with a similar process for Diff Eq. The institutional identities of students based on credit hours completed determine when they can select the courses that they will be defined by for the rest of the semester during registration. Before the first day even starts, students are well aware of the reputation held by the courses of Calc 3 and Diff Eq, as they have distinct characteristics propagated by upperclassmen through their stories and memories. Instructors like Dr. Hayes further define these classes on the first day, distributing the syllabus to students and using it as an organizing element for the rest of the class. The syllabus succinctly combines the disparate actors relevant to the class, ascribing importance numerically to exams, homework, projects, and recitation. In class, salient identities of instructors vs. students are clear immediately, and allowable identities for students are modeled through the instructor's words and descriptions of historical class averages.

5.2.2 After-ANT Perspectives on Problematization

Before proceeding to discuss the second moment of translation, *interessement,* we consider the identities that are excluded or on the periphery of *problematization* in sophomore mathematics. We follow the suggestion from after-ANT scholarship to be reflective on what is included naturally in a network analysis and what gets left behind, in line with our second research question.

5.2.2.1 Missing the First Day of Class or Dropping the Course

As explained above, the first day of class is crucial in defining the class tasks and their relative importance, as the syllabus serves to identify and organize class artifacts like homework assignments, projects, exams, and textbooks. But what if students miss the first class entirely? The first weeks of the semester typically hold some uncertainty in student schedules, as choice of classes and for some, majors, are in flux. The university allows students to "drop" classes, remove them from their schedules with no penalty or marker on their transcripts, until the third week of the semester. Students can drop classes with a "W" for withdraw on their transcripts until the tenth week of the semester. After the tenth week, students can still withdraw from courses with a "special action form" featuring a signature by the instructor and dean. Students can add classes during a semester up through seven class days after the start of the semester, about a week and a half.

The opportunity to drop the course is listed briefly on the Calc 3 syllabus, which explains, "Advice from the Dean's office and your department advisor is recommended before dropping any course" (the syllabus is included in Appendix F). Information about dropping the course is not listed on the Diff Eq syllabus, and the instructors observed during the first day do not mention the concept of dropping the class in their overview of the syllabus, perhaps to stay optimistic about students persisting through the course. Nonetheless, many students do drop these courses, in sufficient number that it is obvious for the students who continue attending lecture that they are the survivors. Leigh, a nontraditional student interviewee, explains her perception of this in Diff Eq:

> And sitting in that class is kind of a joke. Because I feel like Dr. Greene goes, maybe it's just that he's too smart for me, obviously. But obviously he's too smart for a lot of people because a lot of people drop the class. I mean, compared to what it was when we first started, it's just a pittance.
>
> ~ Leigh (student), Interview 1

Leigh's perception of Diff Eq and her instructor, Dr. Greene, is that "he's too smart for a lot of people because a lot of people drop the class." The context of her statements is in response to a question about what she gets out of attending lectures. She explains that "sitting in that class is kind of a joke" since Dr. Greene is "too smart." "Obviously" to Leigh, her peers in the course also struggle with learning from Dr. Greene's lectures, since many have stopped attending lecture or have dropped the course entirely. Clearly to Leigh, "a lot of people drop the class," since "compared to what it was when we first started, it's a pittance." Students like Leigh notice the fullness of the lecture hall on the first day of courses, the subsequent dwindling in attendees, and conclude that the absent students have dropped. These missing students are not included outright during the process of *problematization,* these identities are not officially defined. Though many students may drop a course during their undergraduate careers, it is not an action emphasized on the first day of class or in class at all. Undergraduate advisors, who are outside the overriding focus on classroom activity on the first day, are hugely impactful in assisting students with these choices of classes to register for and/or drop. However, their role remains on the periphery during the defining of identities in sophomore mathematics.

5.2.2.2 Supplementary Class Opportunities & TAs on the Margins

The first day of Calc 3, as discussed in the previous section on *problematization,* includes a detailed description of historical exam averages and what makes the instructional team "happy" with regards to averages on the final. This focus on the high-stakes exams is justified, though it limits the remaining time available to discuss other features of the class. Particularly for a class like Calc 3, in which there are three streams of homework, projects, exams, and two optional courses designed to support students enlisted in the course, the first day is a blur of information that is difficult to take in all at once. For instance, the 1-credit, pass/fail laboratory courses associated with Calc 3 and Diff Eq are barely mentioned in the flood of information though they are meant to assist students in learning software packages required for completing projects in the course. These lab courses are administered by experienced graduate TAs and have limited enrollments, enough for approximately a quarter of the total students enrolled to participate if desired. Calc 3 also has a workgroup section associated with it, another 1-credit pass/fail optional course meant to support students with additional practice doing Calc 3, guided by another graduate student TA throughout the semester. The lack of emphasis on the two optional 1-credit supporting courses results in some students being unaware of their existence after the first day. These optional courses and the TAs who run them are on the edges of this actor-network, in contrast to the lecture activities featured in the center.

The role of graduate student TAs is similarly on the margins of class activity on the first day, as recitations are discussed but little attention is given to the people who are charged with running them. TAs, though vital to the functioning of these sophomore mathematics courses are not focal in the description of tasks that students must complete. Students quickly find out if they don't know already the importance of TAs in setting up the student experience in the course, as described in the following excerpt from the second student focus group, again with Erika, Ralph, and Becky:

> *Erika*: Another thing I noticed is that your recitation TA can make or break the class.
>
> *Ralph:* Yeah.
>
> *Erika*: Because I have had TA's that don't know how to teach really well and grade really really harsh on the homeworks. So then that makes a huge difference in your overall homework grade. But then other semesters I have had great TAs that know

> how to teach super well but they are also not harsh graders. And it is a huge part of your grade. It also helps when it comes to understanding material. I have had TAs that have accents and you can't even understand what they are saying, it's so strong. And you notice because by the third week, 80% of the kids don't even show up anymore. I had one class where we averaged 3 people a week. 3 people in a recitation, it was really sad. And I almost went because I felt bad for the TA. He was a nice guy, but I could tell that no one could understand him. And no one wanted to be there. You know what I mean?
>
> ~ Student Focus Group 2

Erika describes how "your recitation TA can make or break the class," due to their effect on homework grades and "understanding material." Ralph agrees, as Erika goes on in detail about how she has had TAs that "grade really really harsh on the homeworks" while not teaching very well, compared to TAs who "teach super well" and "are also not harsh graders." Clearly, she prefers the latter as it "makes a huge difference in your overall homework grade," which gets factored into the overall course grade under the conditions described by the syllabus and the professors on the first day. In addition to affecting grades, TAs can also make an impact in how well students understand the content of a course. Erika relates her experience with TAs "that have accents and you can't even understand what they are saying," which leads to students not attending their recitations. She empathizes and feels bad for TAs who are unintelligible, as "by the third week, 80% of the kids don't even show up anymore," leading to awkwardly small recitation sections. When only three students show up out of a class of approximately 30, you can tell "no one wanted to be there." Erika describes how she "almost went because I felt bad for the TA," but she did not actually attend recitation either as she couldn't understand the TA, joining the 80% of her peers that also chose not to go. In Calc 3, 50 points of the total 800 points, or 6.25% of the final grade is based on recitation assignments. In Diff Eq, there is no component to the grade related to recitation, so the stakes for not attending are nonexistent. Thus attendance at recitation is officially encouraged, but students choose for themselves if it is worth it for them.

As described in the later section related to *enrollment,* TAs are critical to the functioning of these courses, yet they remain on the margins of the course as defined on the first day. Students identify TAs as being impactful to their success or lack of success in these courses, but their contribution is de-emphasized and valued significantly less than the activities in lecture and exams. The work of TAs is not entirely visible to the students; instead it is *black-boxed* away from their view. During *problematization,* the first identities to be defined are those of the students and the instructors, with the TAs establishing their roles later during the semester. The aspects of the courses that the TAs run, including the optional 1-credit laboratory software class and the optional 1-credit Calc 3 workgroup, are adornments to primary class activity of lecture. Recitations, though ostensibly required, are less central to the grades in each course, and can be sparsely attended if students do not perceive their value.

5.2.2.3 Academic Honesty & the Official Policy on Cheating

During the first day of class, Dr. Hayes in Calc 3 briefly discusses academic honesty and their official policy on cheating, which is also included on the syllabus:

> “Here’s the nasty part, I hate saying this. Solutions for this stuff, I know it’s out there. I’ve actually gotten my solution manual from students before I get it from the publisher. I know they’re out there, I know you have them, you know I know you have them, and I know you know I know… and so on and so forth. Don’t just copy down stuff, because you will be shooting yourself in the foot. If you have solution manuals, use them wisely. Have at it, we encourage you to work in groups… the only thing I ask is that at the end of the day, you write it up in your own words. The only

> penalty for cheating is that you fail the class. Please don't do it. If you have any question of cheating or plagiarism, come ask me."
>
> ~ Fieldnote Excerpt, Calc 3 large section, Dr. Hayes Week 1, Monday

Dr. Hayes prefaces the discussion of academic honesty by admitting, "I hate saying this," and calling it the "nasty part" of the introductory lecture. It is clear that Dr. Hayes knows that "solutions for this stuff" are "out there," commenting that past students have accessed the solution manuals before the publishers have even distributed them. Dr. Hayes knows that the students have them, so now the students know that Dr. Hayes knows they have them, etc. as the point is reiterated a few times for effect. According to Dr. Hayes, students will "be shooting yourself in the foot" if they "just copy down stuff," meaning that students who "just" copy solutions are hurting their own chances of actually learning the material and succeeding in the course. Later, to end this speech on academic honesty, Dr. Hayes concludes, "The only penalty for cheating is that you fail the class," a stark and intimidating admonition to students. "Cheating" here is not directly defined, as Dr. Hayes explains the penalty for cheating but not what constitutes cheating itself. Dr. Hayes does not forbid the use of solutions manuals, but warns students in possession to "use them wisely," apparently meaning not to "just copy stuff." No specific instructions are given on what wise use means, as Dr. Hayes then moves onto discussing collaborative work in groups. "We encourage you to work in groups" yet "at the end of the day, you write it up in your own words" are the two directives issued about teamwork on homework assignments.

The information given from Dr. Hayes about "cheating" and solutions manuals does not reflect the myriad ways students use various resources to assist them in doing their homework. As we will see in the *interessement* section, students see a lot of gray areas in-between "cheating" and using a solutions manual, or using any other internet-based sources for answers including Google, YouTube, Wolfram Alpha and Chegg.com. While it should be clear based on the university's honor code that "cheating" is not allowed, if it is only defined as "just copying" directly from a solutions manual, many students would not consider themselves cheaters. There is a similar level of ambiguity regarding Dr. Hayes's statement on working in groups. Even students who "just copy" a peer's homework will be writing it up in their own words, depending on how they interpret this directive. Dr. Hayes invites students who have "any question on cheating or plagiarism" to ask, so the opportunity is open for students to clarify if needed. However, as we will illustrate in *interessement*, students easily justify their actions, including "cheating," broadly defined, and rarely seek clarification on issues of academic honesty. While Dr. Hayes does mention "cheating" and the penalty for it, the specifics are left out.

There is limited time available on the first day and not all of the details of the course can possibly be explained in just fifty minutes. It is not Dr. Hayes's fault that cheating is not focused on during class, in fact it is probably better in setting the students up for success to minimize the discussion of the "nasty part" that Dr. Hayes hates talking about anyway. It is understandable that the role of TAs is not discussed during the first lecture, and that the process to drop the class is not detailed either on the first day. We identify the facets of the course that are on the periphery only to keep track of them, in hopes of understanding the consequences of their positioning on the edge of this actor-network during *translation.* Earlier (Section 5.1.2, Incremental Translations), we quoted Dr. Lewis asking "how do we get all the students moving, more or less in the same direction?" given the multitude of communication channels available now. This question remains pertinent after the major identities are defined, as a full understanding of all the elements of these math courses cannot be fully communicated to students on just the first day. The things that are missing are significant, as students may be unaware that they exist until too late. For example, absent from the first lecture is awareness of the resources available to students who may be struggling, including free tutoring opportunities through various student success programs. If these were emphasized on the first day, perhaps more students would know about them. Finally, we do not forget the students who miss the first day – how do they get the information they missed?

5.2.3 Interessement

The second ***moment of translation, interessement,*** **describes the processes in which actors are** ***interested, invested in,*** **or** ***convinced*** **to join a network's movements**. The graphic shown in Figure 4 demonstrates how **becoming** ***interessed*** **in one actor-network typically comes at the cost of building barriers or limiting access to others.** In the realm of sophomore mathematics, the devices of *interessement* are both human and non-human, arising dually from instructors cajoling students to care about mathematical content during lectures and from the unending tasks assigned to students in these courses like homework and projects. As we will demonstrate, these required tasks are routinely scheduled and demand significant amounts of time and effort to complete. The need to complete these tasks severely restricts the free time of students to pursue their other interests, cutting them off from non-engineering activities.

5.2.3.1 Lecture Professors Modeling Their Interessement

After the first day of classes in which salient identities are defined, lectures continue in which the instructors describe mathematical content through words and representations on the chalkboard. In addition to modeling desired problem-solving practices and logical progressions, the instructors also model their attitudes towards math during these classes. Since the instructors are doctoral mathematicians by training, their relationships towards math are generally characterized by enjoyment and emotional responses. For instance, "fun" is part of upper division math in Dr. Greene's Diff Eq section:

> Dr. Greene asks if Euler's method is a good approximation and students generally say no. Dr. Greene continues, "We actually have courses like this, the 3000, 4000 level Numerical Methods… we try to write code like this, investigating error control." Dr. Greene moves on to introduce and demonstrate "the popular method RK4, or Runge-Kutta 4… it's a superior algorithm… how well did that do?" A male voice from the seated students replies, "pretty well." Dr. Greene again pitches the numerical methods class and other advanced math classes if students are interested in doing more of this work and "think they're fun. You learn to be writers of algorithms rather than users of algorithms, that's always fun."
>
> ~ Fieldnote Excerpt, Diff Eq large section, Dr. Greene Week 2 Wednesday

Dr. Greene seizes the opportunity to discuss upper level mathematics electives in the context of the basic numerical methods being introduced in Diff Eq. Piggy-backing on Euler's method and Runge-Kutta, Dr. Greene encourages the students to "learn to be writers of algorithms rather than users of algorithms," explaining, "that's always fun." This sounds not unlike a recruitment pitch, an enticement to students to engage in "3000, 4000 level Numerical Methods" after completing their 2000 level Diff Eq course. These numerical methods are personified, given the attributes of being "popular" and "fun." Dr. Greene is emphasizing the enjoyment derived from working with these algorithms, trying to capture the interest of the students in the material and in potentially going farther in mathematics than is required by the engineering curriculum. As such, Dr. Green is attempting to *interesse* and engage students in the larger actor-network of mathematics, reaching past Diff Eq.

Relatedly, Dr. Lewis also connects the Runge-Kutta algorithm and fun in setting up the day's lecture for the smaller honors section of Diff Eq:

> "Check your watches, we have like 1 more minute before class officially starts…" says Dr. Lewis while writing on the board the topics that will be covered today, including "Euler's Method, Runge-Kutta 4, and Picard's Theorem."
>
> Upon seeing the name listed on the board, Ethan, a male student in the course says, "Please tell me we're talking about Jean-Luc Picard."
>
> "Sorry to disappoint…" responds Dr. Lewis.
>
> "I just like saying Runge-Kutta…" says a male student in the front row out loud.
>
> Dr. Lewis replies, "It's fun to say Runge-Kutta… if you guys ever have children, make a song out of Runge-Kutta so that they'll grow up to be mathematicians."
>
> ~ Fieldnote Excerpt, Diff Eq small section, Dr. Lewis Week 2 Wednesday

Compared to the excerpt from Dr. Greene's section on the same day, it is evident that these two male students in this smaller honors section volunteer their thoughts freely, regardless of how nerdy they may sound to their peers. Many of the students in the smaller honors section of Diff Eq already know each other from the residential academic community in which they reside, and consequently are apparently comfortable speaking up in class from the start of the semester, a theme we will see illustrated more throughout the fieldnote excerpts from the observations of honors sections. Simply based on the writing on the chalkboard previewing the topics the class will cover during the lecture, these two students already have comments to share with the class. Ethan, the first to speak up, expresses his hope that "we're talking about Jean-Luc Picard," the fictional captain from *Star Trek: the Next Generation*. Dr. Lewis's response validates the reference by stating "sorry to disappoint," instead of questioning who Ethan is talking about or how *Star Trek* relates to the content in the lesson. Michael then comments on his enjoyment of "saying Runge-Kutta," which Dr. Lewis corroborates through agreement that "It's fun to say Runge-Kutta." Dr. Greene also commented on the "fun" of "Runge-Kutta," but in the use of the algorithm instead of saying the name. Dr. Lewis continues, explaining to students "if you guys ever have children, make a song out of Runge-Kutta so that they'll grow up to be mathematicians." This exchange is how the lecture period starts, situating Runge-Kutta as something that would attract young children to math. There's an element of recruitment and initiation in this invitation to "have children" and "make a song" to encourage them to "grow up to be mathematicians," an apparently desirable outcome. Dr. Lewis is trying to *interesse* these hypothetical children through a singsong rendition of a numerical method.

The two students in the honors section who speak up before the start of class are already *interested* in the numerical methods listed for discussion in the day's lecture, and Dr. Lewis capitalizes on their initial expressions of interest to reinforce the "fun" in the name of Runge-Kutta. Similar to Dr. Greene, Dr. Lewis is encouraging the students to engage with math on a bigger level than just in this class. Where Dr. Green advocated for the upper level Numerical Methods courses, Dr. Lewis encourages the students to integrate math into their personal lives and their future children. These devices of *interessement* may not entice all of the students in the room, but they apparently work for a few of them. Dr. Lewis and Dr. Green are modeling their enjoyment and "fun" derived from these mathematical subjects, inviting the students to participate in the same way – to enter the actor-network of math, to connect to the mathematical content the same way that they are demonstrating.

5.2.3.2 Complete Focus on Math as Interessement Device

These lecture periods provide the format and time for instructors to engage and *interest* students in the mathematical content and in the math classes. The environment of the lecture hall may be littered with distractions, but the instructors are focused solely on communicating mathematics via the board to students, regardless of surrounding events or factors. In order to learn from lectures, students must focus in on the instructor's activity at the chalkboard, and ignore the other messages being displayed around the room. In addition to the main chalkboards at the front of the lecture halls, each lecture hall features additional chalkboards running along the sides of the room. Frequently messages are left on these side chalkboards, typically announcements from student organizations about meeting times and upcoming events, or messages from the student government begging the students to vote. Yet these messages are not discussed during the official dialogue of the class, or even outwardly acknowledged by the instructors or students observed. Each classroom in the Engineering Center also features a placard stating "no food, no drink, no smoking" though typically only the last one of this admonitions is followed. Students frequently eat food and drink beverages during class, outright ignoring the official signage, with no punishment or penalty. Thus students learn to selectively ignore aspects of their environment as they attend lectures, they are trained to listen to the instructor's words, focus on the main chalkboard, and disregard the rest. This is *interessement* working on students on the level of the physical environment, funneling them into the math as presented by the instructor and separating them from all other elements of the classroom.

Interessement is also evident in the prioritizing of math-related activities over everything else. Current events rarely seep into the classroom regardless of their magnitude, as math overrides holidays, tragedies, and even natural disasters. For instance, Halloween falls during Week 10, on a Thursday when recitations are held in Calc 3. The recitation observed, run by the graduate TA Roger, unfolds largely undisturbed by the holiday:

> As this recitation starts, Roger has drawn an arrow on the board to point out a few bags of candy at the front of the room, but no students have budged to get any yet.
> "We could just call it a day…" says a male on left side of room, hopefully.
> Roger replies, "I think we need to do math for at least a few minutes before calling it a day."
> After ten minutes, no students have gotten up to get candy. Roger invites the class to come up and get candy, that he won't be offended if students are walking around while he's talking. Several students (all males, mostly the ones seated along the aisle

> towards the left) stand up to get some. Meanwhile, Roger makes an announcement about the first problem of the previous homework that many students got incorrect regarding the "contradiction of a theorem."
>
> ~ Fieldnote Excerpt, Calc 3 Recitation, Roger (TA) Week 10 Thursday

Roger has generously provided candy for the students in honor of Halloween, but the students are hesitant to take it. One student suggests stopping the recitation before it even starts, but Roger insists on "at least a few minutes" of doing math. The recitation proceeds as every other recitation meeting has, with Roger at the board solving problems and answering questions for students before proceeding to distribute a worksheet with practice problems for students to solve. After ten minutes have gone by with Roger working on the board, he explicitly invites the students to come up and grab candy, as none have disrupted the standard operating procedure of recitation to actually stand up and walk to the front of the room. Roger has to reiterate that he does not mind if students come up to grab candy before several men actually stand up to retrieve some. By week 10, the students are trained and *interessed* in the lecture, they have been habituated into sidestepping things that are not math related upon entering a math class. The overriding focus of the recitation class meeting is on math, candy is but a small part of this recitation on Halloween.

Aside from Halloween, more serious events are minor disruptions to the stable practices of lecturing and problem solving in these mathematics classes. For instance, a tragedy on the very last day of Calc 3 is acknowledged in the course of class, but does not significantly interrupt or redirect the ongoing content review for the final:

> Before class starts and Dr. Oliver arrives, news of a school shooting at a nearby high school filters through the room. Jason and two other men in the room appear particularly shaken/interested in this. Others acknowledge the news but do not comment further.

> Fifteen minutes into class, Jason announces to everyone, "I know someone at the high school…I found out the shooter is dead…"
>
> Dr. Oliver turns around, surprised, saying "Today? God, it doesn't end, does it? Just processing…" Dr. Oliver pauses for a moment at the board before continuing with the content, "so we have a vector field…two possible paths…."
>
> ~ Fieldnote Excerpt, Calc 3 small section, Dr. Oliver Week 16 Friday

The tragedy of a nearby school shooting momentarily pauses the class, but cannot fully disrupt the review of content before the final exam. Jason, the student who gets wind of shooting from a high school student he apparently knows, brings it up before class starts but manages to focus on reviewing for the final once Dr. Oliver arrives. Not included in the above fieldnote excerpt are the questions Jason asks during the first part of class regarding the format of the final and strategies for studying, as he is able to compartmentalize his concerns about the shooter separately from focusing on preparing for the final exam. Fifteen minutes into class, when Jason finds out and announces that "the shooter is dead," Dr. Oliver becomes aware of the situation and reacts, pausing to allow time for "processing." Rhetorically Dr. Oliver asks, "It just doesn't end, does it?" referring to the numerous acts of gun violence that have occurred in Colorado schools. Yet, like Jason, Dr. Oliver ably compartmentalizes the shock at this tragedy and moves on with the content review for the final. Both Jason and Dr. Oliver respond to the news of the shooting, but they do not allow the event to disturb the agenda for the class. Jason is *interested* in doing well on the final, he has to do well to succeed in the course, and so he is closely tied to the activity of the lecture. He separates his concern about the school shooting from his need to understand the math content. Similarly, Dr. Oliver is *invested* in the students doing well on the final exam, and attempts to prepare them as much as possible in advance of the high-stakes cumulative exam. Diverting the class from the math content is not an option for Dr. Oliver; they must continue the content review. This event encapsulates the unceasing nature of the mathematical focus of these courses. External events, however tragic, remain on the periphery while the main aim is necessarily on moving through math content during these classes. The class meetings serve to *interesse* the students in math within a setting centered solely on math content, separate from all other concerns and local events.

5.2.3.3 Stability in Interessement after a Natural Disaster

The ongoing *interessement* of students in these math courses is also demonstrated in the response of this educational system to the 100-year flood in Boulder, which caused campus to close its doors and cancel classes for two days, and forced many residents to relocate in the middle of the semester. Upon resuming classes on Monday during the fourth week of the semester after the campus closures, students are still flustered at the fallout from the flood:

> Dr. Hayes writes on the board, "Proj #1 is due…" and then says, "Okay" to quiet the class and get their attention before saying, "I'm glad you're all okay, I hope you're all okay… how many have you started the project yet?" A few scattered hands rise around the lecture hall.
>
> A blond woman wearing a headband lets out an audible sigh of relief as Dr. Hayes announces a delay in the project due date. Dr. Hayes explains that out of a desire to allow students who need introductions to Mathematica to attend Mathematica bootcamp sessions, and out of a desire to keep the exam date, it's likely that the project due date will be delayed until after the first exam, the exact date will be posted on the webpage. "But the rest of the homework, for better or worse is still due…" Dr. Hayes explains that special accommodations can be made for the homework on an individual basis as needed, and says the project due date will extended to a week from now, if not later.
>
> ~ Fieldnote excerpt, Calc 3 large section, Dr. Hayes Week 4 Monday

In the aftermath of the flood Dr. Hayes first checks in to see that "you're all okay, I hope you're all okay," before proceeding with the math tasks at hand for the class. The due date on the first project is delayed due to the flood, but it is still due. Dr. Hayes is very clear in explaining the motivation behind extending the project's due date, pointing to two other class-related reasons to justify the extension – the desire for everyone who needs "Mathematica bootcamp" to be able to go, and the desire to keep the exam on the scheduled date. This indicates that the project is delayed not because of personal needs or flood-related remediation efforts, but because of required math tasks (learning Mathematica) and exam scheduling. "The rest of the homework, for better or worse is still due," explains Dr. Hayes, as even a natural disaster on the scale of the 100-year flood is not enough to change the homework schedule or adjust the scope of assigned problems. Dr. Hayes points out that individuals can arrange special due dates for specific circumstances, but as a whole the class is not changing the official due dates for the homework. This demonstrates the overriding stability of the system that keeps these math classes running, as the flood is but a hiccup in the otherwise orderly progression of homework assignments, projects, and exams. The demands of the class keep students *interessed* in math, even when their homes and friends have been uprooted. In other words, the actor-network of sophomore mathematics *interesses* the students by holding them responsible for completing the required class assignments through thick and thin. Keeping the focus on math and math tasks separates the students from the trauma and aftermath of the flood.

5.2.3.4 Interessement as Isolation

Some students dislike this narrow focus on math and math tasks when they see the rest of the world as equally relevant, and the tunnel vision unjustified. Some resent being cut off from the rest of their interests as they are brought closer and closer to actor-networks of undergraduate math and engineering. One student interviewee, Leigh, is a nontraditional student who sees the engineering program as isolated from the rest of the world, to its detriment:

> I mean, like this one little engineering center, it's a cement block that's the same people, it's the same instructors, it's the same everything, cycling around in here over and over and over. This is all you see, and this is all you know, and you're in the computer lab and you're in a lecture hall, and you're back in the computer lab and then you're trying to find a table. And a lot of the engineering students don't know - they may be acing Diff Eq but they don't know that a ferry capsized outside of Korea. They don't know who Air Calder is, they don't know Cary Grant. You know, it's just a world; it's so insulated that way. It's all consuming academics. Does that make sense? There's nothing else, I mean you're an engineering student, I mean it's nothing but academia all the time, and I get really sick of it. Really sick of it.
>
> ~ Leigh (student), Interview 1

Leigh's powerful explanation of the "all consuming" process of being an "engineering student" highlights the powerful devices of *interessement* at play. She first describes the physical isolation that accompanies being an engineering student and taking classes within "this one little engineering center," separate from the rest of campus and non-engineers. She explains "it's the same everything, cycling around in here over and over," referring to the students and professors she interacts with, apparently frustrated that there's not anyone new to meet or work with, no diversions to the sameness that she sees in engineering. The repetition of "cycling around" "over and over" is also described in terms of physical movement through the building, as Leigh explains, "You're in the computer lab and then you're in a lecture hall, and you're back in the computer lab and then you're trying to find a table." There are limited spaces for engineering students to go during the day, as highlighted by Leigh's description of moving from one confined space to another, circling back and never leaving the building. Her explanation illustrates the limitations of being bound up tightly in the engineering actor-network with no external outlets, when "this is all you see, and this is all you know," which is nothing of the outside world or real life.

Leigh demonstrates a perspective broader than many of her peers, concerned about world events, famous actors, and other non-engineering, non-school related topics. On the subject of her peers, she comments "they may be acing Diff Eq but they don't know that a ferry capsized outside of Korea," referring to the tragic sinking of a Korean-operated ferry boat resulting in over 300 deaths. She lists classic actors that her younger peers don't know about, but that matter to her, to illustrate how little they know of culture and history. Leigh recognizes that engineering is "just a world" unto itself, explaining, "it's so insulated that way", cloistered from the rest of the world. She describes the life of "an engineering student" as "nothing but academia all the time," since the workload for her engineering coursework demands all of her attention, all of her life, instead of allowing her to explore alternate pursuits. She is "really sick of it," the demands of engineering that restrict how she spends her time; she is sick of being cut off from the other things she is interested in. Leigh is suffering from engineering's *interessement:* the more she has committed to her classes, including Diff Eq, required for an engineering degree, the less time she has for the rest of her life. Her words illustrate that there are downsides to *interessement,* especially when it works.

5.2.3.5 Interessement via Financial Investment

We've discussed how students are *interessed* via the activities of the lecture hall as well as the required tasks of these mathematics courses, homework and projects. Another feature of their *interessement* is evident in the financial *investment* students and their families make in these courses. For example, students must *invest* in a Calculus or Diff Eq textbook required for the entire semester, a cost ranging from $20 to $200 depending on the edition, and if the text is rented for a semester or purchased for perpetuity. The cost of the courses is a much larger investment. In-state students pay around $2,000 for each 4-credit math course while out of state students pay much greater amounts. Elizabeth, a highly motivated sophomore interviewee, describes how the investment in her education obliges her to attend lectures:

> *Elizabeth:* Yeah, I went [to lecture] every time. And I probably could have done about the same if I hadn't, so. We'll see.
>
> *Interviewer:* So then why would you go to lecture?
>
> *Elizabeth:* Because thanks to CU tuition it is more than 100 dollars per every hour of class, and that's not money I want to waste. And I do get something out of it, I definitely do. I don't wanna think that I'm wasting money, if I'm gonna pay this much for an education, I'm going to get my education.
>
> ~ Elizabeth (student), Interview 2

Elizabeth describes how her consistent attendance at lecture is not motivated by its effectiveness, but rather because "that's not money I want to waste." At first she says "I probably could have done about the same if I hadn't" gone to lecture consistently, but then argues "I do get something out of it, I definitely do." Exactly what the "something" she gets out of attending lecture is undefined here, but it is palpable that Elizabeth feels that she has to attend class. She calculates "it's more than 100 dollars per every hour," a serious investment in each meeting of lecture. Though our calculations are different for the cost per class meeting, Elizabeth is vehement in her explanation "if I'm gonna pay this much for an education, I'm going to get my education," directly connecting the cost of tuition to her efforts in learning. Elizabeth is a highly motivated student, elsewhere in our fieldnotes telling a friend that she is a "survivor" in the engineering program, a powerful self-identification which, like her statement that she's "going to get" her education, positions herself as an active agent in her own learning. Thus, we see Elizabeth as an example of a student who is successfully *interessed* in the actor-network of sophomore mathematics. The cost of the program is a serious factor in her *interessement,* as it motivates her to "get" her education.

The devices of *interessement* are numerous in enticing students to enter the actor-networks of these sophomore mathematics courses. Instructors and TAs attempt to engage students in the mathematical content through their lecture activities, typically at the front of the room with the chalkboard and also via their personal enjoyment of math. We identified a couple instances in which the professors equate math with "fun," as one means of encouraging students to engage with the material and enjoy it similarly. We have also identified how the lecture periods are largely focused on math, ignoring the other messages of the environment and bypassing holidays, tragedies, and natural disasters. The required tasks of the math classes are consistent and perpetual, as homework assignments, project reports and exams remain due despite punctuated events like the 100-year Boulder flood. The constancy of these requirements keeps students *interessed* in math, demanding their time and attention and limiting students' bandwidth for alternate pursuits. Some students, like Leigh, resent the all-consuming isolation of the engineering program and these required math classes, while other students, like Elizabeth, are compelled by their financial *investment* to remain fully *interessed* in getting the most out of the classes and in obtaining an education commiserate to the money paid.

5.2.4 After-ANT Analysis of Interessement

Now adopting an after-ANT perspective on these devices of *interessement,* we examine the ways in which students are not fully *interessed* into the actor-network of these courses and look for things that are on the periphery of the actor-network instead of the centers. The previous section highlighted ways that the engineering program *interessed* students by ignoring environmental and surrounding events, restricting students' time and physical movements, and by requiring significant financial investments. We now look to the experiences of students in doing homework assignments and projects to identify how some resist the enticements of required tasks in engineering.

5.2.4.1 Academic Honesty for Students, "Cheating" on Homework

In the after-ANT section on *problematization,* we described how Dr. Hayes introduced the concept of academic honesty and loosely defined cheating as copying others' work. In listening to student opinions of cheating and their justifications for it, we see evidence of alternate, unofficial pathways to completing homework assignments that are not sanctioned in the actor-network of sophomore math. For example, the students of the first focus group describe in this extended excerpt how "everyone cheats together" as a means of saving time and thus combatting the all-consuming nature of engineering coursework:

> *Dean:* I don't want to admit to anything, but I have cheated on homework, several times. And I mean, sometimes it's just like, "I have no more time. If I don't cheat, I'm not going to finish this." And so, you know, everyone cheats together.
>
> ~ Student Focus Group 1

This focus group has three male participants: Travis, Tommy, and Dean. Travis and Tommy are seniors. Dean is in the second semester of his sophomore year, having just finished his first semester at this institution after transferring in. Dean starts the conversation explaining that he does not want to "admit" to any wrongdoing, but confesses to cheating. "Sometimes," he says, "I have no more time. If I don't cheat, I'm not going to finish this," as he cites the lack of time as a reason to cheat, so that he can "finish" the assignment or project that is due. Instead of "not" finishing something, Dean feels that he has to complete the task and is forced to cheat. He continues, "You know, everyone cheats together," grouping his actions together with many of his peers. "Everyone cheats" is an impressive declaration, indicating that what Dean describes is commonplace or the norm among students in the engineering courses he's taken. As our data will show, there are many different student accounts of "cheating," that mostly support Dean's view.

Dean elaborates on what he constitutes as cheating:

> *Interviewer:* What do you count as cheating?
>
> *Dean:* Looking up answers online, or basically [asking a friend], "I don't know how to do this, help me," and they're like, "well here's my homework, whatever." And you're just like, "okay, whatever, and you just [pantomimes being rushed and then copying down the homework]." And then there's this magical website called Chegg! [laughs, *Travis,* and *Tommy* laugh too].
>
> *Tommy:* I was gonna say, "let me tell you about a website called Chegg".
>
> *Dean:* And I feel so bad saying this, but I mean, sometimes I'm just like, "Hey, I know you have a Chegg account, -" [speaking to a friend]
>
> *Tommy*: "…Do you mind?" [finishing Dean's statement]
>
> *Dean:* And it's just like, "Yeah." and so you just take the answer, off the tree.
>
> *Tommy:* You punch it in, and your TA doesn't say anything about it, and you just kind of sit there going, well [shrugs his hands].
>
> ~ Student Focus Group 1

Dean describes three distinct ways of cheating: "looking up answers online," copying from a friend's homework, and using Chegg.com. Dr. Hayes's discussion on the first day of class explained that students who work together should write up their answers separately, so Dean's use of his friends' homework is cheating. He distinguishes between "looking up answers online" from using the "magical website" Chegg, a name which makes Travis and Tommy laugh in recognition. Chegg.com's tagline is "the Student Hub." It boasts access to textbooks, tutors, and "step-by-step solutions to textbook problems," searchable by ISBN, title or author's name (see Figure 31).

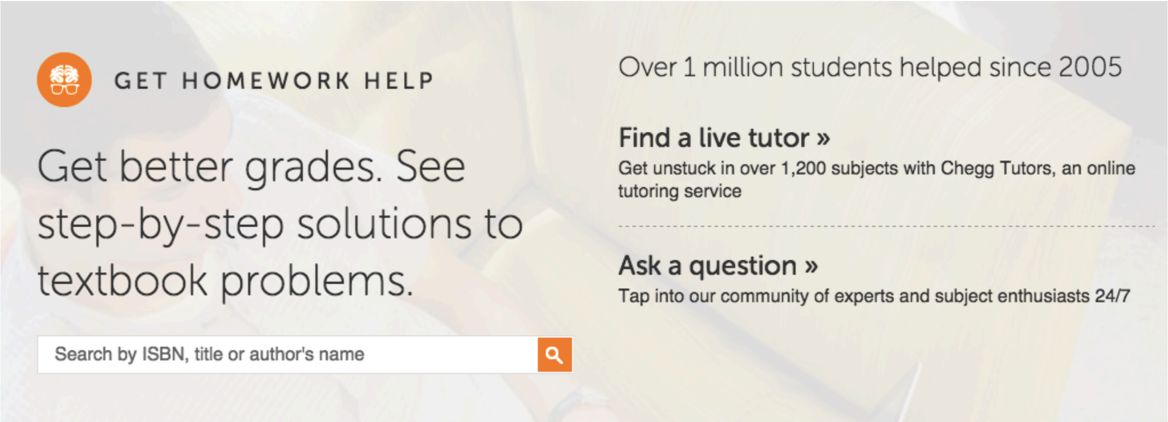


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Figure 31: Screenshot from Chegg.com Front Page ("Chegg.com," 2015)

Chegg is the "magical website" allows Dean to "just take the answer, off the tree," as they are ripe for the picking. The bulk of the solutions on Chegg.com are only accessible to members with paid accounts, though the information is easily shared between friends. Dean describes how he does "feel so bad saying this, but" he asks a friend with a Chegg account to help look up online solutions for various homework problems. Tommy joins in on the conversation, explaining how once you have the solution from Chegg "You punch it in, and your TA doesn't say anything about it, and you just kind of sit there." According to Tommy, there is no penalty to submitting a homework assignment that has been copied from Chegg, where the answers were just taken "off the tree." If the TA doesn't say anything about it, then there is no consequence, and it's easy to do it again.

The focus group conversation continues, as Dean further details the reasons to cheat:

> *Dean:* This makes me feel really guilty but at the end of the day I've got a lot of homework to do. And I don't want to - again banging your head against a brick wall, that's what happens sometimes, it's like you're staring at a friggin problem, for like hours, and you're just like, I did all my other problems, I don't know how to do this problem. Or, I don't know how to do like half of these problems, sometimes it gets really bad, and I just don't know what to do at that point, because the professors are at home, the LAs have gone home, it's like 1:00 in the morning and I have 8:00am

> class, I'm done. And if I don't- cheat -then I'm not going to get any sleep. And if I don't get any sleep, then the next day is going to suck, and I'm not going to learn anything in lecture, which I don't learn anyway because like the stupid writing all the notes doesn't work, so it's this perpetual cycle of, you have only so much time, and you have your job, and you have like your classes, and your homework, and like do you want to do a club or whatever, like do you actually want to have any fun, do you want to like relax a little bit?
>
> ~ Student Focus Group 1

Dean's long statement centers on the idea that his time is limited, and so he has no alternative but to use a resource like Chegg. He explains, "at the end of the day I've got a lot of homework to do," and he can't spend "hours" for all of them, "staring at a friggin problem," "banging your head against a brick wall." Sometimes, he only has to get help on one problem out of the whole assignment, "sometimes it gets really bad," and Dean needs help on "like half of these problems." This brings up an issue of proportions not defined on the first day – how much of an assignment do you need to "cheat" on for it to count as cheating? Dean does not describe cheating on every problem, just on "like half." He illustrates the situation he finds himself in when "professors are at home, the LAs have gone home, it's like 1:00 in the morning and I have 8:00am class, I'm done," and he has to "cheat" in order to get some sleep. The resources available during business hours including professor office hours and undergraduate learning assistant (LAs) could help, but they are not accessible at 1:00am in the morning. Evidently, Dean does not see any options for help from 1:00am - 8:00am other than Chegg and the Internet. Even a friend's homework is less accessible than the all-hours online world of solutions manuals, so it's Dean's only choice when he doesn't know "what to do."

Dean reasons that cheating is what enables him to sleep, while not cheating will result in him not sleeping. The situation sounds dire as Dean identifies consequences from not sleeping including "the next day is going to suck, and I'm not going to learn anything in lecture." He describes the situation as a "perpetual cycle," meaning it propagates itself once initiated. Since "you have only so much time," and there are fixed tasks that require a lot of it like "your job," "your classes," and "homework" there's not much time left over to do "a club", "have any fun," or "relax a little bit." The compressing of Dean's available time is not unlike what Leigh described earlier, as Dean is similarly cut off from his non-engineering pursuits by the demands on his time from engineering. Dean resists being completely *interessed* in the math class by taking the unofficial route to getting his homework done: cheating. Cheating enables him to sleep, instead of devoting literally all of his time to his homework assignment. In line with our second research question, Dean's discussion of cheating is on the edges of *interessement*, as it is a means of defying the tasks that would otherwise consume him fully in the actor-network of sophomore math. Cheating is also explicitly not allowed per the definitions given on the first day. Many students, like Dean cheat anyway, but it is not officially acknowledged or discussed. Thus cheating is on the periphery of the actor-network of sophomore math, along with the resources that students use to cheat.

Dean also remarks that he doesn't "learn anything in lecture" "anyway" because "the stupid writing [of] all the notes doesn't work," identifying another way in which the *interessement* activities employed by the instructors to engage their students do not work on him. As discussed in the Findings Section 5.1.5 – Disconnects and Vestiges of the Past, the predominate mode of teaching in the lecture hall remains via the symbols and words written on a chalkboard. Traditionally, students are supposed to replicate the marks on the board in their notebooks to help them learn through the process of "note-taking." However, Dean says, "writing all the notes doesn't work," calling it stupid and he's "not going to learn anything in lecture" as a result. Clearly, the lecture as an *interessement* device does not work to entice Dean towards math. Instead, it frustrates him and drives him away from the standard lecture resources and towards illegitimate resources, like the online solutions manuals provided by Chegg. While lectures work well for some students, Dean is not one of them. He is on the edges of being *interessed* in this actor-network.

Data collected from the other student focus groups and a variety of student interviews indicate that Dean is not alone resisting the *interessement* devices of sophomore math. Since nearly each interview or focus group protocol included explicit questions on how students did their homework, or what TAs thought of as cheating, we amassed a full spectrum of ways students can cheat. In addition to the Chegg usage described by Tommy and Dean above, Ralph in the second focus group session alluded to the "art of Googling:"

> *Ralph:* I feel like you learn the art of Googling a lot [when doing homework].
>
> *Becky:* Oh yeah.
>
> *Erika:* Like when in your search result you find the exact question and are like-
>
> *Becky:* -Yes!
>
> *Ralph:* My roommate, I remember, there was this one problem we could not get and so I just like copy and pasted the problem and searched it. And it didn't find anything. And then he was like you have to take the numbers out of it because sometimes the numbers are different. And as once we took out the numbers it found the exact same problem but with different numbers in it.
>
> *Becky:* Yeah, that's perfect.
>
> *Ralph:* Survival of the fittest.
>
> ~ Student Focus Group 2

Ralph describes the method and usefulness of learning the "art of Googling" to find solutions and help on homework problems. Becky and Erika resonate with this description; they exhibit excitement about learning to search the Internet in a way that leads to finding "the exact question" and presumably its solution as well. It's not as straightforward as simply copying and pasting the problem. Ralph swiftly learns that you need to be crafty in optimizing a search to find good results. Since many textbooks have been revised and reissued over decades, often a solution will exist online for a problem from an earlier edition of the textbook, which can be used as a template to solve a similar problem from a more modern edition. Becky appreciates this story, indicating "that's perfect" in response to Ralph's story of how he honed his skill at the "art of Googling," The last phrase Ralph utters in this excerpt, the "survival of the fittest," reflects his mindset. To Ralph, the other students are competing against him in the class, and so he must use whatever advantages he has to succeed. If he does not use these resources, if he is not good at the "art of Googling," he will fall behind to those who can. This is another justification employed by students for cheating, demonstrating in a slightly different vein how students like Ralph prefer to go online for help instead of reaching out to an officially-allowed resource in person. Homework does not effectively *interesse* Ralph, as he chooses to develop his methods of Googling over developing his math abilities.

We examine one more student perspective, from Leigh, before proceeding to discuss instructor and TA perspectives on cheating and point out a few student counterexamples of cheating. Leigh describes when doing homework, "For anything I can, I'll use Chegg. Completely, I mean I have no problem with that, I don't think it's cheating, it's the only way that I can know that I'm doing it right" (Leigh, Interview 1). Here she identifies another justification for cheating, slightly different than those espoused by Dean and Ralph – "it's the only way" that she can know she's "doing it right." Her words imply a necessity to do her homework correctly, that there are no alternatives, that she her hand is forced into using Chegg. Leigh also doesn't view this behavior as cheating. To her, using Chegg to know that she's "doing it right" aligns with the course policy to use solution manuals wisely as told by Dr. Hayes on the first day. If indeed her use of Chegg is not cheating, then Leigh is a model citizen for doing her homework and she fits neatly into the actor-network of sophomore math; the *interessement* of the homework assignments works to engage her in the math and she is completing her work in accordance with the course policies. If her use of Chegg is indeed prohibited, then Leigh joins Ralph and Dean in resisting the *interessement* of homework, finding a different way to complete homework assignments that is not officially sanctioned.

5.2.4.2 TA Perspective on Cheating and Unauthorized Resources

The instructors and TAs are aware of the rampant use of solution manuals, but seem less familiar with some of the technologies out there today, including Chegg. In an interview with Roger, an experienced TA of Calc 3, he describes confronting his students about cheating with solutions manuals:

> We've had some issues with students just copying what's out of the solution manual, which is cheating. We had to address this to a pretty large group, my first or second semester here. Because there was a problem that we gave them, that the solution manual had wrong. And so we noticed when a lot of students had that exact wrong solution that came out of nowhere that they were just copying. And so I had to sit down with both my recitations and explain to them, "copying out of the solution manual is cheating, [you] can't do that." But if they understand that, they can still use it as a reference tool. But I think a lot of students as soon as they get stuck [snaps], they jump to the solution manual to try and get to the next step. And they don't put as much thought into the problems as they should. I think that they need to just sit down, try and figure out what concepts are involved in the problem, and try and fight their way through it instead of just jumping to the solution manual. That being said, like, if it gets to a certain point, if they've been working on the same problem for 20 minutes and can't get anywhere, I think it's okay for them to go get help from

> some source, whether it's a TA, instructor, or if they need to get some help from the solution manual. So there are benefits from it, but I don't think students use it in the right way. I think that they are too reliant on the solution manual if they have one.
>
> ~ Roger (TA), Interview 1

Roger first relates an anecdote from one of his first semesters teaching Calc 3, in which he had to address his recitation students and explain to them that “copying out of the solution manual is cheating, [you] can't do that.” The instructional staff was clued into the students cheating based on a problem that “the solution manual had wrong,” since many of the “students had that exact wrong solution,” “out of nowhere.” Roger believes, “if they understand that” copying is not acceptable, “they can still use [the solution manual] as a reference tool.” Roger elaborates on what using “it as a reference tool” means, suggesting that students need to “sit down, try and figure out what concepts are involved in the problem, and try and fight their way through it,” before looking at the solutions manual for “reference.” Roger even quantifies his suggestion, describing a workflow in which students should try “for 20 minutes” before seeking help in the form of an instructor, a TA, or the solutions manual. Ideally, in those 20 minutes students would “put as much thought into the problems as they should,” a loose definition of student effort. Roger adds, “There are benefits from” using solution manuals, but most students are not using them the “right” way. Yet direct instruction on how to use a solution manual is not part of the formal education in lectures or in recitation. Roger tells the students what not to do, but not how to actually use this resource for “reference.” How are students supposed to know that they should work for twenty minutes diligently before consulting the solution manuals for clues? As indicated in the above excerpt from Roger, most of the instructional discussion of solutions manuals and unauthorized resources is to tell students not to use them, not to copy from them, not how to use them intelligently. These unofficial resources are on the edges of the math actor-network as defined by the instructors, but are central to students' work in the class.

The instructional staff tries to *interesse* the students in the math content itself, scheduling opportunities including lectures and recitations for students to ask questions to the allowable resources of professors and TAs during allowable times like class meetings and office hours. The official policy is that solution manuals are not allowed, that students should not copy off them, attempting to distance students from these unapproved resources and eliminate the connection between them. But with the advent of new technologies like Chegg.com and increased content on the Internet, students are using resources that are not even officially discussed in class. Students including Dean, Leigh, and Ralph ignore this attempt at *interessement* in terms of allowable resources and instead use the items that are undesirable to the instructional staff. Roger confirms this interpretation as he believes students "are too reliant on the solution manual if they have one," as they choose to work closely with these illicit resources instead of working with him or the other TAs who wish to help. Students are *interessed* in getting their assignments done, not necessarily in learning the content, which compels them to use solution manuals, Chegg, and other sources of unofficial, unauthorized information.

Now there are many possible sources of information to assist students in completing their homework assignments that did not exist before the Internet age. In addition to the aforementioned online solution services and manuals, there is another powerful website, Wolfram Alpha, which is based on the Mathematica software package but accessible via an easy-to-use web interface (see Figure 32).

Figure 32: Wolfram Alpha Home Screen ("WolframAlpha," 2015)

Named after the mathematician who begat Mathematica, Stephen Wolfram, the Wolfram Alpha site can take any mathematical input or problem, perform calculations, and provide an output or solution. The software can also illustrate step-by-step how the output was determined, with additional instructions and help available to those with paid accounts. Roger describes what he thinks of Wolfram Alpha and student use in the context of Calc 3:

> There's a lot of times where I'll tell the students to go there and use it, because at least with Calc 3, I don't think it gives them much of an advantage using Wolfram Alpha. Because the problems are usually too involved, that Wolfram won't solve the whole problem for them. They can use it for visualization, which is great, they can check some derivatives or integrals which I think is okay, but there's too much work required that Wolfram Alpha isn't going to tell them how to do their problem. For Calc 1 though, it's a different story. Because they're just doing simple derivatives, simple integrals, and, at least I think with Wolfram Alpha now you have to pay if you want the step-by-step solution, but back when that was free I think a lot of students were relying on that for Calc 1. They told it to do a derivative or an integral, then they click "step by step" and they show them how to do it, and that's essentially the

> solution manual. So I don't like it as much for Calc 1, but for Calc 3 I think that it's totally okay, because it gives them a nice way to visualize these 3 dimensional objects.
>
> ~ Roger (TA), Interview 1

The acceptability of Wolfram Alpha as a resource changes from Calc 1 to Calc 3, as the problems get more complicated and the website can no longer provide all of the answers. Roger describes telling the Calc 3 students to go to Wolfram Alpha and use it, believing that "there's too much work required that Wolfram Alpha isn't going to tell them how to do their problem." He contrasts this with Calc 1, where they are "just doing simple derivatives, simple integrals," and students would "click step-by-step" and the website would "show them how to do it… essentially the solution manual." For Calc 1, this website is prohibited, yet for Calc 3, its use is encouraged and "totally okay" as it offers "a nice way to visualize these 3 dimensional objects" being studied. The change in this technology's status, from not allowed to acceptable, reflects in part the apparent gain in student learning from Calc 1 to Calc 3. This is a shift in what was considered cheating to allowable that is not immediately clear to students, nor discussed by instructors during their lecture classes.

Students who use Wolfram Alpha starting in Calc 1 may continue using it throughout their undergraduate careers, with apparently increasing support of the instructional staff. Students who know about this resource and use it become connected to it, even subscribing via a paid account to access the "step-by step" feature of the software. This connection comes at the cost of their attachment to the math content in Calc 1, or in harmony with their content mastery as in Calc 3. It is up to the instructional staff if this is considered fair use or not, and consequently if the *interessement* of students will be towards the desired content knowledge or away from it. At least Wolfram Alpha is computationally based, as it has the Mathematica software running behind it, ensuring that its calculations are correct. Students who copy from Wolfram Alpha can be more confident that their answers are correct, as opposed to the solution manuals from more dubious places of origin.

5.2.4.3 Perspectives of Students Who Don't "Cheat"

Now we return to listening to student perspectives of cheating and resource use, pointing out a few more on the non-cheating side of the spectrum. We was previously introduced Ethan in the context of *interessement* in Diff Eq with his comment regarding Jean-Luc Picard from *Star Trek*. Ethan is a precocious mathematics student, a freshman enrolled in the sophomore-level courses of Calc 3 and Diff Eq, and in the honors section of these courses as well. He dominates most lectures with his rapid questions and immediate understanding of the math concepts presented, as he is clearly *interested* in the content and topics of the lectures. Ethan is a high achiever who described in interviews that he had never found math challenging, even through Calc 3. We examine Ethan's response to questions of using solutions manuals and other resources to complete homework assignments:

> *Interviewer:* Do you have a solutions manual?
>
> *Ethan:* I don't, I borrowed it from friends.
>
> *Interviewer:* And how did you use it?
>
> *Ethan:* I would check my answers. Um, yeah.
>
> *Interviewer:* And similar with the Internet?
>
> *Ethan:* Wolfram Alpha is really the only Internet source I would use. But I would mostly use Mathematica, so I don't really use the Internet.
>
> ~ Ethan (student), Interview 2

Ethan describes using Wolfram Alpha and Mathematica, not really "the Internet," in doing his homework. Interestingly enough he has a solutions manual borrowed from friends, that he uses to "check [his] answers." Though he has a solid command of the content and appears during lectures to be enjoying the material, he still feels compelled to "check" his responses on his homework to ensure that they are correct. Recalling that homework scores are only factored into the final grade if the exam scores are passing, and then they are only 12.5% of the final score, it is surprising that the majority of students, including Ethan, try so hard to make sure they have all of the right answers. Ethan is *interessed* in getting full credit for his homework and consequently checks his answers using the solutions manual, Wolfram Alpha, or Mathematica. It's likely that his description of using these resources simply to "check" answers would not be considered cheating by the instructional staff, as it is a wiser use of these resources than simply copying as others students (like Dean) have described. However, Roger the TA described how students have become "reliant" on solution manuals in doing their homework, and it is unclear from Ethan's sparse replies how he would function if he didn't have his friend's solution manual. Of our student interviewees (nine total) and student focus group participants (eight total), only one described that he was okay with turning in homework without checking the answers or Googling the results, and that it was okay to turn in homework only half completed. For most students enrolled in these courses, solution manuals and other solution services are important allies in completing homework assignments. They provide a pathway for completing homework that does not require students to be *interessed* in truly engaging with the material and understanding the concepts.

Travis was the one student who did not utilize solutions manuals in these courses, and was a participant in the first student focus group. He countered Dean's discussion of "cheating" with his own interpretation of the worth of homework:

> *Travis:* I saw that it was worthwhile, just looking at the rubrics at the beginning of the semester, the tests are so heavily weighted that I wouldn't cheat on the homeworks. Because I would rather spend the time figuring stuff out for the test, even if I got the homework wrong, so that's where that came from.
>
> ~ Student Focus Group 1

For Travis, looking at "the rubrics at the beginning of the semester" in the syllabus convinced him that the "tests are so heavily weighted" that it wasn't "worthwhile" to "cheat on the homeworks." From the start, Travis paid attention to the way that these entities were *problematized* in order to understand their relative importance and his corresponding effort, his corresponding *interest.* Realizing that the bulk of the grade in these courses is dependent on the tests, Travis decided that he "would rather spend the time figuring out stuff for the test, even if I got the homework wrong." He utilized the homeworks as practice for applying concepts, unafraid of the consequences of being incorrect, instead of needing the homeworks as to be completely correct and complete before being turning in (like Ethan and Dean). There is a significant divide between Travis's perspective and outlook of those who feel that they need to cheat in order to survive, despite their being trained ostensibly the same way via the same courses and lecture formats. Travis's *interessement* in doing well on the tests diminishes his *interessement* in completing the homework through the use of solutions manuals or other unauthorized resources.

5.2.4.4 Instructor Perspective on Cheating

Finally, we look to Dr. Lewis for an instructor's opinion on cheating and the use of unauthorized resources in Diff Eq. Differing from Roger the TA, Dr. Lewis sees Wolfram Alpha as an unacceptable resource and that it doesn't matter that there are already solutions of some sort online to most textbook problems:

> For the good students, the ones that are going to work on their homework and do the homework and try, and really puzzle it out, it doesn't matter where the problem [textbook or original] comes from. And it's only the students who feel the need to cheat that are going to use those homework websites and stuff like that, or, Wolfram Alpha, or wherever they get their solutions. They're not going to pass, they're not going to do well, or not that well anyway in the class. And so, I don't know that we

> need to rewrite solutions or write exam, or homework questions just for those students if they don't have enough integrity to work on the problems themselves.
>
> ~ Dr. Lewis, Interview 1

Dr. Lewis characterizes students as either "the ones who are going to work on their homework" or "the students who feel the need to cheat," without acknowledging the gray area in between those extremes. Dr. Lewis believe only the cheaters will "use those homework websites and stuff like that, or, Wolfram Alpha, or wherever they get their solutions," not mentioning students like Ethan who only uses these resources for "checking" answers. Dr. Lewis also specifically mentions Wolfram Alpha as a place that students "get their solutions," without describing the different levels of Wolfram Alpha that are acceptable and not as Roger the TA did. Dr. Lewis believes the students who do cheat are "not going to pass, they're not going to do well," as they don't try to "really puzzle it out" and will not learn the material as a result. Dr. Lewis does not believe in adjusting the system to address these students who cheat, commenting that it seems inappropriate "to rewrite solutions or write exam or homework questions just for those students" who cheat. "Those students" are further characterized by not having "enough integrity to work on the problems themselves," as Dr. Lewis connects cheating to integrity, matching the university's honor code. Each classroom, we should note, has the honor code printed on a plaque near the front: "On my honor, as a University of Colorado at Boulder student, I have neither given nor received unauthorized assistance on this work." Student's "honor" is not mentioned or discussed actively in the math classes observed, only arising in the context of "academic honesty" and "cheating." Dr. Lewis posits that students who do not have "enough integrity" to really try on the homework do not warrant the creation of new or different questions, as they will probably "not pass" anyway. However, many of the students quoted here have passed (through Calc 1 and Calc 2) despite their propensity to use solution manuals or the Internet to find answers. Dr. Lewis's words illustrate that the instructional team is not all standardized regarding what counts as an unauthorized resource, and that cheating exists on the periphery of the official actor-network of sophomore mathematics. Dr. Lewis knows it happens, but sees it as an issue that works itself out when cheaters do not pass, not an issue worthy of legitimate discussion and attention.

5.2.4.5 Recap of Unofficial Activity Around Homework & Interessement

In our examination of how students do their homework we have identified both acceptable and unauthorized use of resources. Students describe how they "cheat," and how "everyone cheats," mostly with regards to looking up answers online via the "art of Googling," copying from a friend's homework, or using Chegg.com. By Calc 3, the use of Wolfram Alpha is no longer considered cheating, but is an acceptable method of checking your work and visualizing the results. As students move through these sophomore level math courses, they navigate the use of these various resources, choosing for each homework assignment how to find assistance when they get stuck. Some students follow official course policies, using office hours and recitation as the primary venues for asking their questions, while others choose the unofficial route and become users of alternate, unauthorized resources. Sometimes it's not immediately clear when something is allowable or not, as in the case of Aurora whose mother purchased the solution manuals for her, leading her to believe that it was a standard part of the course. The instructional staff is forceful on how not to use these resources, but is vague regarding how students should effectively and "wisely" use a solution manual. Students negotiate their own methods of completing their homework, largely justified due to their time constraints. Homework is a contentious topic and a polarizing non-human element of these sophomore actor-networks, as students, faculty, and TAs each have distinct perspectives on its purpose and method. Thus homework is an *interessement* strategy that is differentially effective in enticing students to join fully into the actor-network of math class. Cheating is on the periphery of the legitimate actor-network of sophomore mathematics, as it exists yet is not discussed often by the instructional staff.

5.2.4.6 Projects, Groups and Consequences for Interessement

Projects are another *interessement* device of these sophomore level math classes, which differentially interest students in joining the movements of the mathematical actor-network, and exclude student experience from what is officially valued. Dr. Hayes is quoted in Section 5.1.2—Incremental Translations, describing how projects were initially added to the curriculum in the interests of showing students a large-scale, realistic problem. Since their inception, a giant infrastructure has grown to support students in completing projects. Yet they remain contentious assignments that some students struggle with, while others complete easily, resulting in another spectrum of *interessement* not unlike the homeworks. One distinguishing feature of projects is that they are to be completed in teams of up to three people, yet occasionally students end up working alone. Aurora describes how she ended up working alone on the last two projects in Diff Eq:

> I had a group the first project, and I don't know how to Matlab code very well or at all, really, and so they would do the coding, and I'd do the writing, and it worked out really well. And then they both dropped the class like the week of the second project, and so then I had to do it all, by myself, and it went really bad the second time. And then the third time I was still by myself, but I had a lot more time to try to figure it out, instead of just the week of. It was really stressful.
>
> ~ Aurora (student), Interview 2

Aurora describes how her project team went from three people to one during the "week of the second project." She had to learn to "Matlab code" quickly in order to complete the second project without any teammates, a process that "went really bad." As we will see in the words of several other students, knowing how to code and program in Matlab and Mathematica is a highly valued and sought-after skill in terms of project teammates, and in terms of the engineering curriculum in most majors. Aurora describes in her group for the first project, they divided the work "so they would do the coding" and so Aurora would "do the writing," a division of labor that is common and accepted in completing the projects in Calc 3 and Diff Eq. Unfortunately, since her teammates dropped the course during the week of the second project, Aurora had to scramble to cover both sides of the project, coding and writing. She comments, "It was really stressful" as she had no partners to lean on or assist with the work, she had to do it all herself.

Ideally, students would in teams of three to complete these projects, but as Aurora's case demonstrates, that does not always happen. In Diff Eq class, Dr. Lewis asked Aurora about her teammates for the project, resulting in the following interaction:

> There was one class, where I came in, and Dr. Lewis was the only other person there, and I was like, "This is weird.'" And I sat down, and Dr. Lewis was like, "have you gone over the exam solutions?" and I was like, "no, I've been working on the project." And Dr. Lewis was like, "do you have a good group for the project?" And I was like, "No, I don't have a group, Dr. Lewis." And Dr. Lewis was like, "Why not?" And I was like, "Because my group dropped the class." And Dr. Lewis then asked the first couple people who they came in if they were alone too and I was like, "Dr. Lewis, nobody's alone." And they were like, "No, we have partners," and that was it.
>
> ~ Aurora (student), Interview 2

Dr. Lewis means well in initiating conversation with Aurora, but ends up alienating Aurora by asking other students in the class to be in her group. The question, "Do you have a good group for the project?" demands Aurora to evaluate her nonexistent teammates to see if they are "good" or not, since she is working alone. Dr. Lewis is apparently surprised that Aurora is working solo, and questions her further regarding why she does not have teammates. Dr. Lewis takes action on behalf of Aurora, asking other students who enter the room if they already have project teams or not. Aurora characterizes her own situation, knowing that “nobody’s alone” aside from her in the class. Her peers confirm this, as they all “have partners,” and Aurora is left by herself, as she thought she was. Recalling that the projects are intended to provide students with experience working a bigger problem in an applied context, that they are meant to *interest* the students to a larger degree than the homework assignments, it appears that for Aurora they are mostly an unpleasant, “stressful” experience. Instead of working with a team of people and only being responsible for one part of the project, the writing, doing the project alone requires her to learn how to code in Matlab as well. While this means that Aurora gets more practice honing her writing and coding skills, in comparison to her peers who have teammates she is doing too much and it is unfairly “stressful” on her. This stress is silenced since it is not accounted for in the grading process, it is not acknowledged outside of Dr. Lewis’s concern.

5.2.4.7 Grading Criteria for Projects: Getting the Right Answer

As explained by Dr. Lewis in the excerpt below, the projects are not graded on teamwork or interpersonal skills, and it does not matter to the graders if students work in teams or alone. Consequently, the struggle that Aurora goes through to do the work on her own is not credited on the grading rubric, it is invisible to the graders and on the margins of the legitimized work:

> *Interviewer:* How are the projects graded based on the write-up?
>
> *Dr. Lewis:* Well, there's actually 50 points or something, and it's distributed - and this changes somewhat - there's some on the grammar and just the write-up part of it; there's some on, did they get the right answer, because usually there's a right answer or a right-ish answer; are the graphs labeled; are they described in the text properly. There's the mechanics of writing the paper as well as the answers. And most of the

> projects have multiple steps, and so each step has some right answer, some point that is being looked for. And so there's points awarded, dependent on the question.
>
> ~Dr. Lewis, Interview 1

As Dr. Lewis indicates, the bulk of the grade on the project reports is based on the write-up as well as getting the "right" or "right-ish" answer for "each step." Again, this grading scheme excludes how teams worked together or if someone worked alone, if one person on a team did all the coding or if it was shared equally, if the students were good teammates or not. Dr. Lewis distinguishes between "the mechanics of writing the paper" as well as "the answers," naming them as the two main categories the project grades are split between. In writing up a project report, students practice their technical communication skills including their ability to label graphs properly and describe them in text. Additionally, Dr. Lewis describes how "the projects have multiple steps," "each step has some right answer," and "some point that is being looked for," further emphasizing that these projects are not open-ended creative experiences, they are closed-ended, predetermined exercises in which students must replicate the results on the answer key. The focus on the "right answer" excludes the other aspects of the project and puts the actual experience of the students on the margins of the class instead of the center. In the awarding of points for right answers, the projects are similar to the homeworks except that students are allowed to work in groups, there are no solutions manuals or online solutions available to copy, and there is a greater emphasis on writing. The projects are meant to *interesse* the students in the math concepts and content, as they require students to integrate coding skills and writing skills in communicating the math. Even without the solution manuals or other unauthorized resources, students still find alternate pathways than what is expected to complete the projects (like Aurora's working alone) that are not officially recognized or valued, that remain on the periphery of the course.

5.2.4.8 Learning Goals of Projects, Team Task Division & Recruitment Strategies

Dr. Lewis later clarifies that the learning goals of the projects do not require all students to learn the software packages of Matlab and/or Mathematica. Instead, since the students are allowed to work in groups of three, "you just need one person on your team to know Mathematica or Matlab. Not everybody on the team has to know it" (Interview 1). Consequently, the students who do possess experience and comfort in coding with these languages are valuable to their teams. Aurora explains in hindsight:

> I wish I had gotten more help on the second project. There was an email from my TA that went out that same week that was like, "Does anybody still need a group?" because I think that somebody else must have needed a partner. And I was really stressed about it, and I didn't want to add on somebody I didn't know, and I was like, "No, I'm not going to do that." But I kind of wish I had, because maybe that person would have been a Matlab expert.
>
> ~ Aurora (student), Interview 2

Aurora's hesitation to "add on somebody" she was unfamiliar with results in her working alone, even when a potential partner is brokered by her TA. In hindsight, looking back on her semester, she explains during her interview that the person may have been "a Matlab expert," an identity that would have helped her out considerably in completing the projects. Aurora was hesitant to work with a stranger due to a variety of past experiences working in groups with other students of lesser work ethic and greater arrogance, things that she did not want to risk for this class. Instead, she chooses to work by herself, and gets pushed out to the periphery of what's recognized in the required task of projects as demanded by *interessement.*

Other students choose vastly different strategies for navigating the projects, including this process as described by another student interviewee, Nate:

> Well I was previously friends with one of the kids in the class, and he basically picked the smartest kid in the class (laughs) and we would both basically do whatever the smartest kid like requested of us. We would do most of the write-up, and he did most of the programming, and it just was really easy. Kind of just like good networking, basically, you know, picking a kid that's really good at what you're bad at, and working together.
>
> ~ Nate (student), Interview 2

Nate's "networking" story highlights the impact of knowing people in the room and being assertive in selecting teammates. He describes how his friend "basically picked the smartest kid in the class," and "it just was really easy" to work together to complete the project. In addition to being a sophomore in engineering, Nate is also in a fraternity on campus and he has an active social life. Elsewhere in our interviews, he describes his skill at networking as his biggest strength, as it enables him to have summer internships and opportunities despite having failed Calc 3 the first time he took it. Here, his networking abilities enable his team to pick "a kid that's really good at what you're bad at," and subsequently have an "easy" time of working through the projects. Nate also describes how the "smartest kid" did "most of the programming," again putting programming skill on a higher plane than the work of writing up the report. Nate's team includes his friend and the "smartest kid" in the class, leading to a straightforward process in completing the projects. His lack of struggle contrasts with Aurora's "stressful" experience, and highlights how the process of completing the required projects, of being *interessed,* is contingent on the team or lack thereof.

Interestingly enough, the projects also illustrate a divide between what is actually learned by students in doing the projects and what they award points for while grading. Students in focus groups expressed that they learned "teamwork" and "time management" from the projects, much more than they learned math skills or practiced their writing (Focus Group 2). Yet these two actual student outcomes of the projects are not assessed or emphasized by the instructional staff, they are on the margins of what is officially viewed as the student experience of doing projects. The instructional focus on getting the right answer and labeling the graphs correctly ignores the rest of the events and experiences of actually working on the project, with or without a team.

5.2.4.9 Summary of After-ANT Perspectives on Interessement

Purposely looking at what is not included in the central focus of *interessement* highlights the activities at the edges and margins of the actor-network of sophomore math. Though cheating is defined during *problematization* as something that is explicitly not allowed, students do it anyway, with their own interpretations of why they need to cheat or why their use of resources like solution manuals, Google, Chegg, or Wolfram Alpha does not count as cheating. Instructors and TAs demonstrate slightly different expectations of what constitutes cheating at the level of Calc 3 and Diff Eq, with little indication that these nuances of acceptable use are communicated in detail to students. While students with “integrity” should be expected to do their own work, the myriad ways students find to check their answers or get clues point to a large gray area surrounding academic honesty and dishonesty. Several students in our dataset describe how “everyone cheats,” yet the activity of cheating largely falls off the radar of official course activities, pushed to the margins of what is officially recognized in these courses.

Looking at the periphery of the actor-network surrounding the completion of projects in these classes, we see a great deal of student activity which is not accounted for in the grading rubric used to assess students’ work. Project grades are based on written communication and accuracy in terms of getting the right answer at every step. Missing is any acknowledgement of the process through which the project was completed, the interactions between project teammates, and the individual work required to learn a specific software package. Students who work alone on the project are treated equally to students who are one of three on a team completing the same assignment, as the individual experiences of each team get disappeared in the grading process. The projects are closed-ended, predetermined assignments, which are graded on a limited set of criteria that condense the variety of student experiences into a single numerical assessment. Examining the margins of what is recognized in projects shows how much of student life and effort is not incorporated in their grades.

Homework assignments and projects are both means of *interessement*, encouraging and demanding students to do work towards learning the mathematical content and connecting with the actor-networks of sophomore math. Looking past the official focus on these assignments, we see a great deal of student activity on the margins that is not accounted for in the grading or legitimized academically. Taking a broad view of student effort in these courses, we begin to identify the unofficial, unsanctioned actions that affect student learning as much as the institutionally recognized and expected actions do.

5.2.5 Enrollment

The third moment of translation, *enrollment*, describes processes wherein systems of alliances in an actor-network become confirmed. *Enrollment* is the flipside to *interessement,* in which questions about identity or connection become solidified into statements that are somewhat more certain. In our analysis of sophomore mathematics, we see the impactful artifact of exams as the main signifier of *enrollment*. Exam scores literally determine if students will be confirmed or denied in passing these classes, since they must be above a certain level in order for students to pass. Exams organize the activity of students, lectures, recitations, and additional review periods, and they happen four times a semester: three midterms and one final exam. To understand *enrollment* through exams, we walk through the activities surrounding an exam and the exam itself, investigating the instructor perspective that drives exams, the TA-led activities surrounding the exams, and then some of the student reactions to their exam experiences.

5.2.5.1 Exam Characteristics and Importance

The defining characteristic of exams is that they are taken in a controlled environment which separates students away from the human and non-human resources they typically use: their computers, the textbook, peers, instructors, TAs, calculators, the Internet, notes, etc. Exams are distinct in both time and space, with midterms lasting exactly 90 minutes and the final exam lasting 150 minutes - except for students who can prove a need for extra time via institutional documentation. Exams are held in specific large rooms on campus, separated from the normal classroom and meeting times. The isolation of exams is why they are valued above homework assignments and projects, as explained by Dr. Hayes in our first interview:

> All the homework, and three projects, that's essentially 300 out of 800 points, so you can not really know the material that well, and because you choose partners well that will boy up your grade, and so you can end up passing the class, even though you really don't know the material. The only thing we really know you do on your own are the exam scores. So we look at the exam scores, and we figure, if you're one and a half standard deviations down on the exam scores, then you probably don't actually know the material. And so that's where that comes from. And if you do clear that hurdle, then we add in, all that other stuff. So the first cut is, on your own, can you demonstrate some proficiency with the material. And the way it usually works out is that mean minus one and a half standard deviations, that number usually ends up in the mid-40 percent. I gotta be honest with you, if you can't do 40% of the problems that we've asked on exams, I don't think you know the material, so you go back.
>
> ~ Dr. Hayes, Interview 1

Exams are valued because they are “on your own.” Students who “choose partners well” may not “really know the material” but can still have high scores on homework and projects since these well-chosen partners “will boy up your grade.” Consequently, “all the other stuff,” that is homework and projects, constitute 300 out of the 800 total points in the class (37.5%), but they are not factored in unless students “demonstrate some proficiency with the material,” on exams first. Exams are “the only thing [instructors] really know you do on your own,” and thus they are the first “hurdle” that students must clear, they are valued above everything else. Each exam is graded by the group of TAs and instructors, and assigned a point value between 0 and 100. Basic descriptive statistics are calculated for each set of exam scores to identify things like the mean, median, standard deviation, and range. This allows the instructional staff to determine a numerical cut-off, “one and a half standard deviations down” from the mean where students “probably don't actually know the material” and thus do not pass.

Dr. Hayes further quantifies what “usually” the “mean minus one and a half standard deviations” works out to be, estimating it typically “in the mid-40 percent.” This value is appropriate to Dr. Hayes, who in being “honest” believes if students cannot “do 40% of the problems that we've asked on exams, I don't think [they] know the material, so [they] go back” and repeat the course. The cut-off is discrete, as students are either above or below it on each exam, and averaged over the four exams in the course, the cumulative scores are similarly either above or below the cut-off line. For students scoring above the cut-off, their *enrollment* into the actor-network of their sophomore mathematics course is confirmed. Their successful exam is their ally, marking their membership in the course, and these students can be confident in proceeding to the next set of courses knowing this prerequisite is satisfied. Students who are below the cut-off on their exam scores must “go back” and try again, as their low exam scores mark their membership in the group of students who must repeat the course if they wish to complete the requirements and remain in engineering. Being unable to "do 40% of the problems asked on exams" is the mark of students who are refused *enrollment* in these courses. As described by Dr. Hayes, *enrollment* is not signified lightly, it is a process of statistical calculation, exam by exam, semester by semester, in order to determine if students will be above or below the cut-off line.

5.2.5.2 Durability of Exams and the Power of Historical Data

Exams are thus hugely powerful non-human elements of the actor-networks of sophomore engineering, as they determine whether or not students can be successfully *enrolled.* Exams are also a durable artifact of these courses, having been administered over decades and decades in relatively constant formats, assessing the immutable content we introduced in Section 5.1.1—Instructor Perspectives on Stability. As a result, there is a large amount of historical data surrounding typical student performances on exams, trends based on this data that are described to students as part of the *enrollment* process. For instance, from the first day of Calc 3 Dr. Hayes introduces exams and describes how the instructional staff doesn't even need to grade the third exam, since their historical data predicts student performance:

> "The exams, we give them back to you the next day." Dr. Hayes jokes about how the 3rd exam is not even graded, that they just assign a score after the first two based on the performance on the first two. The students laugh tentatively as if they're not sure it's really a joke.
>
> ~ Fieldnote Excerpt, Calc 3 large section, Dr. Hayes Week 1 Monday

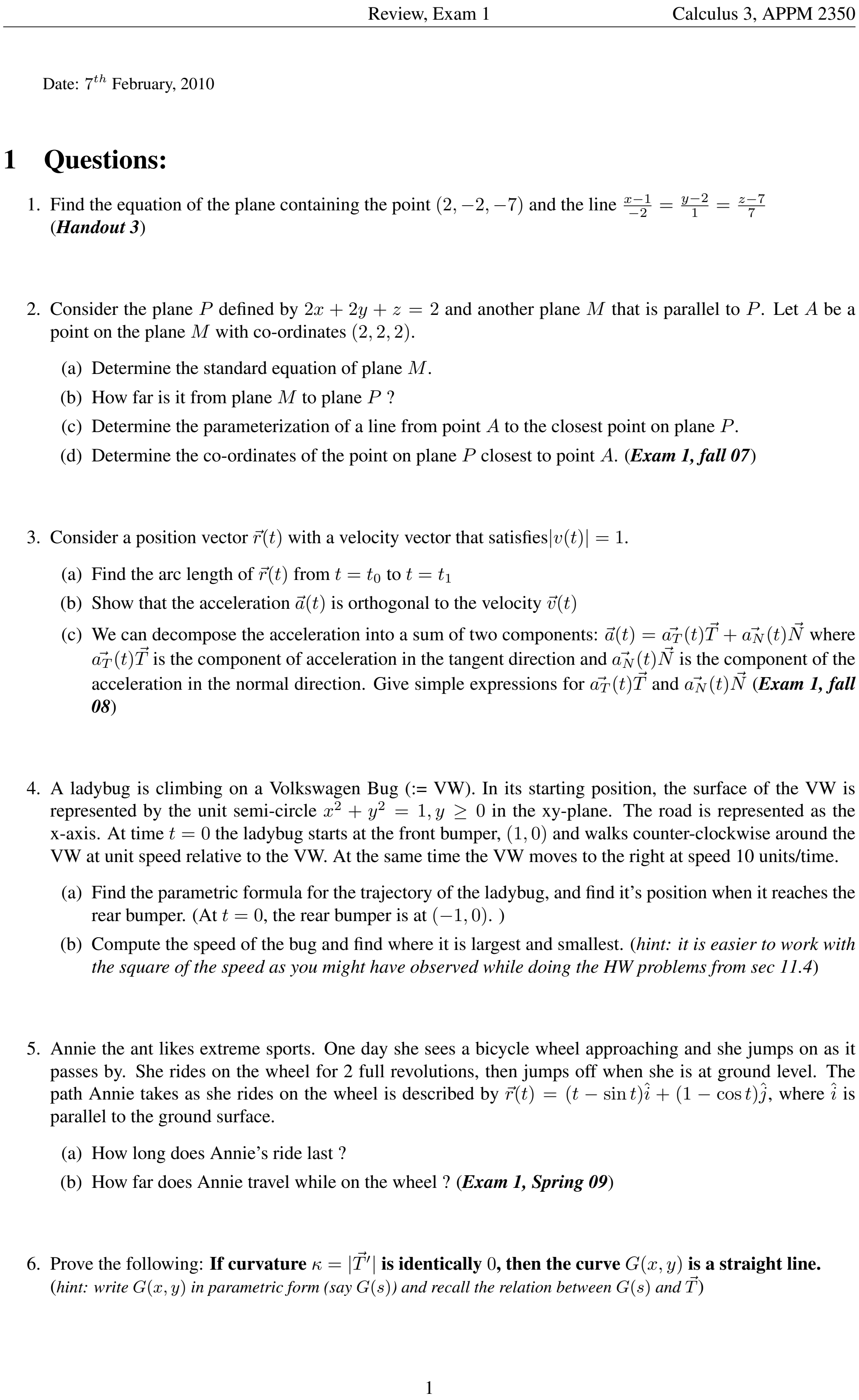
Mentioned offhand by Dr. Hayes to lighten up the mood of the lecture, some students take the joke seriously and seek clarification to understand if the 3rd exam will really be graded or not. Dr. Hayes is guided by the historical data in describing how past students have faired on exams through time in the course. Each exam score is a powerful determinant of subsequent student attitudes and beliefs, since after the first exams are graded and returned, each student has a personal precedent that they must either maintain or improve on to survive.

5.2.5.3 Analysis of Optional Exam Review Session

We follow the activity surrounding the first exam of Calc 3 during the semester it was observed intensively to further identify how the process of *enrollment* works. Preceding the actual exam are three out-of-class, TA-administered optional review sessions; one in-class review session for lecture sections with sympathetic instructors; and countless hours of individual student studying. One of the out-of-class review sessions was observed on the Monday preceding the test on Wednesday:

> The TA distributes a "Review for Exam 1" worksheet that is dated February 7, 2010, around the room. In the row in front of me are two students from the large section I know, Jamie and Nate, who entered a few minutes after me, close to the start of the session. The TA explains that he will go somewhat slowly through the sample problems, but he says that he will make it through most of the review worksheet while leaving the last 45 minutes of the 90-minute long official "review session" open for student questions. We run out of review worksheets, I give mine to Jamie and tell him that he owes me one. I feel bad that I didn't offer it to the women who are seated in the back row who didn't even know that there was a review sheet since they came a minute or two too late and all the worksheets have been claimed.
>
> ~ Fieldnote excerpt, Calc 3 review session for Midterm 1, Week 5 Monday

The atmosphere of the review session is a bit wilder than a typical lecture, as it features several students entering late, sitting with their friends, and discussing worksheets with one another. Apparently the TA did not anticipate the level of attendance at this review session, as there are not enough of the review worksheets to go around. The worksheets are organizing artifacts for the review, as the TA explains he will go through most of it in the first 45 minutes of the review session. The worksheets are scarce and thus valuable, as many students who arrived late do not have worksheets and a few are even unaware that the review is structured around these worksheet problems anyway. The review worksheet is two-sided, with 14 total problems and a 15th directive to "remember to review section (10.6) on your own!" Dated February 7, 2010, the worksheet was apparently initially created for a review session several years ago, and reused for the current class, since the passage of time has not caused the review problems to be any less relevant. Several of the problems on the review worksheet have labels to designate that they were taken from exams administered in 2007, 2008, and 2009, further reinforcing that these problems have no expiration date, they are relevant despite being over five years old. The first page of the review worksheet is included below as Figure 33.



Review, Exam 1 Calculus 3, APPM 2350

Date: 7^{th} February, 2010

1 Questions:

1. Find the equation of the plane containing the point $(2, -2, -7)$ and the line $\frac{x-1}{-2} = \frac{y-2}{1} = \frac{z-7}{7}$
   (***Handout 3***)

2. Consider the plane P defined by $2x + 2y + z = 2$ and another plane M that is parallel to P. Let A be a point on the plane M with co-ordinates $(2, 2, 2)$.
   (a) Determine the standard equation of plane M.
   (b) How far is it from plane M to plane P ?
   (c) Determine the parameterization of a line from point A to the closest point on plane P.
   (d) Determine the co-ordinates of the point on plane P closest to point A. (***Exam 1, fall 07***)

3. Consider a position vector $\vec{r}(t)$ with a velocity vector that satisfies$|v(t)| = 1$.
   (a) Find the arc length of $\vec{r}(t)$ from $t = t_0$ to $t = t_1$
   (b) Show that the acceleration $\vec{a}(t)$ is orthogonal to the velocity $\vec{v}(t)$
   (c) We can decompose the acceleration into a sum of two components: $\vec{a}(t) = a_{\vec{T}}(t)\vec{T} + a_{\vec{N}}(t)\vec{N}$ where $a_{\vec{T}}(t)\vec{T}$ is the component of acceleration in the tangent direction and $a_{\vec{N}}(t)\vec{N}$ is the component of the acceleration in the normal direction. Give simple expressions for $a_{\vec{T}}(t)\vec{T}$ and $a_{\vec{N}}(t)\vec{N}$ (***Exam 1, fall 08***)

4. A ladybug is climbing on a Volkswagen Bug (:= VW). In its starting position, the surface of the VW is represented by the unit semi-circle $x^2 + y^2 = 1, y \geq 0$ in the xy-plane. The road is represented as the x-axis. At time $t = 0$ the ladybug starts at the front bumper, $(1, 0)$ and walks counter-clockwise around the VW at unit speed relative to the VW. At the same time the VW moves to the right at speed 10 units/time.
   (a) Find the parametric formula for the trajectory of the ladybug, and find it's position when it reaches the rear bumper. (At $t = 0$, the rear bumper is at $(-1, 0)$.)
   (b) Compute the speed of the bug and find where it is largest and smallest. (*hint: it is easier to work with the square of the speed as you might have observed while doing the HW problems from sec 11.4*)

5. Annie the ant likes extreme sports. One day she sees a bicycle wheel approaching and she jumps on as it passes by. She rides on the wheel for 2 full revolutions, then jumps off when she is at ground level. The path Annie takes as she rides on the wheel is described by $\vec{r}(t) = (t - \sin t)\hat{\imath} + (1 - \cos t)\hat{\jmath}$, where $\hat{\imath}$ is parallel to the ground surface.
   (a) How long does Annie's ride last ?
   (b) How far does Annie travel while on the wheel ? (***Exam 1, Spring 09***)

6. Prove the following: **If curvature $\kappa = |\vec{T}'|$ is identically 0, then the curve $G(x, y)$ is a straight line.**
   (*hint: write $G(x, y)$ in parametric form (say $G(s)$) and recall the relation between $G(s)$ and $\vec{T}$*)

1

Figure 33: Review Worksheet for Calc 3 Midterm 1

It is amazing that the TA plans to get through 14 problems in 45 minutes, as several of the problems have multiple parts and require several steps of manipulation. Exams usually have four or five problems for students to complete in 90 minutes, indicating that this TA is going through the review problems at a significantly accelerated rate. According to the fieldnotes, it takes about 11 minutes to complete the first problem on the board, including a question from a student that the TA replies to, clarifying a "step [he] skipped." It is not surprising that the TA skips steps in going through the problems faster than the students typically do, though it suggests that many students may not be able to keep up with the TA's speed in working through these examples.

Problems 4 and 5 on the worksheet are word problems describing a "ladybug" and an "ant," respectively, while problems 1, 2, 3, and 6 are relatively dry, mathematical derivations with no physical meaning or applications attached. Considering this review worksheet as reflective of the exams, the exams as the primary means of signifying successful *enrollment* into these courses, and these math courses as controlling access to engineering coursework, it is interesting to note that these problems have little if any outright connection to engineering. The problems have no units, and relatively few actual numbers, as symbolic manipulation is preferred over actual computation. The problems on the review worksheet are truly mathematical, and indicative of the exam problems which determine student *enrollment* into the actor-networks of sophomore math and in turn, engineering.

After about an hour of elapsed time in the review session, the TA has indeed covered the bulk of the problems on the exam, skipping numbers 3 and 5. Many students have already left, with some students leaving after twenty minutes of sitting in the review, and others like Jamie and Nate staying for almost sixty minutes before departing. Upon leaving the room, Jamie comments that he can do the problems on the worksheet, but doesn't understand what the TA is talking about up at the board. After an hour of listening to the review, only a few students remain to ask questions during the open question time the TA promised at the start of the review. It is unclear how much sitting through the first part of the review helped students learn or study for the exams, as many did not have worksheets so they did not have the definition of the problems the TA was working on. Nonetheless, the review sessions are scheduled times which offer additional opportunities for students to hone their math skills. They are chances for students to practice the skills that if successfully employed, will ultimately lead to *enrollment.*

5.2.5.4 Lecture the Day of the Exam

Moving chronologically forward, the next class event after the optional review session Monday night is the class lecture on Wednesday, the same day as the exam. Dr. Hayes does not do a formal in-class review, but spends the first fifteen minutes of the class discussing the upcoming exam and answering questions from students about it:

> Dr. Hayes starts class, saying, "A couple comments on the exam… first of all I hope that you have looked through old exams, to see the length and relative difficulty of the problems… you get your exams back tomorrow, in recitation…When you go to the exam… one of the most important things is you need to know your recitation. In the upper right hand corner, we're going to ask you to put a recitation number. The other thing, because not everyone knows what you look like, I recognize you, but depending on the room you're in, the people proctoring may not recognize you. So you have to bring your student ID. The other thing is, it's closed book, closed note, but if you looked at the old exams you know…."
>
> ~ Fieldnote Excerpt, Calc 3 large section, Dr. Hayes Week 5 Wednesday

In reviewing the format and process of identification for the exams, Dr. Hayes also introduces important resources for students to set their expectations for the upcoming test environment, content, and experience. Starting the class, Dr. Hayes refers to the online exam archive of past Calc

3 midterms, telling the students, "first of all I hope that you have looked through old exams," since they demonstrate the "length and relative difficulty of the problems." The exam archive is the primary resource for students studying for exams, as it features both past exams and their solutions. Referring to the "old exams" as analogs for the current exam also demonstrates the stability and durability of these classes. The current midterm is apparently not much different from the exams taken five years ago that are available on the exam archive website for student reference, similar to the problems on the review session worksheet. Dr. Hayes spends more time covering the logistics of the exam, while the review session focused only on reviewing mathematical content in advance of the test; Dr. Hayes explains what students should be studying and how they will identify themselves on their tests.

Students must properly identify themselves and their exams so that the exams can be graded and handed back in recitations. To help with identifying each exam, as mentioned in *problematization,* the recitation section number is used as a student identifier. Their recitation section is also used to assign students to specific testing locations, the recitation section number must be written on the students' exam in the "upper right hand corner," and the exams are handed back to students during recitation on the following day for Calc 3 (or the following lecture for Diff Eq). With well over 200 students per class per semester, collecting all he exams to grade and redistributing them back to students is a logistical nightmare. In addition to being identified by recitation number, the students must also identify themselves via their student ID cards to verify that indeed they are taking the exam for themselves, so there is little chance of cheating or foul play. Dr. Hayes covers these details, reiterating that the exam is "closed book, closed note," so students will be aware of the process when they enter their first Calc 3 midterm exam.

Continuing the lecture, we follow a student asking about the difficulty of the exam and Dr. Hayes's response:

> Male student in front row asks, “How bad is it?”
>
> Dr. Hayes says, “I was looking at it, and I can work most of the problems…” and students laugh in response. Dr. Hayes continues, “Look, you know, there’s nothing in there that you haven’t actually been asked to do before. You may not have been asked to do a couple things at once, but topic wise there should be no surprise. It’s all basic skills that we think you need to know to go on. And if you think about it, look at the old exams, there are problems about geometric constructions…”
>
> ~ Fieldnote Excerpt, Calc 3 large section, Dr. Hayes Week 5 Wednesday

Here Dr. Hayes replies to the student’s question about how “bad” the upcoming midterm is by first joking that “I [Dr. Hayes] can work most of the problems,” again trying to defuse the students’ stress through a bit of humor. Dr. Hayes reminds the students of all their previous exposure to the material that’s on the test, saying, “there’s nothing in there that you haven’t actually been asked to do before… topic wise there should be no surprise.” This reminder is meant to reassure the students that they’ve already seen the topics that are on the test, there are no surprises waiting for them on the exam. Dr. Hayes then states that the test is assessing “basic skills” that the instructional team believes students need in order to go onto subsequent coursework, further downplaying the difficulty of the exam. And again, Dr. Hayes references the “old exams” as a resource to establish student expectations and calibrate their anticipation for their first Calc 3 midterm. In using the “old exams” as the baseline for the current exams, the durability of the course is promised to students as a reassurance that there will be nothing new or unanticipated. If the course was not so durable and past exams could not be used as proxy or study guides for current students, there would be even more stress as students would not have prior examples of what to study. Thus, the durability of the course and consistency of exams from year to year stabilizes the *enrollment* process, allowing all parts of the exam system to be described in advance and planned for by students, TAs, and instructors.

Dr. Hayes gives a few more instructions and pointers to students regarding the exam, advising them to read over the all of the exam questions before starting to work, and to be cautious in allocating time to each problem. After about fifteen minutes, Dr. Hayes commences lecturing on new material that will not be on the exam, explaining that in part due to the 100-year flood they lost a class and must continue moving onto new content so the schedule can be maintained, all of the required content can be delivered.

5.2.5.5 The Exam

We move onto the next part of the official exam process, which is the exam itself, the 90 minutes that determine if students will consider themselves as on-track to pass the class or in need of serious help. Our fieldnotes from observing the exam first describe the testing environment before the exam is passed out:

> For seven of the recitation sections (about 200 students), the exam is in Math 100. This room is a giant tiered lecture hall with a total capacity of 425, formed of concrete walls and levels with a large 3-level chalkboard at the front center of the room. Students are instructed to sit at least 1 seat away from other students, and aligned so that every student not in the front row is looking straight at the back of another student's head. Dr. Hayes is walking around, instructing the students when they enter where to sit during the test. Many students had seats well before 15 minutes before 5:00pm, the exam start time. Dr. Hayes announces that they will start passing out blue books and draws a schematic of what the students should write at the top of their blue books, including their recitation number and name. Dr. Hayes also gives the students instructions on what will happen when they turn in their exams and bring up their student IDs for identity verification. The TAs start passing out blue books 5 minutes before the exam. The hall is quiet, with a few more

> students entering 3 minutes before the official start time. Students fill out their blue books and some look around, others talk to those around them (I see Jamie smiling/joking with a friend on his left) and then Roger the TA starts passing out the exams about 2 minutes before 5:00, the official exam start time. Depending on where students are seated in the hall some get the exam before others. Conversation has now ceased as the class focuses on the exam.
>
> ~ Fieldnote Excerpt, Calc 3 Midterm 1, Week 5 Wednesday

The exam environment is regimented and controlled, as students are assigned which room they have to go to in order to take the exam, which seat to sit in to allow for appropriate spacing between students, and which blue book they will use for the test. Dr. Hayes is undoubtedly in control, telling the students where they will sit, what they will write on their blue books to identify them, and how they will turn in their exams and have their IDs verified as well. The TAs act in harmony with Dr. Hayes, passing out blue books and then passing out exams around the room. The system is orderly with everyone playing their part, students seated around the lecture hall, Dr. Hayes in the front, and the TAs moving around to distribute blue books and exams. TAs move quickly in getting the exams to each student so there are no significant differences in when students first get their exams. There is nothing to signify that this exam is being taken in the twenty-first century, as the only artifacts or technologies utilized during the exam are paper, pencil, chalk, and a clock.

The remainder of the observational fieldnote describing the exam captures one announcement from Dr. Hayes to clarify one of the exam problems, one student who almost gives up on the exam but Dr. Hayes intervenes and convinces him to keep trying, and the first student who finishes the exam after 50 minutes and walks up confidently to turn it in. Students complete the exam in waves, several around 58 minutes and then many more after 70 minutes of elapsed time. Students exiting the testing room have varied expressions, some relieved, some excited, some happy.

All students must turn in the exam after 90 minutes. Immediately following the students' exam completion, the TAs and instructors start their "grading party," a six to seven hour-long window in which all the course TAs and instructors work together to grade every single exam just taken.

5.2.5.6 Exam Aftermath in Recitation

For students, they re-encounter their exams the following day in recitation. Class starts with Roger, the TA, having written the following statistics on the board before passing back the exams in our fieldnotes:

	2350	Rec 5xx
Mean	61.2	57.5
St. Dev	20.8	24.2
Max	100	99

> "F--- you," I hear a male student say to another male behind me, conceivably because of his performance on the test (likely in reference to the student who got a 99). Male on my left has his test face down – so does the woman in front of me, probably because they do not want their scores to be visible or they don't want to look at them anyway. Roger continues passing out the homework assignments as well.
>
> "I turned it in early too… I had time to do it…" says one male on my left to another next to him, sounds like he is talking about a stupid mistake that he made that he could have caught/corrected if he had taken the time to check his work.
>
> Roger gets the class's attention and explains the class averages and "population standard deviation, for those of you who know what that means…" with regard to the statistics on the board. Roger says, "Good job, person!" about the student in the section who got the 99, adding, "I'm not going to say who that person was, because some of you may be vengeful…"

~ Fieldnote Excerpt, Calc 3 Recitation, Roger the TA Week 5 Thursday

The numbers drawn by Roger on the board let each person in the class know if they are above average or below it, with additional clues about the curve based on the standard deviation values. Roger reports the statistical results for both the entire Calc 3 class and for the specific recitation section. The distribution of the recitation section does not matter to the students; it's the overall class or "population" average and standard deviation that matter in the determination of passing or failing. The first thing I heard a student say during the class was to curse at his friend for some reason, probably due to his achievement of a 99 on the exam. This student does not brag, however, and neither does Roger, as they are both cautious about the potentially "vengeful" students in the class. Several other students turn their blue books facedown so their scores are not visible, as they do not want others or even themselves to look at what they got on the test. One student expresses regret at turning in his test instead of checking it over, after apparently realizing that he made a stupid error. The atmosphere in the room is tense, with a variety of emotions being expressed and "vengeful" students being mentioned by Roger.

In describing the "population standard deviation," Roger adds, "for those of you who know what that means," recognizing that not all students in the class have the statistical background to understand what that value means for their scores. A student asks for clarification and Roger answers:

> Another student asks, "If this was the only test, what would the curve look like? "
> Roger does a quick calculation, telling the students that if your grade is approximately 30 or above you are probably passing.
> A male student in the first row asks, "[Dr. Hayes] knows our grade before we even take the 3rd test? What if we do way better?"

> Roger explains, "We're going to take your actual grade… it's just, usually the grades end up being pretty consistent… so if you average a 60 on the first and second you'll probably get that on their 3rd… scores don't shoot way up, usually it's pretty consistent. So if you're not happy with your first test score, you can put in more time studying for the second… by the 3rd you can figure out what kind of studying works for you… you should know that by the second test, or by the 3rd test at least. That's what Dr. Hayes means by it."
>
> "But you still actually grade them?" the student asks one more time to make sure that the tests are actually graded.
>
> "Yes, we do, and we actually grade the final…" Roger replies one more time.
>
> ~ Fieldnote Excerpt, Calc 3 Recitation, Roger the TA Week 5 Thursday

Roger helps the students interpret the statistics regarding "the curve" on the first exam, calculating that a score of 30 would be approximately the cut-off for passing if there were only this test. This excerpt from the fieldnotes displays the confusion of one student regarding what Dr. Hayes said earlier about historical exam averages and being able to predict student performance on the third exam. The student asks repeatedly to make sure that the 3rd exam and final are "actually" graded, with Roger reassuring him at every step that they "actually grade" these tests. Roger explains, "usually the grades end up being pretty consistent…scores don't shoot way up," which, while true, may sound like a death sentence for a student who scored poorly on the first exam and is hoping to do significantly better on subsequent tests. The historical data showing the "consistent" nature of student performance on exams tells students that if they scored low on the first exam, they will score similarly low on the second, third, and final exams as well. Roger adds, "if you're not happy with your first test score, you can put in more time studying for the second," suggesting to students that "more time studying" will improve the outcome for students who are dissatisfied. The confusion level of the student who repeatedly asks about the grading of the exams is indicative of the power of Dr. Hayes's messaging about the predictability of student exam scores. The questions and emotional atmosphere of the room are also telling as students realize their performance on the first exam is a strong indicator of their likelihood of being successfully *enrolled* or needing to repeat the class.

5.2.5.7 Exam Aftermath in Lecture

During the lecture period Friday that follows the return of the first exam grade in Calc 3, Dr. Hayes further highlights the takeaways for students based on their score:

> "Let me tell you the truth: this was not a hard exam, there were no surprises, there were no curveballs. I would have loved to see the exam average on this at least 10 points higher overall. Take this as a first data point of where the standards are. I'll be honest with you, but the average should have been higher than this. Now having said that, what usually happens is that we tighten the screws as the semester goes on. We see a 5 and 10 point drop in the averages. We're starting at 60… trust me it starts to drop off. You should be spending at least 10-12 hours per week on this class, do not underestimate. You have to roll up your sleeves, get your hands dirty, this is how you learn the material. Sounds silly, but you have to put the time in. You have to be above the mean minus 1.5 standard deviations… if you are at 30 or below, I would come see me as soon as possible because whatever you've been doing isn't working. I'll be blunt. The competition gets stiffer…"
>
> ~ Fieldnote Excerpt, Calc 3 large section, Dr. Hayes Week 5 Friday

Dr. Hayes commences the lecture with a long discussion of "the truth" for the students. The average on the exam was 60, but it "was not a hard exam, there were no surprises, there were no curveballs." Dr. Hayes says at least twice that the "average should have been higher," at least by 10 points. These statements are opinion, and do not seek to precisely identify blame or the deficiencies that caused this lower than expected exam average. But Dr. Hayes is disappointed and what "should" have happened is a higher exam average nonetheless, a somewhat confusing message. Dr. Hayes continues, suggesting students "Take this as a first data point of where the standards are," as now the students should know what is expected in Calc 3 after experiencing the first exam. The grade on the first exam signifies if students are up to the "standards" of the class or below. The first exam either helps students to feel *enrolled* or made it clear that they need to do better if they want to pass.

Historical experience is invoked again by Dr. Hayes explaining, "what usually happens is that we tighten the screws as the semester goes on," causing a "a 5 and 10 point drop in the averages" on each subsequent test, through the second exam, third exam, and the final. The image of tightening the screws is uncomfortable, as it suggests that the pressure is being magnified gradually "as the semester goes on," with nothing the students can do to alleviate it. This statement is historical data presented as near fact, as Dr. Hayes says, "trust me" speaking to convince about what "usually" happens, what will probably happen this semester as well. With so much tradition and history behind Dr. Hayes, how can this cohort of students be any different? Dr. Hayes also explains that students should "be spending at least 10-12 hours per week on this class," during which time "You have to roll up your sleeves, get your hands dirty," in order to "learn the material." The past discussion of *interessement* is referenced here, as if students are not spending sufficient amounts of time per week on the class, if they are not *interested,* they cannot be *enrolled* either. Dr. Hayes advocates for an engagement with the math that gets students' "hands dirty," a symbolic level indicating serious effort and willingness on the part of students to try and work hard to learn, a serious level of *interessement.*

Dr. Hayes has the same approximate cut-off as Roger the TA told his students, telling students "if you are at 30 or below… whatever you've been doing isn't working," as it is in the danger zone below "the mean minus 1.5 standard deviations." Dr. Hayes concludes, bluntly, "the competition gets stiffer," reminding the students that as the semester goes on, weaker students drop the course and it becomes harder and harder to be above the cut-off line since the remaining students are all strong. This comment about "competition" is also a reminder that ultimately each individual student is being compared against the class average, so everyone is in competition with everyone else.

After the first exam, the subsequent exams continue in much the same format – reviews beforehand, the test itself, grading party, and the aftermath in both recitation and lecture. Students learn to deal with exams and make them their allies, or they resist connecting with exams at the penalty of failing the class. Exams control student grades and student outcomes, and they are the main feedback mechanism for letting students know where they stand with regards to the class average, against their competition. Exams determine *enrollment* into the actor-networks of sophomore math, just as they have for decades and decades. Students, TAs, and instructors are all informed by past exams and past exam grade distributions, as the apparent consistency of student performance across the semester is another indication that exams are intensely durable in controlling *enrollment* and are thus a means of stabilizing the entire sophomore mathematics actor-network. Students entering these classes encounter the durable actor-networks of these math classes and the equally durable artifacts of exams. They manage either to join the actor-network's movements by performing acceptably on exams and becoming *enrolled*, or they remain on the outside, inadmissible because they are below the cut-off level determined by the exams. These immensely powerful artifacts are central to the experiences of students, TAs, and instructors in the course, and serve as gatekeepers for potential student *enrollments*.

5.2.6 After-ANT View on Enrollment

In line with our second research question, we turn to look at the activity on the margins of *enrollment*, on the aspects of exams that are hidden or not accounted for in the process of grading. While the prior section showed exams to be monolithic, durable artifacts central to the administration of a course, we examine how they got that way, how they came to be structured in their current form.

5.2.6.1 How Did Exams Get This Way?

Interviews with Dr. Lewis shed light on the negotiated aspect of exams, as they are designed uniquely to fit in the constraints both within and outside of the actor-network of sophomore mathematics. For instance, Dr. Lewis explains why there are three midterms during a semester instead of only two or one as in many other engineering undergraduate classes:

> *Interviewer:* Would you ever consider going to 2 midterms, instead of 3?
>
> *Dr. Lewis:* No! [sounds aghast] Oh God, that would be horrible. That would be absolutely horrible. Two is too short, is too few. And the reason for that is because the students have a hard enough time putting 4 weeks of material into their head, if they had to put in 6 or 7 weeks of material, no - that would be, then it would be almost like a final. No no no, no. No, I would not want to go to two midterms.
>
> ~ Dr. Lewis, Interview 2

Dr. Lewis says having less than three midterms per semester would be "horrible," "absolutely horrible," indicating that the current frequency of exams is appropriate and non-negotiable. Dr. Lewis describes, "students have a hard enough time putting 4 weeks of material into their head, if they had to put in 6 or 7 weeks of material… it would be almost like a final." Apparently it is important that midterms are distinct from finals, with less material and less pressure. For Dr. Lewis it is also important that the students are tested approximately every four weeks instead of every six or seven weeks as in other engineering classes. Increasing the material put "into their head" from four weeks' worth to six is untenable for math. The vehemence of Dr. Lewis's response indicates that the current exam setup cannot be tampered with, and if it were to shift down by one midterm the consequences would be "horrible." This highlights that the durability of exams is partially due to the durable attitudes surrounding them, maintaining the exam system exactly as it is.

Dr. Lewis also explains how the exams came to be scheduled on the 5th, 9th, and 13th weeks of the semester, regardless of how the content breaks over these weeks:

> Before I came here, there were already all these large classes, so the calculus classes, the physics classes, the chemistry classes, some of the biology classes, we needed to have common evening exams. And so there was a division made, that the math common exams would be on a Wednesday night. Fine, that's fine. And then there's not enough rooms for Math and Applied Math to be on the same night, so we made a sub-arrangement with the Math department that the Math department would be in weeks 4, 8, and 12, and we would be in weeks 5, 9, and 13. It's just a question of where are the rooms that we can take exams in, and we need all the big rooms on campus, and we can't both have our exams on the same night - there's just not enough space. And so that's why we just made that decision, and so they're evening exams, and they fall where they fall, as far as the material is concerned. It's not necessarily where you would want them to fall, but it's just where they fall. So there are a lot of non-pedagogical constraints that are associated with running the calculus classes.
>
> ~ Dr. Lewis, Interview 2

What Dr. Lewis describes is not frequently discussed in the context of the exams, as it is taken-for-granted from the first day of class that the exams will be on Wednesdays of the weeks specified in the syllabus. This passage from our interview uncovers the underlying dynamics of room scheduling that control when exams can be held, regardless of "pedagogical" desires. Additionally, Dr. Lewis explains how the nights of the week were divvied up a long time ago, as the actor-networks of undergraduate mathematics negotiated the current arrangement in concert with the equally large and powerful actor-networks of physics, chemistry, and biology. Dr. Lewis says that the arrangement wherein "math common exams would be on a Wednesday night" is "fine," as that is the default scheduling which has been the standard for decades. Furthermore, Dr. Lewis describes the "sub-arrangement" made with the Math department, which resulted in the Applied Math classes taking the Wednesdays on the 5th, 9th, and 13th weeks of the semester. These arrangements are driven by the fact that "there's just not enough space" on campus to accommodate all the students and tests they need to take without assigning these divisions of time for each department's classes. As a result of these arrangements, the exams "fall where they fall," regardless of if it's convenient timing for student learning or not. "It's just where they fall," repeats Dr. Lewis, minimizing the impact of this mechanistic scheduling on the flow of the math classes through a semester. Yet it's interesting, as Dr. Lewis describes, that there "are a lot of non-pedagogical constraints that are associated with running the calculus classes," perhaps referring to the credit hour limitations we discussed earlier. In Section 5.1.1—Instructor Perspectives on Stability, we traced how restrictions on total credit hours for engineering degrees compressed the seat time and credit hours allocated to the math classes; here we see another limitation on these classes imposed by the physical restrictions of room capacity on campus.

From Dr. Lewis, we learn that the exam system is on one hand designed so students only need to keep 4 weeks of information in their heads at a time, until the final. On the other hand, we see that the actual scheduling of exams was determined long ago due to the physical constraints of campus and in negotiation with other powerful academic departments, with no choice but to let the exams fall where they fall, regardless of the flow of content in these courses. Understanding the various ways exams have been adjusted to allow for their current implementation deepens our view of exams, seeing the ways exams have been controlled in addition to the ways that exams control student *enrollment*.

5.2.6.2 Student Experiences and Opinions of Exams and Fairness

Continuing our investigation of things on the periphery of *enrollment,* we look to students to understand their experiences of exams and identify what is lost when assigning a single grade to their exam. Similar to *interessement,* students find ways to resist *enrollment* and locate alternate pathways to deal with exams. Unlike in *interessement*, however, there are no perceived or documented instances of cheating on exams, yet events still occur which are not recognized or valued within the official actor-networks of the math classes. We examine student opinions of exams, noting that exams are a form of standardized assessment, as all students take the same exams and are graded on the same rubric. We recall the work of Star (1990), discussed in section 3.2.4.2—Star's Allergy to Onions, who encouraged a critical look at the *'distribution of the conventional'* to recognize that the "public stability of a standardized network often involves the private suffering of those who are not standard" (p.43). In our case, we have discussed the stability and power of the standardized network of exams in the previous section on *enrollment*, so now we turn our attention to the private suffering of those students who are not standard, who do not easily *enroll* in the actor-network of mathematics due to various difficulties with exams.

We start with a conversation captured in our second student focus group, which illustrates the frustration students experience in response to the exams:

> *Erika*: I don't understand why it is necessary to have an exam average that is in the 50s and then curve it. I've had teachers that say they never had to curve before, they never gave an exam and had the average be really bad. It is like this emotional torture

> you go through every time you take an exam (*Becky* and *Ralph* nod in agreement). That is the part that is frustrating. I have had a few exams where I have walked away crying. Like, no joke. I think it was Diff Eq. I don't know if it was just everything going on and I was a little unstable, but I walked out of that test to my car and cried and was like "Oh my God I am going to fail". I ended up not doing that bad, but still…the test was so awful.
>
> *Ralph:* Yep, psychologically-
>
> *Becky:* Yeah, like it just murdered you.
>
> *Erika:* You start questioning everything. Is engineering right for me? Is college right for me?
>
> *Ralph:* Yeah. Well I agree.
>
> ~ Student Focus Group 2

This excerpt starts with Erika commenting that she doesn't "understand why it is necessary to have an exam average that is in the 50s and then curve it," expressing resistance against the exams in math that are used as a measurement device to resolve students along the full spectrum of 0 to 100. She contrasts this with other teachers she has had, who "say they never had to curve before, they never gave an exam and had the average be really bad," proving that there are other ways to do exams aside from having averages in the 50s and then curving the course afterwards. Erika describes her experience in math as "this emotional torture you go through every time you take an exam," with Becky and Ralph nodding in agreement as they can commiserate with Erika's sentiment. "Emotional torture" may be exaggerated, but clearly the tests inspire strong feelings in Erika that are unpleasant, feelings that Becky and Ralph understand and relate to as well. "That is the part that is frustrating," concludes Erika, with regards to the feeling of "emotional torture." To illustrate her point, Erika describes the aftermath of an exam in Diff Eq when she "walked away crying," thinking "Oh my

God I am going to fail." It is unclear if the potential of failure is what causes the tears, or the general stress of the situation. Erika continues, explaining that she "ended up not doing that bad, but still…the test was so awful." At this point both Becky and Ralph chime in in agreement, as they can relate to an "awful" test experience that feels "like it just murdered you," "psychologically." These are extreme words the students are using to describe their experience, between "torture" and "murder" it sounds like the math tests are more than frustrating, they are damaging and painful for students to undergo. Even in Erika's example, when she described, "not doing that bad," she still suffered and the experience was "awful." In the aftermath of an exam, Erika describes, "questioning everything," wondering if engineering and college are worthwhile pursuits if they require this type of stress and pain over every exam. Ralph agrees, having questioned his own choices in the light of a taxing exam experience, as this type of trauma causes students to take stock of their engineering careers in context of their emotional reactions to tests and their overall desires for college and their lives. This illustrates that *enrollment* via exams is not without struggle, that there is suffering just at the perception of a poor performance or exam grade.

Erika continues, explaining more of her opinion about exams with Becky and Ralph contributing:

> *Erika:* That is where I feel like it is unfair. A test shouldn't be that emotionally scarring to people. My friend told me last semester that in like her Calc 1 or 2 exam someone had a panic attack.
>
> *Becky:* Uh-huh. That was Calc 1. The paramedics came in and I was like "What the-?"
>
> *Facilitator:* Did they give you more time or anything?
>
> *Becky:* No, you could see it happening. It was in the front of the biggest lecture hall on campus. I could tell everyone was kind of like, "What is going on?" and trying to continue their test. But they didn't give us extra time at all.

> *Ralph:* Yeah it is funny because my friend was so in the zone he did not even know it happened. Later, he was like "What happened?"
>
> ~ Student Focus Group 2

The three students in this focus group have all heard this story of a student having a panic attack during her Calc 1 exam, as apparently news traveled quickly after the event. Erika brings it up in the context of her belief that "a test shouldn't be that emotionally scarring to people," as an example of the damage done to students through these exams. Similar to the way the lectures focused in on math content and sidestepped everything else (as we described in Section 5.2.4–After-ANT analysis of *interessement*), the exams are so focused on getting the exam done within the time allotted that there is no leeway to react to serious events occurring in the room. From the perspective of the instructors, it makes sense to minimize the attention on the person having the panic attack, but it is surely distracting to students to have paramedics in the room while trying to focus on an exam. Becky describes that she "could tell everyone was kind of like, 'What is going on?' and trying to continue their test," as the event was an interruption of the exam for everyone who noticed in the room. Ralph mentions his friend who was "was so in the zone he did not even know it happened," as he was focused entirely on his exam, his tunnel vision was effective in eliminating distractions and even awareness of his surroundings. Perhaps Ralph's friend is the ideal test-taker as he was fully consumed and absorbed in his exam, but for all other students who noticed the events occurring in the front of the room, the focus on their exams suffered. The rigidity of the instructors in not allowing any additional time to compensate for the unfortunate distraction at the front of the room highlights the standardization required in administering exams. The instructors could not allow this room any additional time because it would not be fair to students taking the exam in another location; the need for everyone to have the exact same conditions is meant to level the playing field but in this instance causes one group to suffer a disadvantage. This anecdote highlights the frustration and negative feelings students can easily take away from their exam experience. Even students who are successfully *enrolled* and pass the exams can find them frustrating, torturous, and emotionally damaging. Fairness requires the exams and exam conditions to be standard, but frequently this standardization causes suffering.

5.2.6.3 Limited Time & Competition Cause Students Stress

Travis, Dean, and Tommy from our first focus group were also vocal regarding their experiences taking tests and being ranked in the process:

> *Travis*: So, it seems that the exams are designed so that you can't finish them in the time period that you're given [*Dean*: Yeah! *Tommy* nods]. This is one of the big problems in Calc 3 and Diff Eq especially, is that they try to make you prioritize on the exams to try to get as many points as you can, because you're not planning on finishing it [*Dean* nods], and a lot of students get very frustrated with that.
>
> *Dean*: I heard they do that because it's an accurate way to judge a broad spectrum of students…
>
> *Travis:* A result of that kind of stress is, my Diff Eq class, the final in it, the average was a 48.
>
> *Dean:* Yup. Isn't that great? [sarcastic].
>
> *Tommy:* Mine was a 56. At that point, you're literally required to curve the class. That's the only way you can do it.
>
> *Dean:* And you know what that implies? Some people did really bad, and they're just going to get left in the dust [*Tommy*: Mhm-hmm (affirmative)]. And like, I guess just, that's how the system works. It's not, we need to pass as many people as possible, it's just like, "well they fell off the wagon, they're screwed, looks like, see you next year."
>
> ~ Student Focus Group 1

Travis starts this passage with the proposition that the exams in these math classes are “designed so that you can't finish them in the time period that you're given,” making “you prioritize” “to try to get as many points as you can, because you're not planning on finishing it.” The time restriction is an important characteristic of these exams, as it apparently limits how much students can complete of the exam and requires them to be strategic about choosing portions they feel like they can solve correctly. Dean expands on this, agreeing with Travis that the exams cannot be completed in the allotted time, saying they’re designed this way because “it's an accurate way to judge a broad spectrum of students.” Since all students are taking the same exam in the same amount of time, limiting the time for everyone increases the pressure on the students and, Dean believes, helps instructors “judge” how much students know. Standardization allows for all students in a course to be compared on the same measuring stick, the same exam.

The focus group students describe how the “stress” of a test that is too long to complete in the time provided leads to low exam averages. Travis remembers the average on his Diff Eq class “was a 48,” while Tommy remembers that his “was a 56.” With such low averages, it is clear to Tommy that instructors have to “curve the class.” Dean builds on the meaning of the curve and the low exam averages, describing the suffering of the students who are on the bottom part of the distribution of exam scores. “They’re just going to get left in the dust,” “they fell off the wagon, they’re screwed,” describes Dean, as he views the system churning on regardless of how many students fail. Dean sees an alternative, the system could say “we need to pass as many people as possible,” but it does not. Instead, students are assessed on these timed exams and those who fall off come back next year. The nameless “system” that Dean refers to could also be thought of as the actor-networks of Calc 3 and Diff Eq.

The students describe how the time limit of exams exacerbates their difficulty, helping instructors locate students along a spectrum of achievement. Since all students take the same exams, everyone is being assessed via the same criteria. Those who do not satisfy the criteria, who are on the lower end of the distribution of exam scores, are not *enrolled* and are left behind to repeat the course. Dean, Tommy, and Travis are cognizant of the curve and its impact on deciding which students pass and which fail, even if they are successful on their exams and become fully *enrolled* into the actor-networks of Calc 3 and Diff Eq they know of students who are not *enrolled*, who need to take the class again.

5.2.6.4 Looking Into the Perceived Trickiness of Exams

Dean, Tommy, and Travis also seem to agree that the exams are purposely designed to be difficult and too long to be completed in the given time. This attitude that the exams are out to get students, that they're designed intentionally to be tricky, was referenced by several of our students, but rebuffed by TAs and professors. For instance, Roger the TA explains how a specific exam question that many students found tricky was actually fair given the context of the exam:

> In the first Calc 3 Exam this semester, there was this pretty long question and it was a hefty paragraph. And all that was required was a cross product between basically two given vectors. But most of the students actually did pretty poorly on that because they couldn't quite visualize what was going on in the problem. And I think that's a pretty good example, that we expect them to be able to read a physical scenario, and try and figure out what's going on, and realize that, "oh it's just one cross product that I have to do for this whole problem." But they get scared with these long word problems, and they freak out, but we do expect them to be able to do those problems. Whether or not they can is a different story. But it's what we expect. A lot of the students were pissed off when they found out that it's just one cross product-they had some pretty creative approaches that just didn't work.
>
> ~ Roger the TA, Interview 1

Roger describes his perception of “this pretty long question” on the “first Calc 3 exam this semester” that many students “did pretty poorly on.” Out of a “hefty paragraph,” “all that was required was a cross product,” a simple mathematical operation, but the long description in words apparently confused or tricked the students, causing them to “freak out” and misunderstand what the problem was asking. Roger explains that this problem is a good example for the divide between the instructional team’s expectations and student behavior during exams. As Roger indicates, the TAs and instructors “expect [the students] to be able to read a physical scenario, and try and figure out what's going on, and realize” that what’s being asked of them may actually be simple. Roger recognizes that students “get scared with these long word problems, and they freak out, but we do expect them to be able to do those problems” by the level of Calc 3. The exam Roger is discussing had 5 problems, each worth 20 points that the students were given 90 minutes to complete. In such an environment, the fact that students “get scared” and “freak out” with these long word problems is unsurprising, though getting scared and freaking out is not helpful for thinking clearly, visualizing the problem correctly, or solving it properly. Roger adds that “a lot of the students were pissed off” when they found out that the solution was simpler than they were making it out to be, as they felt they had been tricked by the exam. Their frustrations are not captured during the process of grading the exams, their feeling of being tricked is not on the rubric, but it affects their attitudes and perceptions of the exams and their purpose.

Dr. Hayes also shared an instructional opinion regarding this specific problem on the first Calc 3 exam of the semester, expanding on Roger’s perspective with greater experience and context:

> So, the actual problem was very very simple. It was, tell me about the intersection of two planes. So, all month long, prior to the exam, we were in [the lecture hall classrooms] telling them, “you should expect to see a problem where half the problem is figure out what the problem is. And, be prepared for word problems.

> They're all going to be expected geometric construction of some sort…" So, Calc 3, very intentionally, we put in problems like that. And we've done it, every semester for quite awhile now. And to be honest with you, students need to learn how to do things beyond the ordinary.
>
> ~ Dr. Hayes, Interview 2

Dr. Hayes confirms Roger's opinion that the problem was simple, but the students still got confused somehow. "All month long, prior to the exam," Dr. Hayes discusses how the instructors explicitly told the students to "be prepared for word problems," "geometric constructions of some sort," so the students were warned that there would be longer text descriptions for some of the exam questions, they knew that word problems would be on the exams. This fits with the tradition, as Dr. Hayes says, "we put in problems like that," "very intentionally" "every semester for quite awhile now." These longer word problems also fit with the identity of Calc 3, as "students need to learn how to do things beyond the ordinary," they need to learn how to deal with word problems without panicking or being scared. Dr. Hayes's perspective on this tricky problem is that it was actually intentionally crafted in accordance with what the instructors warned students would be on the test, that it might be "beyond the ordinary," but it is part of what they "need to learn" and are being assessed on in Calc 3. While the student opinions and suffering are not included in the grading rubric, Dr. Hayes's opinions are, implicitly. Instructors are in charge of writing the exams and deciding what types of questions will be asked of students. Dr. Hayes explained how the incorporation of this problem was "very intentionally" done, as a means of identifying which students could stay calm and understand it versus which students got scared and could not solve it correctly. Dr. Hayes is in a powerful position that oversees *enrollment*, controlling what problems students must solve correctly in order to be awarded passing scores on exams, which in turn signify their belonging in the actor-network of sophomore math.

5.2.6.5 Cycles of Student Outrage & Consequence of Online Exam Archive

Dr. Hayes also describes how the exam archive with solutions leads to students having very short-term memories, and how they always think questions like this long word problem are tricky:

> And you tell [students], look at old exams, which is a real problem because they look at old exams and the solutions, which defeats the purpose of them seeing a problem that they haven't done before. And so they look at this kind of oddball problem, and then they look at the solution and say, "oh yup I see it," and then they go on, and they never have to struggle with it. And I think the process of struggling with it is how you actually learn stuff. And so, I fully support problems like that on exams. But do you know what's going to happen? Next semester, nobody's going to have a comment one way or another about [this] problem. It's like, "yeah, okay whatever, it's two planes," and to them, it's going to be perfectly normal. But if you were the first group of students was asked that problem, there's all sorts of kicking and screaming. And so in the spring, we'll have another of this type problem, and they're going to kick and scream about that, and in the fall, those students are going to look at that problem and go, "psssht, okay whatever, it was a perfectly fine problem." And so, when you're the one experiencing that problem for the first time, you kick and scream.
>
> ~ Dr. Hayes, Interview 2

Dr. Hayes calls the online exam archive "a real problem," because when the students look at past exams, they also look directly at the solutions, "which defeats the purpose of them seeing a problem that they haven't done before." Dr. Hayes describes a stereotypical student who looks immediately at the solution and never has to "struggle with it," and consequently never really learns the concepts or gets into the nuances of a problem. That's why Dr. Hayes says, "I fully support problems like that on exams," as they challenge students to truly "struggle" and hopefully, learn. Dr. Hayes explains the ongoing cycle in which one semester's contested exam problem becomes last semester's solution, when students will take one look at it and it will be "perfectly normal." Dr. Hayes suggests students only "kick and scream" when they are the ones "experiencing that problem for the first time," in a real exam environment. On a past exam solution the trickiness of the problem becomes benign and imperceptible, as the students are not struggling with it since they have the answer immediately available.

The cycle that Dr. Hayes describes repeats itself semester to semester, as instructors are around much longer than students and can see these repetitions of "kicking and screaming" and then subsequently accepting the problems as fine next semester. Students, if *enrolled* successfully, only see these tricky problems over one semester and do not have the long view of how solutions bypass the struggle of learning. Instructors like Dr. Hayes can see the phenomena play out over multiple semesters, cycling through. While students can protest, "kick and scream," and complain indefinitely about the trickiness of certain word problems on exams, instructors have no reason to get rid of them, as they are an integral part of Calc 3.

5.2.6.6 Integration of After-Ant Perspectives on Enrollment

The previous section, which introduced *enrollment,* described how exams were a powerful mediating artifact in determining student *enrollment* into the actor-networks of sophomore math. Taking an after-ANT perspective here, we have identified a few others salient characteristics of exams which do not appear on official score sheets or grading rubrics, which are lost after a student's semester-long experience is condensed into four exam grades on three midterms and a final. From Dr. Lewis, we learned that the timing of exams is not incidental, that in the past, days of the week and then weeks of the semester had to be divvied up between powerful departmental actor-networks to ensure that the students in each department's classes would have enough room to take their exams. We also learned that three midterms is the appropriate amount, as testing the students every four weeks for their math knowledge is less strenuous than making them keep six or seven weeks of knowledge in their heads, according to Dr. Lewis. These features of exams have also been in place for decades, proving that exams are an intensely durable way of assessing students and consequently making the actor-networks of sophomore math stable through time. Yet even with these frequent exams on shorter blocks of content, students find the exam process in math to be fraught with stress. Both focus groups gave detailed accounts of past experiences on exams that were torturous and psychologically painful, making them question if engineering was worth the stress of taking these exams. Seeing exams as a standard measuring stick against which all students in the courses are compared demonstrates how individual suffering occurs in attempting to meet the standard. The standardization of tests is apparent as great efforts are undertaken to normalize the testing environments, the time allotted for tests in different locations, the exam questions asked, and the grading of each question via a rubric. Keeping everything standard for all students is meant to level the playing field as the conditions are fair for all students, but students nonetheless interpret the inflexible rigidity of exams as purposely painful.

Students see exams as being out to get them, filled with tricks that they must solve in order to survive. Perspectives from TAs and instructors describe how what students think are tricky problems are part of the expectation for Calc 3 (and Diff Eq), that it's the ephemeral nature of students passing through these courses in one semester which causes them to see their exam questions as tricky compared to past exam questions which were equally so. Thus instructors and students are on different time scales, with students flowing through the courses relatively quickly as instructors have a much longer view. The instructors and students are also on far ends of the spectrum when it comes to power in controlling exams, as the instructors write the tests, including the questions and concepts they want. Instructors also control the point distribution per question and to some extent, the grading rubric, so their opinions manifest in student grades. Students' opinions of tests are not incorporated in their grade, and they are not captured officially in the exam process.

The after-ANT approach allows us to identify the power differential between instructors and students, and gives insight into the highly contested process of exams that has persisted relatively unchanged over decades. We highlight the perceived suffering of students at the hands of the standard exams, while also sharing the instructor's opinions that struggling is necessary for learning. None of the differing opinions on exams challenge their power as *enrollment* devices, as it is apparently accepted that exams are the deciding factor in students passing or needing to retake these math classes, in allowing the students to join the actor-networks of sophomore math or repeat these courses and try again. Exams are a highly durable technology of these courses; they are controlled by instructors and mediate student progress through the actor-networks of sophomore math.

5.2.7 Mobilization

***Mobilization,* or the fourth moment of translation, captures the aspects of an actor-network that begin to move through time and space, extending or lengthening the reach of a given actor-network**. For the actor-networks of sophomore math, *mobilization* can be identified in what students take with them after a math class ends, what remains with them as they move through their undergraduate careers. Similarly for *mobilization* of TAs and professors, we examine what persists through time and space after the close of a semester. We also study the movement of people and important artifacts during a semester, mapping out the scope of resources that are *mobilized* to make a single class run smoothly. In this section, we trace the evidence of *mobilization* in tangible artifacts that are common across all students and classes. Then, in the following section we take the after-ANT approach to understand what is left out, what is not tangibly *mobilized* following the end of a class.

5.2.7.1 Final Grade Calculation and Institutional Mobility

For students, the most obvious and influential item they travel with after a course is the final course grade. A flowchart representation of how this grade is calculated and how it controls access to subsequent coursework is below in Figure 34. We start at (A) on the flowchart, with the student's average grade over all the exams. As discussed in earlier sections, this grade is compared against the distribution of exam scores of all the students in the class to determine if it's above or below the cut-off threshold of 1.5 standard deviations below the mean, indicated visually in the first decision box (1) on the flowchart. Students who are above the threshold are eligible to pass and have their homework and project scores counted into their course grade as well, to their benefit. Students who

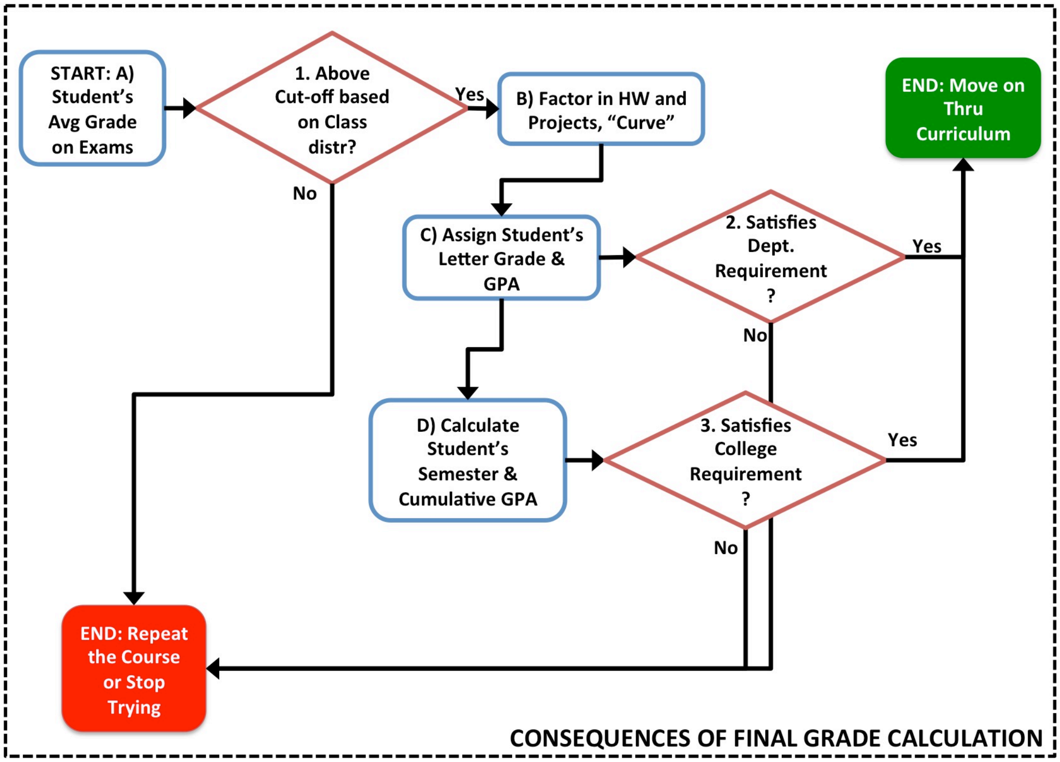


Figure 34: Flowchart Showing Decision Points for Final Grade Calculation & Consequences

are below the threshold are ineligible to pass the class; they must repeat the course. The cut-off threshold is described in numerous class meetings as 1.5 standard deviations below the mean, which in a normal distribution is approximately 6.7% of the total population. Yet the failure rates of these math classes over the last five years, as shown in Table 1, have varied considerably away from 6.7% in both Calc 3 and Diff Eq, demonstrating that the failure rates are not fixed at any level, after all.

To understand how to reconcile the variation in historical failure rates and the statistical description of the cut-off threshold given to the class, we look to the instructors and TAs to explain. On the flowchart shown in Figure 34, we are investigating the activity of box B, in which final course grades are assigned based on the "curve." Dr. Lewis comments that the instructors do not use statistical percentages of the normal distribution in assigning grades, instead they use a more abstract concept referred to as a "baseline of knowledge":

> What Dr. Hayes does, and what most of us do, it's not that we go by percentages. When we're assigning grades, I tell the students - it's sort of a baseline of knowledge, if everybody has that same baseline of knowledge, for an A and a B, everybody in the class would get an A and a B. If none of them have that baseline of knowledge, well that would be a little trickier, but you know, then there wouldn't be many A's and B's. And there'd be more failures. But we try not to go with always 18% are going to have D's and F's. We try not to go with that. It's really a baseline of knowledge.
>
> ~ Dr. Lewis, Interview 2

Dr. Lewis introduces the concept of a "baseline of knowledge." If everyone in the class possesses this "baseline of knowledge," then "everybody in the class would get an A and a B." Dr. Lewis explicitly says that "it's not that we go by percentages," and that "we try not to go with" fixed percentages of D's and F's in explaining how the instructional staff assigns grades. The concept of a "baseline of knowledge" is not quantitative or fixed, instead it is much more abstract and ambiguous. The instructional staff, including Dr. Lewis apparently determines the "baseline of knowledge;" they are entrusted with the power to make subjective judgments with regards to what constitutes this "baseline." The variation in the grade distributions across semesters makes more sense now given the abstract nature of the "baseline of knowledge," which is much less predictive or fixed than a statistical cut-off threshold. Yet this muddies the waters even further for understanding what is required to pass, as it is unclear what the "baseline of knowledge" is for Calc 3 and Diff Eq, and how students are supposed to know if they have reached the baseline or not.

One of the TA interviewees, Sylvie, adds her perspective on the situation, describing that students must learn to deal with not knowing their grades given the size of the current classes:

> The way it usually happens is that [the instructors] don't curve it until after the course ends. I don't know exactly how they do it, but they do probably a bell curve and scale everything to that. And then, if you're two standard deviations away, you fail. But it all depends on what's the average, and what's the standard deviation for each exam. The [students] always freak out. And it's just part of the process of them learning, you're not going to know necessarily your grade. But we usually tell them the mean and the standard deviation so they can figure out, for each exam, where they stand. And we usually try to tell them, especially after the first exams if you're two standard deviations below, you either need to really ramp things up or maybe should consider going to the lower-level course. It's just something that they're going to have to deal with. Because it's how many students, 500 students in each course? We can't scale it right away.
>
> ~ Sylvie (TA), Interview 1

Sylvie mentions the potential of a "a bell curve" or normal distribution that instructors utilize to scale their courses. This is different than the official explanation offered by Dr. Lewis, but Sylvie's version is also communicated to students during her recitations. Sylvie suggests that if "you're two standard deviations away, you fail," also different that what Dr. Hayes told the Calc 3 sections we observed, where the cut-off was 1.5 standard deviations below the average. Clearly, there are some conflicting accounts of the cut-off threshold in these courses and how the grades are actually assigned. Sylvie acknowledges that she doesn't "know exactly how" the instructors do the final adjustments to the grades, as the curve is a mystery even to the TAs. She does know that it is done at the very end of the course, after all the grades are turned in. The process is unknown, *black-boxed* away from everyone's sight except for the course instructors. Sylvie feels that students need to accept the *black box,* learn that they will not always know their grades, and become comfortable with it since "it's something they're going to have to deal with." With the number of students increasing each semester, sometimes there are 500 or more students in a course so it is impossible to "scale it right away," as Sylvie says. Though the students "always freak out" upon not knowing what their grades are until they can access their official transcripts, Sylvie argues that it's unavoidable. With so many people taking the class each semester, the curve can't be tracked in real-time so it has to be decided at the end of the semester, by the instructors.

Another piece of Sylvie's description is her advice to students who score less than two standard deviations below the mean on the first exam. She suggests that these students need "to really ramp things up or maybe should consider going to the lower-level course." As discussed in Section 5.2.6 – After-ANT Views on *Enrollment*, the first exam occurs during the 5th week of the semester. As we discussed in Section 5.2.1 – *Problematization,* students can drop the class with a "W" on their transcripts through the tenth week of the semester, but they cannot add a class past the second week of classes. Students who find themselves in the situation Sylvie describes who choose to go "to the lower-level course" the following semester end up putting themselves back an entire academic year. Students who follow her first suggestion, to "ramp things up," run into the predetermined consistency of student exam performance that Dr. Hayes tells students about in Calc 3. Neither of the two choices Sylvie discusses for students who score low on their first exams are very appealing. In any case, Sylvie explains that the curve is unknown to her as well, telling an alternate story than the "baseline of knowledge" mentioned by Dr. Lewis. The curve remains mysterious but powerful in determining students' final grade in the math classes, both numerical and letter.

Returning to our flowchart of grading shown in Figure 34, we now examine the activity of box C, where each student in a course gets assigned three things: 1) a final numerical grade between 0 and 100, 2) final course grade that is a letter between F and A, and 3) an accompanying GPA quality point value between 0.0 and 4.0. That three different scales exist for ranking students at the end of the semester seems redundant, but indicative of the different mobility of these grading scales across official records and time. Only the instructors know the final numerical grade between 0 and 100, as it is the end product of the mysterious curve discussed earlier. This numerical grade does not travel very far in time; it is forgotten and lost after the end of the semester. Meanwhile, the letter grade corresponding to the numerical grade is recorded in the student's official transcript, a durable form of *inscription* that travels easily as the institutional artifact representative of a student's educational career. Transcripts are immutable mobiles, since their format remains the same no matter how far across the world or country they're transmitted. The letter grade assigned to each student is also converted into a corresponding number of "quality points," which factor into the calculation of the GPA (Box D). And, the letter grade is compared against departmental requirements to determine if the student has satisfied the stated prerequisite, as a letter grade of C- or higher is needed to satisfy most undergraduate majors save Aerospace and Mechanical Engineering, which require a grade of C or higher (Decision 2). Students whose letter grades are below the acceptable threshold for their major must choose to either retake the class and try to get a higher letter grade, or switch majors entirely to fall under a different threshold requirement. Meanwhile, students whose letter grades are above the acceptable threshold for their major can continue through the engineering curriculum. The letter grades are an important institutional signal for the authorities (undergraduate advisors and administrators) that students are either ready to proceed or must be held back. Thus the letter grade is another mediating artifact that determines a student's *mobility* through engineering undergraduate.

The quality points corresponding to the letter grade are factored into a calculation of the student's semester GPA and cumulative GPA. A student's semester GPA is calculated as a weighted average of the quality point values corresponding to the letter grades earned in each class a student took that semester. The weighted value for each class is related to the number of credit hours a class occupies, as the 4-credit mathematics classes carry slightly more weight than the 3-credit engineering classes in the semester GPA calculation. Similar operations are conducted to calculate the cumulative GPA, as student's total quality points are divided by their total credit hours. Student GPAs on the cumulative and semester levels are reviewed after each semester to ensure that they are both above the 2.25 GPA requirement enforced by the college (Decision 3). If they are not above this line, students go on academic probation, and if they cannot increase their GPAs during the default two-semester long academic probation period the students then go on academic suspension (University of Colorado Boulder, n.d.-a). Academic suspension is a mandatory break from taking classes on the main campus, as a means of forcing students to consider their academic realities and what it may take to be successful in their coursework on campus. Meanwhile, students who are above the 2.25 GPA line are fine to proceed with their engineering coursework. Thus the GPA calculated at the end of each semester and cumulatively is another influential actor that mediates student progress through engineering.

In tracing out how grades become mobile enough to travel with students through their undergraduate careers, we've encountered the mystery of the curving process as well as several layers of grade conversion as a numerical grade becomes a letter grade, which carries quality points towards a semester GPA and a cumulative GPA. Looking back at Figure 34, our flowchart illustrates the different twists and turns taken during the process, pointing out where students are assigned a grade and at the various decision points where some students are allowed to proceed through the engineering curriculum and others are forced to stop and retake the class or change majors. There's not a single decision point but actually three separate stages where students are checked for their compliance with various requirements, first in comparison to the aggregate performance of the class, second in comparison with the prerequisite grade requirements for their major degree program, and third compared in the form of semester and cumulative GPA against the minimum 2.25 GPA requirement. To proceed in engineering and exit the actor-network of sophomore mathematics, students must satisfy all three of these decision points, and can be turned back or challenged if any of them are not satisfied.

Further compounding the complexity of the situation is the unequal nature of the three different grading scales (see Table 7). The numerical grading scale has the highest resolution, as it is a continuous line between 0 and 100 and students can be located at any point. Letter grades and GPA points are actually discrete categories, assigned based on the corresponding interval on the numerical grade scale. The mapping from numerical grade to letter grade to GPA quality points is somewhat arbitrary and inconsistent, as the range for a B+ is typically 90-87, an interval of 3, while the range for a B is 87-83, an interval of 4. Numerically there is no reason why B covers a greater range than B+; it is just the tradition, demonstrating that our grading scheme is another durable artifact from the past. Instructors can choose if they would like to correlate numerical grades and

Table 7: Comparison of Three Important Grading Scales

Numerical	Letter Grade	GPA points
100-93	A	4.0
93-90	A-	3.7
90-87	B+	3.3
87-83	B	3.0
83-80	B-	2.7
80-77	C+	2.3
77-73	C	2.0
73-70	C-	1.7
70-67	D+	1.3
67-63	D	1.0
63-60	D-	0.7
60 and below	F	0.0

letter grades differently, but what is shown in the table is the typical mapping. Similar to the letter grades, the mapping from numerical value to quality points is also inconsistent over the intervals, as the jump from a D+ to a C- is 0.4 quality points, from 1.3 to 1.7 whereas the difference from a C- to a C is only 0.3 quality points, 1.7 to 2. As a result of this imbalance, if a student earns a 72.5% numerical grade, it is translated to a C- letter grade and 1.7 quality points towards the GPA. Though this student is 0.5% away from a C on the numerical scale, the distance in the quality points is greater, amplified through the discretization. Thus small differences in numerical grades end up cascading through the grade scales to become greater differences in the calculation of GPA. For students who are on the edge of the 2.25 GPA requirement, a difference of 0.3 quality points can make all the difference between academic probation, suspension, or "good academic standing." Thus the consequences stemming from the different grading scales can be severe in affecting student *mobility* through the engineering curriculum. Each student's letter grade and GPA are recorded on their official college transcript, and these two forms of the grade are the primary remnants of student experience in the course after it ends.

5.2.7.2 Tangible Artifacts of Mobilization Stabilizing the System

For the TAs and instructors, their tangible remnants of the course include their ratings on course feedback, known institutionally as the "Faculty Course Questionnaire (FCQ)." Students fill out a multiple choice form during a week near the end of the semester to answer questions regarding their experience in the class and their experience with the instructor or TA who led it. These forms are analyzed per class and descriptive statistics are generated about each class and instructor, and more importantly this FCQ data is hosted on a publicly accessible institutional website and held onto for over 15 years. The FCQ scores for a given instructor are thus *mobilized* electronically, as they can be accessed easily via the web.

One of the duties of the TAs in the course is to be the course historian, in charge of collecting all artifacts related to the class including exams, exam solutions, homework assignments, homework solutions, and project assignments. Collecting the exams is an important step in maintaining the online exam archive, the repository of past exams and solutions that is the students' main resource in studying for tests. Collecting past homework assignments and solutions is important as each new semester tries to vary the homework problems from the ones assigned the previous semester. Also, having a repository of homework problems to choose from helps TAs prepare review worksheets and recitation worksheets. Finally, keeping the project assignments is useful as they can be re-used periodically, particularly since solutions for the projects are never posted. Holding onto all of the artifacts from an implementation of the course also helps to stabilize the course, as it ensures that there are always records of what was done in previous years to guide the next. The course artifacts of interest are largely representational words and diagrams on a page, which can easily be *mobilized* electronically through websites, email, etc.

Finally, we see that *mobilization* is evident in the literal movements of people and things associated with the actor-networks of sophomore math. Coordinating the flow of several hundreds of students a semester requires scores of TAs and typically four to five faculty members. These human actors move from classroom to office hours to recitation sections and back, while students cycle around these spaces as well as the library and computer lab to do class-related tasks. The instructional staff, in particular, masterfully orchestrates the movement of homework assignments, project reports, and student exams as they are turned in by students, graded, and passed back out, a series of actual paper-shuffling which is remarkably secure given the volume of papers being handed in and passed out. TAs report that losing a homework assignment is rare, as the system is effective at properly *mobilizing* both people and things, including papers.

In examining *mobilization* in the context of the actor-networks of sophomore math, we've identified influential *inscriptions* like transcripts, letter grades, and GPAs that control student trajectories upon leaving the courses under study. Looking closely at the process through which a student is assigned a letter grade and a GPA has uncovered mystery, subjectivity, and arbitrariness while also pointing to these items as intensely durable artifacts of higher education. The *mobility* of the transcripts, letter grades, and GPAs is in part because our systems have been designed to accept them, as transcripts remain the default record of a student's educational career and GPAs are reported on resumes as an encapsulation of a student's education. These *mobile* artifacts help stabilize the actor-networks of sophomore math, and they remain with students long after their involvement with these courses ends. *Mobilization* is also examined in terms of what remains after the semester ends for instructors and TAs as well. We find that in keeping all of the course artifacts semester after semester, TAs and instructors stabilize the actor-network of sophomore math by providing past examples for reference in every aspect of the course. In the next section, we move to an after-ANT perspective to investigate *mobilization.*

5.2.8 After-ANT Take on Mobilization

The previous section focused on tangible evidence of *mobilization* including artifacts, grades, and physical movements. Here, we focus on the *mobilizations* that are intangible and varied, including attitudes, skills, relationships, and content gains. We also consider what is missing from *mobilization,* what things are only partially *mobilized* or remain stationary, not moving through time or space.

5.2.8.1 Does the Content Get Mobilized for Students?

For example, we have not yet discussed the *mobilization* of content knowledge, as it is uncertain from our data if students are able to truly take the content learned in their sophomore math courses with them to their next classes at different points in space and time, and beyond that to their future careers, engineering or otherwise. While the official goal of these math classes is to have students learn mathematical content and build their math problem solving skills, many students in our dataset have commented that they forget everything immediately upon completing the final exam. While exams are designed to assess student ability and understanding of the content, they cannot predict how much knowledge students will retain once they are over. Erika from Focus Group 2 comments on this phenomenon:

> *Erika:* I do understand that they want students to understand the material but I feel like it is almost doing the opposite thing because you don't have the time to understand the material. So you are -
>
> *Ralph:* -kinda wasting time.
>
> *Erika:* Like I have had freshmen and sophomores ask me for help with Calc 1 or Calc 2. And I am like, I don't remember. I forgot that the moment the class was done. So it goes to show that I didn’t actually learn it. I just kind of remembered it for the time that I needed it for.
>
> ~ Focus Group 2

Erika is describing how her content knowledge from Calc 1 and Calc 2 was not *mobilized*, since she did not take it with her, apparently, after leaving those classes. When “freshmen and sophomores ask” “for help with Calc 1 or 2,” Erika doesn’t remember. She “forgot” the content “the moment class was done.” She interprets her forgetting as evidence that she “didn’t actually learn” the material and that it was just “remembered for the time needed I it for,” on exams. Erika also describes how the courses do the “opposite thing” they intend to, as instead of students understanding the material, Erika says they “don’t have the time to understand the material.” The rapid pace of the courses causes students to keep up, yet they may not actually be learning the material that they are tested on and complete homeworks on. Ralph comments that it’s a form of wasting time, apparently with regards to the façade of learning without actually understanding. These students have passed the course exams, satisfying the official assessments of learning, but they do not have the internal belief that they understand the material or remember it after the course ends. Their knowledge is only partially *mobilized.*

Another one of our student interviewees, Eric, transferred into the College of Engineering and Applied Science from a community college during the start of his sophomore year. After taking Calc 3 and Diff Eq, he describes how he feels about the two math classes and his understanding:

> Calc 3 it was just sort of a slightly different version of Calc 2, Calc 2 was a slightly different version of Calc 1, Diff Eq was a little bit different, so that was nice. I still do not feel like I fully understand the material, despite all of the lectures and projects and homework and stuff, and recitations. I still don't feel like I have a very good understanding of it. Like I actually got a B minus in the class, which I was not expecting. I thought I would get a C minus or a D. And, I don't even feel like I understand it at a B level but it's over…And a lot of people I've talked to, and tried to get help from, don't seem to understand it either, so, that part's a little shady.

~ Eric (student), Interview 2

Eric describes how he enjoyed that Diff Eq was "a little bit different" than the Calc sequence. He identifies a disconnect between the letter grade he earned, a B minus, and his perceived level of understanding. "Despite all of the lectures and projects and homework and stuff, and recitations," Eric still doesn't feel that he possesses "a very good understanding of it," that he may not be able to *mobilize* the content of Diff Eq and apply it elsewhere if needed. Eric "thought [he] would get a C minus or a D," and even now he doesn't feel that he understands it at a "B level." At the same time, he also recognizes that his perception of lower understanding doesn't matter because "it's over," and he earned a B minus. He is in good company as he recognizes that "a lot of people … don't seem to understand it either," so he's not the only one who doesn't feel a mastery of the knowledge after being done with the course. Eric knows that his grade is the only meaningful artifact that is *mobilized* institutionally after the end of the semester. His actual experience or content knowledge is inconsequential as the official record has a B minus which satisfies the requirements and enables him to continue in the engineering program. The grade is the most meaningful representative of the course, and it silences everything else.

5.2.8.2 Getting Through Calc 3 and Diff Eq

In addition to the students in the second focus group and Eric who discussed their lack of understanding, remembering, and low *mobility* of their math knowledge, several students described how the math sequence is something you have to get through, not something you enjoy or really learn from. For these students, their *mobility* is the desired outcome of the math and foundation courses, less so the content knowledge. For example, Elizabeth describes how she and her peers feel about their current sophomore level classes in context of their larger goals:

Interviewer: Do you enjoy the work you're doing now? You said you love learning.

> *Elizabeth:* It's hard to say. I don't know if anyone, I mean I do know a few people who really enjoy what they're doing [in classes], but I know a majority of us, have a larger goal and this is kind of the stuff you have to go through to get there… I won't be stuck here extra years this way, if I can just pass my courses. I do wish I was more engaged in the material, I wish it was more interesting…
>
> ~ Elizabeth (student), Interview 1

Elizabeth describes how "the majority of us," referring to her community of students, "have a larger goal and this is the kind of stuff you have to go through to get there." Elizabeth's "larger goals" include working in the field of bioastronautics, and she knows that the way to "get there" is to "pass [her] courses." She comments that she wishes she was "more engaged in the material," and that the material "was more interesting," but as a strong-willed student she can "go through" this stuff and get out the other side to her goals. Earlier in this interview she describes how she loves learning but that doesn't mean she particularly loves the classes she's enrolled in during the first semester of her sophomore year. Elizabeth wants to graduate and get into industry, if she "can just pass [her] courses" she won't need to "be stuck here extra years," an apparently desirable outcome. Elizabeth is not concerned about retaining the content, but in the context of reaching her eventual goal she does want to pass her courses and get through in four year; this is her vision of her *mobility* through time. These classes are a necessary to "go through to get there," if she can pass these classes she knows that she will have the *mobility* to keep going, to eventually get to her goals.

Data from second focus group, Eric, and Elizabeth all indicate that students value the *mobility* they gain from receiving passing grades in the math courses perhaps more than they care about retaining the content knowledge that is supposed to be learned in these courses. Thinking back to Section 5.1.1—Instructor Perspectives on Stability, where we uncovered the overriding durability of the content in these math classes and the status of the math content as sacred for it's apparent usefulness to subsequent engineering classes, it is surprising that the students do not seem to care or need to actually retain the content once they pass the class. While the knowledge may not be *mobilized,* the students apparently are.

5.2.8.3 The Immobile Divide between Engineering and Math

Students may have difficulty *mobilizing* their math content knowledge into their engineering coursework because they see math and engineering as different entities entirely. Though the math classes are prerequisites for many engineering classes, the content of the math classes often seems too abstract to have direct application in the world of engineering. During our observations of Calc 3 and Diff Eq, we witnessed problems featuring pendulums swinging on massless rods, equations for phenomena occurring in more than three dimensions, and little emphasis on numbers and units in answers of mostly symbolic results. During Calc 3, Dr. Oliver tells students outright that some of the math problems in these courses have no physical interpretation, nor do they need to:

> Ed asks a question about the meaning of the next integral, and Dr. Oliver says, "I want to get away from the physical meaning, and get to just handing you an integral and having you do it… things are getting more abstract…sometimes they have physical interpretations, sometimes they don't. So take a crack at it and see how it goes…"
>
> ~ Fieldnote Excerpt, Calc 3 small section, Dr. Oliver Week 11 Friday

During the class lecture that day, Dr. Oliver encourages students to stop looking for "physical meaning" in the Calc 3 problems they are trying to solve and instead get to the point where Dr. Oliver is "just handing you an integral and having you do it." Indeed "things are getting more abstract" as they no longer need to have physical meaning to justify students needing to learn about them. Yet engineers typically design physical artifacts for the tangible world. While some engineering researchers may examine abstract concepts beyond three dimensions, most engineers work in the real world on real things that can be seen, held, and modeled. When Dr. Oliver comments that "sometimes they have physical interpretations, sometimes they don't," it is in the context of math problems, not engineering problems, since engineering problems almost always have physical interpretations. Engineering students may not *mobilize* their math knowledge in their engineering coursework because they may feel that the abstract knowledge from their math courses does not apply to the physical situations of engineering.

The students in the first focus group also discussed how applications were often missing from their math classes. Dean and Travis describe how their math classes left them wanting for results with a physical meaning:

> *Dean:* I love it when you ask the professors, "oh, well what does this do?" and they're like, "oh, lots of things," and you're like, "well okay, what kinds of things?" and they're like, "well it has applications in radio transmissions, and computer thingamajigs, and-" while you're just like, [makes dumbfounded face, draws a rainbow over his head with his hand], "okay. What do you mean?"
>
> *Travis:* As engineers, we like to see results, we like to see like "the pressure should be this" or whatever, not happy with just getting a number at the end of it.
>
> ~ Focus Group 1

Dean starts by describing what happens when he asks professors to explain what a certain math concept does or why it is useful for the students to learn it as engineers. He fills in the response of the professor as saying, "oh, lots of things," and when pressed for applications they cite general "radio transmissions and computer thingamajigs," quickly progressing over Dean's head, as he indicates with his hand motion. Upon asking for an application, even when professors respond it does not seem to help Dean understand, as he then asks, "What do you mean?" upon needing further clarification to understand their response. Travis expands on Dean's anecdote, identifying himself as an engineer and explaining "as engineers, we like to see results" beyond "just getting a number at the end" of a problem. Travis wants more physical context, giving the example of "the pressure should be this" as a sample result instead of a purely numerical response. That engineering students want applications and more than just numbers is in line with the rest of their engineering coursework, but not with the math sequence. Perhaps it is difficult for the students to *mobilize* their mathematical knowledge when they do not know where it is relevant to their work as engineers.

Even in Diff Eq, which is considered a very applied subject as differential equations are literally used to describe and model physical phenomena, there frequently exists a disassociation from applications when teaching the pure mathematical content. For instance:

> Dr. Lewis erases the middle section of the board, and begins writing, "For convenience…" and rewrites the original equation.
>
> Simon asks, "Do you have to worry about units at all? It's kind of a weird question but that G/L is going to give you just weird units…"
>
> Dr. Lewis replies, "I wasn't worrying about units. Should you worry about units, in a real physical situation, absolutely. But I was just treating this as a differential equation and not worrying about units."
>
> ~ Fieldnote Excerpt, Diff Eq small section, Dr. Lewis Week 15 Monday

While some engineering courses are very particular about having students always keep track of units as a means of telling if an answer or process makes physical sense, when Simon tries to keep track of units in Diff Eq he gets told by Dr. Lewis that in this lecture example it's okay to not worry about units. Dr. Lewis tells Simon "in a real physical situation" you should "worry about units," "absolutely," but the math class is not a "real physical situation," nor is the example problem on the board, and so it is fine that Dr. Lewis is "not worrying about units." This reinforces the precedent that these math classes do not need to talk about "real" situations; instead they can talk about abstract math situations in which units of measure do not apply. Dr. Lewis is "just treating this as a differential equation," modeling for the students that "differential equations" do not need units or physical significance. Again, there is a divide evident between the content of the math class and reality, between the differential equations and engineering applications. Students have difficulty *mobilizing* across this divide as their math classes and engineering classes are separate and the connections are not often acknowledged during lecture periods.

The disconnect between math and engineering is also apparent in the different notation conventions of the two subjects. Roger the TA explains during his recitation why engineers prefer using one type of notation and mathematicians a different type:

> Roger begins working out the problem and a student interrupts him, asking "I'm confused about what the final product looks like." The student is confused about *ijk* vs. bracket format for notating vectors.
>
> Roger explains that the *ijk* format is fine, "engineers generally like it because they mostly work in three dimensions, but mathematicians like to write in bracket form because it's easier to expand it into 10 dimensions… if you wanted to write it *ijk* we'd have to add 7 more letters…"
>
> ~ Fieldnote Excerpt, Calc 3 recitation, Roger the TA Week 2 Thursday

A student is caught in the divide between engineering and math, between notating vectors with *i, j,* and *k* to designate three orthogonal directions or notating them without the letters, simply enclosed by brackets and separated by commas as typically done in math. Roger explains since engineers "mostly work in three dimensions," and mathematicians "expand" "into 10 dimensions," they have different preferences on how to notate the dimensions. For the mathematicians to write vectors the same way engineers do, they'd "have to add 7 more letters" which would unnecessarily complicate their writing. Consequently, mathematicians use their own notation, distinct from the engineers.

While this may confuse students who need to learn two separate notation conventions for engineering versus math, it demonstrates that the differences in the worlds of math and engineering are significant. Students are taught the unique conventions for each world and learn to keep them separate in order to earn full credit on their answers. There is no incentive for students to *mobilize* their knowledge across the disciplinary divide, so they keep them separate.

5.2.8.4 One Student who can Mobilize the Math Content: Ethan

One counterexample to this divide between math and engineering, between abstract and applied knowledge, is Ethan, our interviewee who is planning to dual major in engineering physics and applied math. In our interviews, Ethan describes his excitement and enjoyment of math, as now in Calc 3 he feels that his knowledge is "getting to the point where [he] can really just jump into any situation, in the real world, and start to apply the math there, and that's really exciting" (Interview 1). Ethan is our only student interviewee who radiates excitement on the topic of math and finds it powerful in the same vein that Dr. Hayes and Dr. Lewis, his instructors, have demonstrated. He describes how Calc 3 has given him tools that can be applied to real situations, and cites the three Calc 3 projects as examples of real-world situations that he can "use math on" (Interview 1). Interestingly enough, Ethan does not see himself as an engineer but is enrolled in the College of Engineering and Applied Science because he "knew that, [he] would be bored in Arts and Sciences just because it's not as challenging" (Interview 1). As he grew up nearby, Ethan is well aware of the perceived difference in challenge between the pure sciences and math and the applied sciences, choosing the latter in the belief that it's more "challenging." Throughout our class observations, Ethan's enthusiasm for math is unparalleled. He participates in every class discussion willingly and as demonstrated in our interviews he possesses a true passion in learning math. Yet, Ethan is the only one of our student interviewees who exhibits this excitement about math, and he is the only one who is looking forward to *mobilizing* or using his math skills on new situations.

While Ethan is excited about *mobilizing* his math knowledge from Calc 3 and Diff Eq in his subsequent coursework, the other students we interviewed and talked with mostly felt that their math knowledge was *immobile*, that it did not directly apply to their engineering coursework. The lack of application in most math lectures makes it difficult for students to see how their math knowledge can be *mobilized* in engineering contexts, as math is often presented abstractly with no physical meaning, units, or significance. The language of math including special symbols and notation is different than the language of engineering and it is difficult for students to translate between the two and *mobilize* across the divide. While the purpose of the math classes is theoretically to instill mathematical knowledge in students, students easily forget this knowledge or feel that it is not transferrable to their engineering coursework. Instead, the most significant *mobile* artifact students end up with after their math courses is their final letter grade, which designates if students got through the course successfully or need to retake it.

5.2.8.5 Relationships on the Move, Network Growth and Contraction

Looking at the margins of *mobilization* we find that relationships are another form of student *mobilization* that are a bit different for everyone, yet enable information to be transmitted over distances and for the actor-networks of sophomore math to be extended over time and space. The relationships forged during the activity of sophomore math classes can persist through undergraduate and even beyond. Many of our student interviewees reflected that the biggest thing they gained from their sophomore year experience was friendships with other engineering students. For instance, Eric describes how the friendships he's made have reassured him that he's in the right place:

> I mean, this semester was kind of like "wow, what the hell have I gotten myself into," but at the same time I've met a lot of kids here and I've made a lot of friends and they're really similar to myself, and I see the same things I struggle with in them,

> like what am I doing, is this really what I want to do, there's way too much homework, I'm so stressed out. I was worried that that was just me, but seeing that in everyone else has kind of reassured me that I may be in the right place, and it's not just about me, and like I should not be so self-centered.
>
> ~ Eric (student), Interview 1

Eric describes that his first semester after transferring into engineering from a nearby community college made him initially question "what the hell have I gotten myself into," but upon making "a lot of friends" that are "really similar to [himself]," he felt reassured. Seeing that his peers and friends "struggle with" "the same things" that he does has made Eric feel less like he's the only one, that it's not "just [him]." His friends made him realize that he's not the only one who worries about if they're doing the right thing, if "this is really what I want to do," since "there's so much homework" and "I'm so stressed out." Companionship and shared experience "reassured" Eric, allowing him to consider that he "may be in the right place." Making friends also helped Eric have a bigger perspective, realizing "it's not just about me," and that he "should not be so self-centered." In connecting with other students, Eric has expanded his network of friends and gained confidence in his current position. The relationships he's developed with his peers keep him from being isolated and are comforting in times of stress. These relationships will likely be *mobilized* past the sophomore year, as some will continue to grow while others subside. Without these relationships, Eric would have a more difficult time convincing himself to persist in engineering.

In addition to the friendships of students, student relationships with professors and TAs are also impactful on their engineering experiences and extend the reach of student personal networks and institutional actor-networks. For instance, Elizabeth describes how the support of the faculty have enabled her to survive through a very challenging semester:

> This stuff is pretty cool, but it's pretty hard. So whether or not I am just here via a fluke and if I should actually be studying this, and if what I'm doing, I don't know if it's right. But now that I have so many people in the program that want me here, like the professors, I have a whole group of them that are actively making sure I'm passing my courses and want me to be in the program, it's hugely beneficial. And, kind of helping me to see it as more than a fluke.
>
> ~ Elizabeth (student), Interview 1

Elizabeth describes her support network as “a whole group of” “professors” “that are actively making sure I’m passing my courses.” Moreover, Elizabeth knows that this group of professors “want [her] to be in the program,” which is “hugely beneficial” in helping her persist through engineering. In our interviews Elizabeth describes feeling that it’s “a fluke” that she’s in engineering, causing her to constantly question if “what I’m doing” is “right.” She feels very uncertain about if she “should actually be studying” engineering, so the relationships with the faculty who support her are crucial to her continued efforts to remain in the program. She admits that the support of the “whole group of them” is “kind of helping [her] to see it as more than a fluke,” helping her recognize that she is as much of an engineer as any of her peers in the program. The influence of her relationships with faculty is far-reaching, as it motivates Elizabeth and makes her feel valuable since “so many people in the program want [her] here.” The personal interest shown by faculty in Elizabeth is a major factor in her choice to continue studying engineering. These relationships extend through time past the end of the semester, and through space as well as Elizabeth describes a faculty member who has recommended her for a local internship. The connections Elizabeth has with these caring faculty members thus help her *mobility* through the engineering curriculum and beyond.

Though these human-to-human relationships are not captured in the focus on actor-networks of sophomore math, they undoubtedly influence student attitudes and feelings of belonging in engineering. These relationships help students *mobilize* over long distances in time and space, through the four years of undergraduate and across the world to other engineering institutions and workplaces. Online social networks offer a virtual means of building relationships, and are used by many contemporary students to connect to their friends and peers. For instance, a cohort of Aerospace engineering undergraduates created a Facebook group entitled "Class of 20XX Aero" that all students in the major who planned on graduating in 20XX could join if they wanted to. Elizabeth describes this online group as "how we got to know each other, when the group started we were all kind of new to Aerospace as a class, so it was just good to get everyone in one place where you were commenting and sharing, and it was all in one confined area" (Interview 2). Students who chose to join the group were choosing to identify themselves by their major and their graduation year, allying themselves with their classmates who chose the same, pronouncing to Facebook friends that they were members of the Aero Class of 20XX. Elizabeth found value in the group, as it was "how we got to know each other" "all in one confined area" where you could comment and share. This Facebook group allows students to *mobilize* even when they are not in the same location, as they can ask questions and share jokes easily online.

Some students, including our interviewee Aurora, chose not to ally themselves with their peers on the Facebook group, and as a result missed out on the community building that Elizabeth describes. Aurora explains:

> *Aurora:* I heard about that [Aerospace Facebook group]. But I was never invited. And I was sad. Because apparently, I heard them talking about it and they were helping people through it, and I was like, "Why wasn't I in there?" But yeah.
>
> *Interviewer:* But you never looked for it or anything?

Aurora: I think I might have once, but I felt awkward, just like, asking to join.

~Aurora (student), Interview 2

Aurora "felt awkward" "asking to join" so she remained on the outside of the Aerospace Facebook group, not included in the jokes or community building experiences that Elizabeth mentioned. Aurora "was sad" that she "was never invited," especially as she heard that her peers "were helping people through" the Facebook group, and she realized she was missing out. She asks rhetorically "Why wasn't I in there?" but answers it herself, as she did not want to ask to join. The Facebook group exists outside of time or space, as it is accessible online 24/7 to those who are in the group. Yet Aurora has no access into the group, she is excluded entirely, and she misses the chance to socialize and develop relationships and friendships with the other people in her major. After the first semester in which the Facebook group was initiated, Aurora ends up leaving Aerospace engineering for a different engineering major, perhaps because she didn't have anyone who wanted to keep her there. By not joining the group, Aurora never self-identifies as a member of the Aerospace class and chooses to *mobilize* elsewhere.

The relationships students develop as they traverse the actor-networks of engineering sophomore year can continue well beyond their schooling, even as they graduate and move away. *Mobilization* in these terms refers to the reach of these relationships through time and space, including virtual spaces like Facebook and other social networks that coordinate student action and interactions. These relationships can play a large part in the student's feelings of belonging and identification with engineering, and thus affect how students themselves are *mobilized* during their undergraduate careers.

5.2.8.6 Study Skills and Time Management

We examine one more unofficial outcome that arises from participation in the actor-networks of sophomore math and is *mobilized* along with students even after they complete these courses: their work ethic and study habits. Many students described learning better time management and planning skills as a result of the time-compression they experienced in the math classes of sophomore year (described in *interessement*). For instance, in describing what was learned this semester that will be helpful going forward Eric replies, “maybe not with like coursework, but I kind of feel like I learned a little bit more how to force myself to study. Like I got a little bit better at that, if that counts. Actually I got a lot better at that. I think I can study now” (Interview 2). The skills that Eric is describing are not explicit learning objectives of the sophomore year math classes, but they are a useful byproduct of the student experience. Eric explains, “I learned a little bit more how to force myself to study,” adding that he “got a lot better at that,” and actually believes that he “can study now.” Learning how to study and how to “force” yourself to study is an important skill for engineering students that will hopefully benefit Eric in his future classes. A self-described slacker, Eric did not possess the ability to make himself study before going through these math classes, it is a skill gain that is not captured on official grading rubrics. This skill is *mobilized* with Eric. As he moves to his next course, hopefully his experience and motivation will follow.

Aurora describes a similar experience as Eric, as she has learned the importance of “Good study skills and like, having a schedule planned out so you can make sure you get everything done in time. Knowing when something isn't right for you, like certain classes” (Interview 2). These skills are all important for success in engineering, as study skills and time management to “make sure you get everything done in time” are crucial for achieving high grades. Aurora also points out the importance of “knowing when something isn’t right for you,” in specific reference to dropping “certain classes” during the semester when she realized she was no longer interested in the major pathway that they led to. These skills are necessary to survive in engineering, as poor study skills typically accompany poor test performance, and poor time management typically causes late submission of assignments, resulting in docked points. Students who do not keep track of test dates or deadlines will suffer in grades and in experience, so learning to "have a schedule planned out" is important for persistence and success in engineering. Aurora also sounds like she knows herself better after experiencing ups and downs in her sophomore year, as she has learned how to distinguish when something isn't right for her. These skills travel with Aurora as she moves onto her junior year, *mobilized* and important even if they don't show up on any of her official records.

Viewing *mobilization* through an after-ANT lens uncovers a variety of unofficial skills, attitudes, and relationships that are not captured by the artifacts of grades and GPAs. While the math courses are meant to teach students mathematical content and give them practice solving mathematical problems, most students feel that they forget the content once they're done with the class. The math content is not *mobilized* for student use in their subsequent engineering classes, perhaps because the traditions and conventions of math seem so different than those of engineering. Most students have difficulty *mobilizing* the skills and content they learn in Calc 3 and Diff Eq because these classes feature problems that are highly abstract, with no units or physical interpretation, making it difficult to solve related but applied problems in engineering. Yet, instead of *mobilizing* content, students take with them relationships and survival skills that enable them to persist in engineering majors. Friendships with other students in engineering help students feel like they are not alone, that they have support and company throughout the challenges of the undergraduate engineering curriculum. Relationships with professors and TAs help students know that they are valued in their undergraduate degree programs, and that people actually care about their progress and life experiences. Social networks that exist on online programs like Facebook can also provide students with webs of support in the form of major-specific cohort groups or just virtual friendships, allowing another format for relationships that makes students feel included instead of isolated in engineering. Finally, students must learn time management and study skills during their sophomore year if they are to survive the rest of their engineering courses. These skills and relationships are intangible and not formally assessed, yet they assist students in moving and *mobilizing* throughout the actor-network of engineering.

5.2.9 Translation

After mapping out the *four moments of translation* in the actor-networks of sophomore math, we can take a holistic look at the overall process of *translation*. Recall that ***translation* is the process wherein a human or nonhuman entity becomes selected, enticed, persuaded and partially or fully changed in ways that mobilize it to join the movements of an actor-network** (Fenwick, 2011). By identifying what is left out or on the margins of each *moment of translation*, we also get a sense for the things that are translated unofficially, partially, or not at all.

5.2.9.1 Translating Sophomores to Juniors

Students who successfully navigate the sophomore math courses are literally translated from sophomores to juniors. In *problematization*, we identified how the class standing of students is dependent on their quantity of completed credit hours and more informally, the number of semesters attended. Students' class standing decides their registration order, and ultimately the courses they choose to take and the professors and TAs who end up teaching them. In order for sophomores to become juniors the students must pass through the *obligatory passage points* that are the required math courses Calc 3 and Diff Eq. These courses have their own identities, propagated through time by the stories of upperclassmen and course instructors. Students encounter these course identities on the first day of class, as the course instructors introduce themselves and their interpretations of the course. Instructors distribute the syllabus, a representational artifact that organizes class tasks and class scheduling and describes homework assignments, projects, and exam dates. On the first day of class students are introduced to official course policies regarding academic honesty, or cheating, and are also warned about historical trends in the class based on the past performances of students on exams. Thus students and course elements are *problematized*, defined in advance, as the requirements for class completion are stated on the first day.

As the semester wears on, students begin to submit required assignments including homework and projects, and attend lecture in the interests of fulfilling their student duties and getting their money's worth in their education. In lectures, professors try to engage students in the content, modeling their own enthusiasm about math that can be contagious for the students in the room. Professors also model the ability to focus on math during lectures, as few external distractions are acknowledged during class meetings and the flow of the class as defined on the first day is rarely disrupted. The requirements of class become all-consuming for students, as the homework and projects begin to dominate student time, leaving little time or energy left for alternate pursuits. In this way the math classes *interesse* students, as their unceasing demands pull students closer and closer to math tasks and farther away from the rest of their lives. Students are pressured to do well on these assignments in the name of learning and potential contribution to their final grade, though some resent the isolation that results from their *interessement* into math.

Student *interessement* in math is confirmed through the process of exams. While projects and homework serve as introductions and evidence of student practice in applying math concepts, exams are the primary method of assessing whether or not *interessement* is successful, and determine if a student will be *enrolled* fully or partially in the actor-networks of sophomore math. Exams are bounded in space and time, and tightly controlled environments in which students must demonstrate a certain level of content mastery in order to pass. The activity surrounding exams is extensive, as out-of-class review sessions, in-class lectures, and post-exam recitations all contribute to students' understanding of the exam process and assist the *enrollment* process. Passing or not passing on the exams is determined by the overall distribution of student scores, as each student is a data point of the distribution that is either above or below the threshold cut-off chosen by the instructors. *Enrollment* is a competitive process as student performance relative to their peers determines their success in the course.

When the semester ends after sixteen weeks, students are assigned a letter grade. This letter grade, inscribed onto an official transcript, is a highly mobile artifact that encapsulates an entire semester's worth of experience in the course. The letter grade itself has been translated from the final numerical score a student earned in the class, which in turn is dependent on their exam performance and potentially also their homework and project scores. The letter grade is also translated into quality points, which contribute to a student's semester and cumulative GPA. The different forms of the final grade are *mobilized* across different institutional platforms, as the letter grade determines if students satisfy their major-specific prerequisite requirements and the GPA decides if students are in good academic standing and can continue their coursework. The grades thus control student *mobility* through the engineering curriculum as well.

The process wherein students are translated from sophomores to juniors relies on a chain of translation largely pertaining to grades earned in the required math courses. The syllabus organizes and defines how individual course components contribute to the final grade, as homework and project grades are only included if student exam grades are above the cut-off threshold. Student exam performances are compared to this instructor-determined cut-off line, and can then be translated into final numerical grades, which are translated into letter grades and then quality points contributing to their GPA. If all of these translations are above institutional and major-specific requirements for both Calc 3 and Diff Eq, the sophomore student can become a junior. If any of these translations are below the requirements, students must re-take the courses and will be behind the rest of their cohort. "Translation is a process before it is a result" said Callon, as demonstrated in the many incremental translations that student grades undergo throughout their math classes that eventually result in the status of a junior instead of a sophomore (1986a, p. 81).

5.2.9.2 Stabilizing Durable Actor-Networks Through Translation

Throughout the *four moments of translation* identified in the actor-networks of sophomore math, we see how reliance on historical precedent and tradition inform and stabilize current practice. For instance, the class standing categories of freshman, sophomore, junior, and senior are archaic divisions still useful in *problematizing* current students, assigning them a cohort, and letting them know if they are ahead or behind the rest of the population. These categories stabilize the student experience of engineering undergraduate, as there is a clear progression and identification at each step. As a similar categorization scheme is used in American high schools, so students already have personal experience with these class years and understand what is expected at each stage. Professors and TAs similarly understand students through these class year categories, as they also represent milestones along the developmental pathways of undergraduate engineers. The class years structure expectations and understanding for students and instructors, and thus stabilize the overall actor-network of undergraduate education as well as the actor-networks of sophomore math.

Similarly, the longstanding tradition of lecture as gospel with instructors lecturing at the front of the tiered room with chalk and a chalkboard remains the dominant mode of instruction. Students are encouraged to attend these lectures, listen to the instructors, and mirror the chalk markings in their own notebooks. This cycle of instructors writing on the board and students copying down the representations repeats during every lecture class, repeats over the course of a semester, and repeats over the course of years and decades. Instructors including Dr. Lewis describe doing the same thing over and over again in the first section of our findings, as the content has not changed and neither has the lecture model's prominence in teaching these classes. New technologies have been added in incrementally, in the forms of online homework and software-based projects, but the dominant focus of the classes remains on the chalkboard and in the form of written work. The lecture is still the primary *interessement* device to engage students in mathematical content, and homework and projects are still the primary means for students to demonstrate their *interessement* in the material and in succeeding in the class. Thus, the durability of the lecture format and written work persists, unchallenged by technological advancements, stabilizing the actor-networks of sophomore math.

Exams are another example of old technology that remains prominent today in determining student *enrollment* into actor-networks of sophomore math. As explained by Dr. Lewis, the scheduling of exams was determined long ago due to resource constraints and cannot be changed or shifted without significant re-negotiation between the departments of Applied Math, Math, Physics, Chemistry, and Biology. Consequently the exams are constant from semester to semester and year-to-year, they are durable events on the calendar that stabilize the flow of content and activity for students, professors, and TAs in the course. Furthermore, since the content of the classes has not changed and the exam dates and formats have also been immutable, the past exams are still relevant for current students. The online exam archive features tests from the last five years as well as their solutions. Students are advised to study by taking practice tests and practice problems from the exam archive to inform their expectations of the difficulty and length of Calc 3 and Diff Eq exams. The reliance on the exam archive demonstrates the dependence on the past to inform the present, as instructors write new exams that are similar in length and challenge to prior exams, and students rate exams as fair or unfair depending on their perception of past exams as well. The durability of exams thus stabilizes the activity surrounding exams and *enrollment* into these courses.

Stability is also evident in the overlapping assessment systems of letter grades and GPAs. These grading schemes are incredibly durable, having existed for many decades, and are taken-for-granted as the determinants of student *mobilization* through the undergraduate engineering curriculum. Students, instructors, and TAs understand the processes wherein numerical grades become transformed into letter grades and GPAs, and they also understand the consequences that are associated with grades above or below various thresholds for departmental and institutional requirements. Without this system it would be difficult for students or institutions to assess their status in a course or their progress in a major, with this durable system students understand where they are in their degree progression and if their grades are satisfactory or unsatisfactory. Institutional systems of recognition and access are based on these grading schemes; they are built-in to the engineering curriculum and overall system of higher education. The durability and omnipresence of these grading schemes thus stabilize the actor-networks of sophomore math through controlling student *mobility* through their undergraduate careers.

In traversing the durable systems of the actor-networks of sophomore math like class year categorization, lectures, exams, and grades, students become *translated* into builders and maintainers of the actor-network as the cost of their participation. The official process of getting through the sophomore year math courses involves understanding the nuances of each part of the system and each part of the actor-network, enough to play the part of a student. As students finish the courses of Calc 3 and Diff Eq, they become upperclassmen that tell younger students about their experiences in these courses, about professors they enjoyed, test averages that were low, projects that were difficult. The upperclassmen characterize the courses and pass on their characterizations to younger students, so the younger students can enter the courses aware of their reputations and what to expect. This is an ongoing, durable cycle that thus helps to stabilize the network.

5.2.9.3 Unofficial and Intangible Translations

In attuning to the activity on the periphery of each *moment of translation,* we have also identified translations that occur unofficially and intangibly. For instance, cheating is defined and *problematized* on the first day of class as directly copying from solutions manuals, a seemingly straightforward definition. However, as students progress through the devices of *interessement,* they develop coping skills to help them combat the time-intense demands of homework assignments and projects, employing unauthorized resources like solutions manuals and online solution services to find answers and get help. Though they may satisfy the original definition of cheating, these students feel their actions are justified, as they see no alternatives to illicit use of these unofficial resources. If instructors or TAs do not catch the students, the cheating is not recorded or identified in any permanent way, though student's understanding of the material and performance on exams may be compromised.

Officially, exams are the ultimate determinant of student success in the sophomore level math classes. Exams are standardized assessments, the same for every student, which can cause suffering on an individual basis for students who do not meet the standards. The complaints of students are not registered officially, their perceptions of the painful testing process only appears anecdotally and is not sufficient to cause any change in the durable network of exams and course grades. Although exams are the official means for students to demonstrate their knowledge and understanding of mathematics, students often comment that they forget everything they learned as soon as the final exam and semester are over. While student scores on exams determine their final course grades, they may not be indicative of how much content students actually retain or can *mobilize* and apply to their subsequent engineering coursework. Similarly, though official course grades are the only institutionally recognized representations of student achievement after the course ends, students also develop a variety of survival skills and relationships with peers and instructors that are valuable to their growth and remain past the conclusion of a semester. These skills and relationships are *mobilized* along with the official course grades and transcripts, and are indicative of unofficial and intangible student translations.

Chapter 6 – Discussion

From the Interlude through the Findings, we have covered a great deal of ground in terms of mapping out the actor-networks of sophomore mathematics. In this chapter we discuss our findings in the context of our research questions, history, and translation, then proceed to make recommendations and conclusions in the following chapter. Our discussion aims to integrate concepts and findings from the overall study, and cohesively present a response to the question of "so what?" for both research questions and engineering education.

6.1 Understanding Through Actor-Network Theory – Research Question 1

Recall our first research question, which asks: How are students *problematized, interessed, enrolled, mobilized, and translated* in the actor-networks of engineering sophomore year and to what consequence? While stepping through each of the four *moments of translation*, we have seen that students encounter durable structures and traditions throughout their interactions with the courses of Calc 3 and Diff Eq. We explain the consequences of this durability through curricular artifacts including lectures, recitations, projects, and more, connecting to *problematization, interessement, enrollment,* and *mobilization* as we go.

Durability has emerged as a consistent theme throughout our Findings and throughout the local and national history uncovered in the Interlude. Large lectures with smaller recitations have been the dominant model of instruction since the mid-1960s, while exams have served as the primary means of assessing student knowledge for even longer. Letter grades and GPAs are also durable artifacts that have been in place for many decades, restricting student progress through engineering and other degree programs. What are the consequences of these durable class structures on modern students, TAs, and instructors?

Recall that recitations were originally added to the math curriculum after a brief trial period from fall 1962 to spring 1963 determined that the large lecture, smaller recitation format did not cause a statistically significant adverse effect on student exam performance. Expanding the size of lecture sections and replacing a lecture class with a recitation each week allowed faculty to have lighter teaching loads and more time for research, while giving opportunities for graduate students to teach, be paid, and do research. Necessary for CU's growth as a research institution in the mid-1960s, recitations have persisted until the present day, still administered by graduate teaching assistants who are compensated for their teaching services, to enable their simultaneous research efforts. As the math courses have grown in size considerably over the last fifty years, and even more rapidly over the last five, the lecture-recitation model has been scaled up to giant proportions. Calc 3 in the fall of 2015 will have six unique lecture sections and twenty-seven individual recitation sections, a considerable logistical challenge requiring formidable human and physical resources to implement. The students who were in the experimental recitation sections from fall 1962 to spring 1963 have enabled countless recitations and innumerable funding opportunities for graduate student researchers in the years since, just by scoring comparable to their peers on exams. We have taken the results from those experimental recitations as representative and accurate for over fifty years, with no regard for how the college's growth and new technologies may have changed the dynamics of learning in lecture and recitation. Yet with so many resources invested in this instructional model, and so much supporting infrastructure in place keeping lectures and recitations durable, it seems impossible to change now, even if we feel that the historical data is not representative or applicable to our current students.

6.1.1 Problematization and Interessement Through Durable Lectures

Lectures are still the cornerstone of the sophomore year math classes, where mathematical content is presented by instructors through their words and through their writing on a chalkboard. Classes are defined or *problematized* through the standard format of these lecture events, meeting three times a week and focused on delivering mathematical content from the professor to the students. Since the lectures are the official time for *interesting* or *interessing* students in the content of the math classes, they are traditionally vital to the administration of these math courses, and are an immensely durable structural artifact.

Occasionally, during lectures the professors will digress from content delivery to discuss class logistics including suggestions for exam preparation, clarifications on homework due dates, and reminders about project assignments. Students are encouraged to attend lecture but it is not required, and as semesters progress attendance usually dwindles, with periodic upticks in attendance during the class meetings before exams and the final. With the exception of the special honors sections, which are held in smaller classrooms with capacity around 40 students, lectures are held in the tiered lecture halls that hold well over 100 students. The largest of the four lecture halls in the Engineering Center has a capacity of 152 students and is the one shown in the side-by-side photo comparison of the lecture hall in 1965 and 2015 (Figure 29). In the last fifty years, this lecture hall has seen the addition of a digital projector and tighter seating to accommodate more students. This lecture hall is frequently scheduled for engineering math courses, particularly for Calc 3 in the fall. Being one of the 152 students present in the lecture hall is a somewhat awkward and uncomfortable anonymizing experience, as the room is crowded, personal space is scarce, and the air and seats stay warm throughout the semester thanks to all of the body heat. This is the environment in which our students are supposed to focus on mathematics and the activity happening in the front of the room, on the board. In the ten minute passing periods between the end of one lecture and the start of the next, hundreds of students cross paths as some are exiting the room while others enter; the stairs become a bottleneck, and the hallways impassable.

Dr. Hayes described how in the time before the Internet, course websites, and e-mail that the classroom was "gospel" and students treated it as such since it was the only opportunity for communication and information, the only authorized venue for *interessement* in the course. Now, with the increase in official communication channels and the simultaneous explosion of mobile technologies, students in the lecture hall can access a multitude of different resources aside from the chalkboard and professor without even getting out of their seats. During our course observations it was not uncommon to see students staring at their phones or laptops periodically through the lecture, some surreptitiously checking for text messages or emails, others brazenly scrolling through Facebook, playing video games through the entire period, checking their e-mail, reading the news, etc. Though instructors like Dr. Hayes discouraged the use of phones during class and occasionally would embarrass students who were on their phones to make an example out of them, the majority of phone and laptop use went without comment. In interviews with students, many explained that when they were bored they would seek entertainment and distraction on their phones, both in everyday life and in class.

For some of the Diff Eq courses in particular, students including Nate and Eric felt that the instructor lectured by writing the textbook examples on the chalkboard and following the book exactly, so they felt justified in skipping lectures or not paying attention because they could always read the book. Eric explained that he would search for new music during Diff Eq, as he was frequently observed during lecture with headphones on in one or even both ears, clearly not paying attention to the instructor's activity at the chalkboard. Students like Nate and Eric were visibly unafraid of missing any of the "gospel" in lecture, as they relied on other sources including video tutorials, Chegg.com, and solution manuals to get through the homework, and a lot of cramming to get through the tests (though Nate did not pass Calc 3, he was excited to retake it over the summer with more time to focus on the course). Instead of effectively *interessing* these students, the lectures caused these easily bored students to develop *interessement* strategies outside of the gospel of the lecture hall, occurring in places and at times far beyond of the boundaries of the standard class meetings.

While the format and content of the lectures have not changed, their success in interesting or *interessing* students may have. Students who are not engaged by the lecture instructor or the content can easily decide to instead engage in alternate material of their own choosing, from social networks to news sites to sports videos, that are available wherever and whenever they want. How can a traditional lecture compare with full color multimedia displays on smartphones or laptops? Considering the rapid pace of technological development and that the current students are already considered the “wired generation” and referred to as “digital natives,” the future of the traditional lecture looks bleak (Adler, 2013).

Looking back, recall the original 1961 description of the intended use of the lecture halls, which reads: “For faculty meetings, large lecture-demonstration sections, student technical meetings, and professional conferences” (see Figure 18). Faculty meetings no longer take place in the lecture halls, since the faculty corps has grown significantly larger than can fit in one room. Though that was one of the original purposes for the lecture halls, there has been no catastrophe in letting that go. Perhaps the second item in the list, the “large lecture-demonstration sections” will be the next thing to cease and reorganize in accordance with the new size of the student body and availability of sophisticated technologies. While the traditional lecture has worked successfully in teaching math to engineers for decades, it is worth investigating the students who do not learn from lecture and considering what would work for them instead. Students who succeed in the traditional lecture model are the students who've always succeeded in this educational system, those with the demographics and high school preparation that our system is designed for.

Newer ideas and pedagogies including workgroups, projects, and the supporting lab course are interventions intended to support student learning, perhaps in part to address the durable reliance on the lecture model and exams central to these courses. However, our analysis has demonstrated that these newer curricular artifacts are not fully integrated into the course definitions; they are not *problematized* at the level of lectures and exams. Appearing less prominent contributes to the interpretation of projects, workgroups, and optional lab courses as ornaments and decorations onto the central activities of these courses, confusing their purpose and effectiveness at *interessing* students. The optional supporting courses like the workgroups and lab class are on the periphery of the required elements of Calc 3 and Diff Eq, their position suggesting they are initiatives meant to address student deficiencies, consistent with the deficit paradigm (see Section 3.1.2.1 and 3.1.2.4 for more discussion on the deficit paradigm). Intended to remediate student deficits in programming experience and practice with problems, these optional courses place students on the margins of the course activities, requiring additional training to make up for deficits and reinforcing the durable hierarchies of the class instead of disrupting them. The positioning of these novel pedagogies on the outskirts of the official class activities needs to be rethought if we wish to retain a broader spectrum of students than have been traditionally successful in engineering.

6.1.2 Interessement via Projects

Recall that three projects per semester are required in both Calc 3 and Diff Eq, and students can work in groups of up to three students in order to complete each one. Projects are largely governed by graduate student TAs who grade the projects and support the lab classes, and are a complex site of *interessement* into the actor-networks of sophomore math. Called a "decoration" on the course by Dr. Hayes, these projects command significant resources, time, and energy as TAs must develop the project assignments, support them in the lab classes and office hours, and grade the project reports as well. The objectives of the projects are to give the students a taste of a bigger math problem and to experience a real-world application of the mathematical concepts they're learning in the class. Students are encouraged to work in teams and divide the tasks, as not all students are required to learn how to program, nor are all students required to write the project report. We identified in the findings sections how students like Aurora end up working alone on the projects and how teamwork or the lack thereof does not matter to the project grade. We also identified how the projects are graded partially on the writing of the report, and partially on the accuracy of the answers at every step. Though based on real-world applications, the projects are closed-ended and prescribed, as students must replicate the predetermined right answers to earn full credit.

The projects are actually the most recent addition to the courses of Calc 3 and Diff Eq, despite being initiated over fifteen years ago, in an effort to offer undergraduate engineering students more project work in their required courses. While a good idea, it appears that the projects have never been fully integrated into the curriculum of the courses, seeming more like an expensive afterthought, costing both time and resources. Dr. Hayes has mentioned the possibility of adjusting the number of projects from three per semester down to two, and other significant revisions to projects may be necessary as resources continue to become scarce. As teamwork and time management skills were cited by students as major learning outcomes from the projects, perhaps the grading could be adjusted to include a peer feedback component or some other acknowledgement of the collaborative work. Considering projects as a relatively recent addition to the curriculum along with the supporting lab course and workgroup, we question if projects are disrupting the status quo in who passes these math classes or if they disproportionately cause difficulty for nontraditional and vulnerable student populations.

6.1.3 Enrollment and Mobilization as Determined Through TAs and Recitations

Since their adoption after the 1962-1963 academic year, recitation sections have met one day a week during the semester, taught by a graduate student teaching assistant in exchange for a stipend, with class sizes of 20-30 students. The syllabi for Calc 3 and Diff Eq describe that the purpose of recitation is partly to help with the homework and, more importantly, to further clarify the concepts of the course (see Appendix F). While this is the official and historical motivation for dividing the large lecture sections into smaller groups, these descriptions ignore the human and social consequences of learning in a class of 30 instead of 150. The graduate students who preside over these recitation sections take a one-semester seminar course on teaching and learning within the engineering math department during their first semester as TAs. This training course emphasizes being organized, particularly on the chalkboard while demonstrating problem solving for students, being methodical in their problem-solving steps, and having sufficient command of the material to answer student questions confidently and accurately. The training course identifies and enforces the reputation that the engineering math TAs are responsible and punctual, showing up for every recitation and every office hour they are scheduled for, and grading homework assignments, projects, and exams on time. In addition to these fundamentals, many of the TAs are passionate teachers who enjoy interacting with students and supporting them through their course experience. Yet, that is not a requirement of the position as the first priority for TAs is to keep their boardwork organized and show up to all of the scheduled events.

Aside from conducting recitations and office hours, the logistical duties of TAs in Calc 3 and Diff Eq are defined well in advance, as the tasks are prescribed before the semester starts and the TAs sign up for them during the week before classes. As the courses are stable semester after semester, durable over the years, the course needs can be forecasted for the entire semester before it even begins, and almost never do any of the course needs or TA duties change mid-semester. The

These duties include: being responsible for maintaining the course website, serving as the course historian, coordinating the food for every exam grading party, coordinating the exam rooms, developing example problems for recitations, developing example problems for exam reviews, holding exam reviews, and writing up homework solutions. There are tangible outcomes for each of these duties, as they all involve the production of an artifact or the coordination of a bounded event in time and space. The durability of this system, planned well in advance, limits the spontaneity and improvisation possible in the recitation courses, though is necessary for executing courses on the scale of Calc 3 and Diff Eq. The need to standardize across so many students, TAs, lecture sections, recitation sections, and instructors, requires the system to be stable and clearly defined. Even in recitation where the official purpose of recitation is to clarify concepts and help with homework, the schedule and content march onwards, regardless of the level of student understanding or individual needs in the courses.

Recitations also provide the fundamental unit of organization for collecting and distributing back graded work in the math courses, as homework is turned in to the recitation instructors, who grade the homework, enter the grades in the course grade book system, and pass them back to students in the next recitation meeting. Students also identify their exams by their recitation section number so that their exams can be routed back to them in recitation the next day (in Calc 3, they are passed back in lecture for Diff Eq). The logistics of collecting over 500 exams, grading them all consistently on standardized rubrics, entering the grades, and getting them back to the appropriate students requires a systematic, almost mechanical approach, though the graders are most definitely human. The feasibility of the current system of grading the exams in the time immediately after students take them is in question as class sizes continue to grow. Sylvie, one of our TA interviewees, discussed how a hiccup in room scheduling caused the exams to start at 7:00pm rather than the traditional 5:00pm start time. As the exam grading party started at 9:00pm, they did not finish until the early hours of the morning, an untenable situation for the TAs and instructors involved. A perturbation of two hours in the exam start time was enough to significantly agitate the TAs, who are now considering organizing or formally complaining about the inhospitable grading hours. The engineering math courses have traditionally graded the exams within 24 hours of the students taking them to minimize the turnaround time and maximize the student learning derived from the exam process. Yet it is unclear if the rapid turnaround time truly benefits the students enough that it is worth keeping all of the TAs and instructors awake until the early morning. As class sizes continue to increase, the grading parties will take longer and longer to finish grading all of the exams, even with additional TAs to help out.

The original designers who experimented with recitation sections over fifty years ago could not have foreseen the variety of ways recitations organize the activities of the sophomore year math classes nor the magnitude of the work that TAs are responsible for that enables the system to keep going. Teaching the math classes without TAs would not be possible, as they grade the volumes of homework, projects, and tests submitted by students, organize the artifacts crucial for course administration, and staff office hours and recitation sections to support student learning. TAs have immense power since they determine the individual grades students will receive for every homework assignment, project, and exam in the course, cumulatively affecting students' grades and consequently their *enrollment* and *mobilization* as a result of the course. Yet despite the large amount of power the graduate TAs yield over the students, they are not trained or expected to address student attitudes, emotions, or fears upon receiving a bad test grade, not understanding a homework problem, or not having a team to work with on a project. While the formal TA training aligns with departmental expectations to communicate mathematics and have organized boardwork, it misses discussing the consequences to undergraduate students that stem from individual TA decisions or tendencies. TAs are critical mediators for undergraduate students in the actor-networks of sophomore math, as they determine whether or not students are *enrolled* via their performances on tests through the process of grading.

The current organization of these math courses places TAs silently at positions of gatekeeping and power, where the work of grading sorts students into different levels of achievement, *enrollment* into the actor-networks, and *mobilization* possible after the course. Going forward, the duties of TAs will continue to grow as the enrollment in their courses grows as well, meaning their responsibilities and power will also increase. Yet the TAs are already at their limit for workload, and further growth will push them past the edge. This system is unsustainable at the current rates of growth and the current spectrum of TA duties. The former is unlikely to change, so the latter may have to in the near future.

6.1.4 Mobilizing Content

The mathematical content of Calc 3 and Diff Eq remains immutable, despite the advances in technology and the changing landscape of engineering today. Our historical analysis indicates that the subject of Diff Eq was added to the undergraduate engineering curriculum by 1959, a change that was viewed as increasing the rigor and improving the engineering program overall (see Appendix H). The incorporation of Diff Eq in the engineering curriculum has been made durable over the intervening years, appearing in curricular flowcharts, serving as a prerequisite for subsequent engineering coursework, and marshaling necessary resources in instructors, TAs and rooms. Linear Algebra is lumped in with Diff Eq, as our instructors described in the first section of the findings, since both of the subjects are compressed together in order to fit within the credit restrictions of engineering. Looking forward, is there any ability for further specialization and change? Do all majors need Diff Eq, or can some take Diff Eq while others take Linear Algebra? Computer science majors do not need to take Calc 3 or Diff Eq in the undergraduate curriculum; instead they select courses from a slew of discrete mathematics courses to complete their math foundation requirement. This is fitting for their discipline, and while computer science is housed within the College of Engineering and Applied Science it is fine for them to deviate from the other majors' prerequisite requirements. Perhaps the computer science model of curricular customization and personal selection can be modified and adopted in some way for the engineering majors, in line with preparing students for contemporary engineering problems instead of continuing to follow a fifty-year old curricular tradition.

"Calculus is calculus, and we teach calculus," says Dr. Lewis, and while that may be true the rest of the world has changed around calculus, with increased sophistication in personal computing and online interfaces like Wolfram Alpha that can do the work of calculus for you. The increase in communication channels has re-organized the delivery medium for course information and homework assignments and has also impacted how students learn calculus, as durable as the subject is. Current students discuss the "art of googling" or watching YouTube videos from third-party sites like Khan Academy, finding these resources more accessible and convenient than actually paying attention during lecture. With the rise of Massive Open Online Courses, or MOOCs, future students may even be able to satisfy the prerequisite math requirements without taking the sequence specified by the engineering college.

The Grand Challenges for Engineering is a codified list from the National Academy of Engineering naming the global problems that are of distinct importance for engineers to solve in the near future (National Academy of Engineering, 2015). The list includes items like making solar energy economical, engineering better medicines, securing cyberspace, and advancing personalized learning, all broad tasks requiring a variety of cross-disciplinary approaches to accomplish. When the engineering curriculum as we know it was instituted in the Cold War era, the grand challenges for engineering were to put a man on the moon, beat the Soviets, and develop the transistor and transistor-based technologies. Clearly, while technology has advanced and the accompanying challenges for engineers to address have also advanced, our education system and content have remained largely static. To solve the broad-scale problems of today, we may need to let go of some of the narrow thinking and siloed traditions of our past. As one of the current grand challenges is about personalized learning, one place to start is within the engineering curricula themselves. How much longer can the math content remain immutable and standard across all engineering majors?

6.1.5 Mobilization, Retention & GPA

Some might say "if it's not broke, don't fix it," as many students are able to navigate the current implementation of the sophomore mathematics courses successfully and eventually graduate with engineering degrees. Yet, we posit that the durability of these math classes and actor-networks have the unintended consequence of keeping nontraditional populations out of engineering disciplines. There are many aspects of the system of higher education that are confusing and nonsensical, but have been made durable through institutional policies and habits. The GPA or grade point average is a good example of a powerful artifact that controls student progress through engineering degrees but makes no logical sense (see Table 7). As discussed in the findings, the GPA is the third in the string of grade representations that starts with the numerical grade a student earned in a class, which is transformed into a letter grade, which then becomes the quality points which contribute to the total semester GPA (see Figure 34). It makes no sense that a continuous number, the numerical grade, is translated into a discrete letter grade and then into a discrete number of quality points, and even more outrageous that the discrete quality points are averaged together to create a GPA that is calculated to the thousandth decimal place and thus appears continuous. This string of grade representations is not mathematically or statistically sound, yet we still use this system to determine the mobility of students through the undergraduate engineering curriculum.

The GPA is a durable and omnipresent artifact in education, as it starts in K-12, is important for college admission, matters for movement through the engineering curriculum, and is even a factor post-graduation as employers use GPA as one factor in screening recent graduates for jobs. In the College of Engineering, students must have a GPA of 2.25 if they wish to continue through the degree program in good academic standing. If their GPA is below 2.25, students go on academic suspension or academic probation, a serious consequence based on this unscientific and flawed calculation. The concept of the GPA cut-off has existed for over fifty years, though in 1960, the GPA cut-off for the College of Engineering was 2.00, a full 0.25 GPA points lower than the current (see Appendix G). In 1960, the "Scholastic Deficiency Committee" distributed a memo on the topic and requested all faculty read the notice in their classes, describing for students the 2.00 GPA minimum and the 2-semester suspension for any students below the requirement. Though our committee names have changed, the sentiment remains as the GPA cut-off line still identifies students who are scholastically deficient and students who are academically satisfactory.

For the uninitiated and newcomers, this system is overcomplicated and its nuances can be difficult to fully understand. There are cut-offs at every level of the grade calculation, as the numerical grade is important in determining pass or fail in Calc 3 and Diff Eq, the letter grade determines if the major-required prerequisite is satisfied or not, and the GPA controls student status and mobility in the undergraduate curriculum. The GPA is bound deeply to institutional systems and traditions including the current online registration system, Latin honors upon graduation, and class rankings. Furthermore, the GPA also determines consideration for entry-level positions in many industries and corporations, as it serves as an easy demarcation that recruiters and human resources personnel use to screen applicants. Thus, the GPA has been made durable through its prominence in multiple actor-networks at various levels, serving as a minimum requirement for *mobilization* into academic and professional networks. If we can't get rid of it, at least we can recognize its faults and encourage students to be cognizant of its power in determining their access to the next set of required courses of their undergraduate careers.

6.2 The Importance of Unofficial Narratives – Research Question 2

At each of the *four moments of translation,* our analysis also explicitly examined unofficial and peripheral activities distinct from central artifacts and officially sanctioned movements in the actor-networks of sophomore math. In line with after-ANT theorizing, turning our attention to the edges of the actor-networks has shown a much different picture of how students travel through the actor-networks under study and the challenges they face along the way. The contrast between the stories and networks of students who follow the official rules and the students who find their own way around the course policies illustrates one consequence of positioning in the actor-network. The contrast between central and peripheral actors has also helped answer our second research question: what can we learn about engineering sophomore year by stepping outside of the network metaphor, or by shifting the focus away from central actors towards those at the margins?

Our findings chapters illustrate the gulf separating the official expectations of work and learning in the course and the actual activities and beliefs of students navigating these courses. Throughout our analysis we have identified the prevalence of unofficial, unauthorized resources and coping strategies employed by students to get through the math classes of engineering sophomore year. We examine and discuss some takeaways and conclusions from the unofficial, marginal activities occurring throughout every *moment of translation.*

6.2.1 The Edges of Problematization, Interessement, & Enrollment: Homework

Cheating emerged as a prevalent activity happening on the edges and margins, away from the official activities at the centers of the actor-networks of sophomore math. Starting with *problematization,* where little time was spent during lecture detailing exactly what constitutes cheating on homework assignments; students were able to define cheating flexibly for themselves instead of rigidly adhering to the rules and standards. For example, on the graded homework assignments of both Calc 3 and Diff Eq, some students verbalized their sentiment that everyone cheats with a variety of justifications for their use of unauthorized resources. The students we interviewed discussed the time pressures and constraints of their semesters, and the ease of copying from a solutions manual or just picking the answers up from the Internet. Though they feel guilty and recognize that cheating on homework is not beneficial to their learning, the students also believe that they have no alternatives but to cheat, as they feel it is critical to turn in completed homework assignments with all of the right answers to receive full credit. This motivation to complete the homework indicates a compelling desire to be *enrolled* into the actor-networks of sophomore math, and simultaneously suggests that students resist the official methods of *interessement* with alternatives of their own devising.

Students who cheat circumvent the standard and expected process for doing written homework problems, as they practice finding solutions online or networking with their peers to obtain answers instead of attempting to solve the problems on their own with the allowed resources like textbooks and TAs. Yet the students' commitment to turning in completed homework assignments, regardless of how they found the answers, is telling of their desire to satisfy the required tasks of the class. Instead of turning in a partially-completed homework assignment, preferring to cheat to get it all done suggests that full completion is what matters to these students, not their actual learning or efforts. Since the only item officially *mobilized* after each homework assignment is the singular numerical grade assigned to it by the TAs, the actual experience of students in attempting the work or cheating becomes invisible, silenced and subsumed by the number TAs write on top of the page and enter in the grade book as the official record. Students who do the homework on their own may *mobilize* their content knowledge on subsequent assignments or exams, but they are not distinguishable from students who cheat based on their homework grades. In submitting completed homework assignments, even if the answers are not their own, students are demonstrating their *interessement.*

This begs the question, what is homework really for? To students who cheat on homework, copying down the answers is important for getting points on their homework grade, which is a small component of their overall grade. To TAs, homework is another task for them to grade weekly and post solutions for, and to help students with during office hours and to a lesser extent, recitations. To instructors, homework is an assigned opportunity for students to practice their problem-solving techniques and get feedback on their work. Homework is *translated* into all of these things, but there is a divide between what the instructors see in homework and how students feel about it. How can we reconcile these viewpoints and at least get both sides to understand the other's point of view?

As the resources available to students continue to proliferate and expand over virtual space, the role of homework in courses will be increasingly contested as it will become easier and easier to cheat for students who find their own way around the processes of official *interessement*. Students may need reminders at the beginning of each semester of their purpose at school, of the penalty of not submitting homework, and the penalties associated with cheating on homework. While Dr. Hayes tells students on the first day of classes that failing is the only penalty for cheating, the students may forget the statement or find it too cut and dry for the nuance of their individual situations. There are many gradations and levels of cheating, some of which can be easily justified as just "checking answers," getting a hint, or only copying the solution for a portion of the entire assignment, not the whole thing. Also, many students who do cheat will still be able to pass the courses, especially if they are good test-takers they can still be *enrolled* despite not following the authorized procedure for doing homework. It may be easy for students to forget Dr. Hayes's warning if they know upperclassmen who pass on their solutions manuals and tips for googling answers, having been successful in the course and *mobilized* through the curriculum. While it is tempting to write off the students who cheat, they are a significant fraction of the population in these courses and will not stop given the current organization of homework and the prevalence of solutions and solution manuals online. We cannot ignore them or simply will them to discontinue their cheating.

Perhaps one way to bring the official and unofficial narratives about homework together is to discuss cheating in the context of ethics. Engineering educators have long been searching for ways to incorporate ethics into their classes, often utilizing case studies of industry engineers put in difficult situations, or commenting on engineering failures and catastrophes that could have been avoided with various preventative actions (Colby & Sullivan, 2008; Stephan, 1999). Yet, rarely do these ethical discussions focus on individual ethics, or a student's personal ethics as they proceed through their courses. The students who cheat on their homework are hardly being ethical, but they are not required to examine themselves or reflect on their morals and ethical behavior or lack thereof. While the university honor code is posted in every classroom, it is easily ignored since it is not actively discussed in the context of class; it is not invoked on every homework or lecture. If we challenge students to demonstrate ethical behavior and remove some of the drivers to cheat, perhaps we can make homework more useful. Ideally homework will be a means for students to practice applying their math skills instead of practicing their googling and copying skills.

6.2.2 The Periphery of Enrollment Through Exams

Exams dominate the world of undergraduate engineering, occurring four times a semester during the math classes of sophomore year and controlling *enrollment* into the actor-networks of the math classes of sophomore year. The students we interviewed and spoke with had no end to the horror stories and battle wounds suffered from their exams, as final exam averages were gleefully compared in focus groups, and stories of personal tragedies were shared in interviews. There is nothing as important as the exams for determining student *mobility* through the courses and through engineering undergraduate; students and professors alike instill exams in a place of utmost importance for survival. The swirl of activity supporting the exams highlights their prominence in the network, as hours of class time, TA time in grading and recitation, and lecture time are devoted to describing or supporting the exams. But is the entire hubbub worth it?

The broader perspective of experienced instructors like Dr. Hayes shows a different view of the suffering of students on exams, highlighting the exam archive as the primary influence on student expectations and beliefs surrounding the tests. If students look at the exam solutions in concert with the exam problems, they tend to see the problems as easy and straightforward instead of difficult or tricky. How can we get the students to hold off on accessing the solutions until they actually try the problems first? Exams are characterized by their isolation away from other resources in space and time, conditions that are difficult to replicate in a dorm room or undergraduate residence. Some students described needing to lock themselves in computer labs or campus libraries in order to minimize distractions while studying for tests, mimicking the insulated conditions of the testing environment. Yet it is impossible to actually recreate the time pressure and isolation of exams, as while studying students can always take breaks, access solutions to past exams, review their homework, notes, and textbook, and confer with their peers. That tests are standardized in time and seclusion across entire course sections is part of what causes the students' individual and unavoidable suffering. How can we make that suffering productive? Furthermore, how do these experiences prepare students for engineering workplaces and industries where resources are more readily accessible and actually encouraged for use?

One participant in our focus groups, Travis, was frequently a counterpoint in our data, describing not cheating on his homework because he knew it wasn't worth it, and offering the opinion that tests should not be easy, that it should not be a given that students can pass the math courses of sophomore year. He suggested that the tests are appropriately challenging and that it is a meaningful accomplishment to emerge out of the math courses having passed these arduous tasks in isolation, on your own power. His viewpoint contends that these exams are tests of intellectual merit, of proving that individuals possess the mathematical problem-solving prowess worthy of remaining in engineering. Yet other students, notably Erika, commented that it was unfair that her friends who had dropped out of engineering majors due to the math classes never got to really try engineering before they were stopped in their tracks by math. This is a serious consequence of the difficulty of the math classes on retention in engineering, as potential engineers are waylaid early on in their educational trajectories through undergraduate if they cannot pass or enjoy the math classes. The gulf between engineering and math remains wide, as the skills are different, the problems are different, and the traditions are different, yet math and specifically math exams still control access to engineering and *enrollment* in engineering actor-networks. Math exams restrict student access to subsequent levels of the engineering curriculum, excluding students with low scores from reaching engineering coursework featuring more direct applications and connections to future employment as an engineer.

Exams are another form of durable educational technology that has persisted through centuries to still affect students today. The ability of students to solve problems in isolation and prove their worthiness through tests is important for getting through engineering school yet has no bearing on their success in the real world. Officially, exams are for assessing student knowledge and providing feedback on problem-solving skills. Unofficially, exams are painful experiences that control access to engineering majors, as students must demonstrate their mathematical skill on standardized and isolated assessments that have little to no connections to reality. While we have studied engineering math classes and examined the function of exams in controlling *enrollment* into actor-networks of sophomore math, many other courses students face during engineering undergraduate also feature exams as central, high-stakes events that all students must pass. Our analysis of the purpose and effect of math exams is relevant for all courses that rely on isolated, standardized test experiences to determine if students will be allowed to pass or required to repeat a course. In line with the movement towards personalized learning, how will the standard exams shift as educational technology becomes more individualized and resources more ubiquitous?

And, considering the ubiquity of exams throughout undergraduate engineering education, how can we learn from the suffering of students to envision alternative assessments that are more connected to engineering practice and the real world tasks required of engineers? Some professional engineers who have survived the gauntlet of traditional engineering education suggest that the high-stress, high-stakes, time-constrained environment of exams helps prepare students for similarly pressured situations in engineering practice when they get there. Yet, many students will never reach the point of becoming practicing engineers if they fail a class due to poor exam performance or if they choose to leave engineering majors and not participate in these stressful standardized assessments at all. Even if exams do help prepare engineering students for the demanding environment of engineering industry, there are many other ways to train them that may not involve the same level of emotional distress, or can be more realistic in simulating engineering practice than the artificial isolation of most exams. Similar to the need to reconsider the purpose of homework in our classes, we need to reexamine the power of exams in controlling student progress and status through undergraduate engineering. Exams upset students and pressure them in compressed-time situations, allowing those who succeed to expect similar suffering and anguish at work and selecting out students who do not perform well under these conditions. Before supposing that all engineering industries require personal misery and stress, it is fair to consider if these are purposeful outcomes of exams and their powerful position in these actor-networks, or unintended byproducts of old artifacts and traditions. It is time to reassess which outcomes of exams are intentional and which are not.

Currently, students are translated via exams to become legitimate actors within institutional networks of closed-ended problem solving, proving their ability to recreate solutions and determine predetermined answers. Instead, envision a system in which students join networks that reward open-ended, creative problem solving and innovative divergent thinking. We aim to start the conversation about the consequences of the current examination system and consider alternatives for future students.

6.2.3 Interpreting Getting Through versus Learning, What's Mobilized?

As students finish semesters and move past the courses of Calc 3 and Diff Eq, what is *mobilized,* what do they really take with them aside from the letter grade on their transcript and the completion of their prerequisite requirements? The courses are designed to teach students mathematical concepts that they will conceivably use in the future, necessary for success in their subsequent engineering courses. Yet students report having to re-learn the math just in time for their engineering classes and also for their jobs. Students celebrate getting through and completing their math courses instead of actually gaining mathematical knowledge, enjoying their *mobility* past the course instead of the concepts that are supposed to travel with them. Rare are the students, including Ethan, who are excited about their ability to apply their math skills to real situations. More common are the students, like Erika, Eric, and Elizabeth, who are thrilled to have survived the class and *mobilized* through to the other side of their sophomore curricular requirements.

Though the purpose of the sophomore level math classes is to teach students math, it is questionable how much math content they retain and is *mobilized* in the weeks, months, and semesters after the courses end. Students comment on actually taking away from the courses valuable skills and connections for their continued survival in engineering including study habits, practice with time management, and relationships with peers, faculty, and TAs. Yet these *mobilized* outcomes of math classes are not officially acknowledged or encouraged by the activity of the courses, it is left up to students to self-organize and figure it out on their own. These unofficial outcomes are arguably more important than the official learning outcomes related to math, as time management and relationship-building skills will continue to benefit students regardless of their chosen vocation. Officially recognizing these unofficial outcomes as valuable and explaining to students that these are important aspects of the course could assist students in taking a broader view of their education, looking past the pure technical content to see the importance of these more managerial and networked skills, and to recognize what they actually want to *mobilize* or take away from participation in these courses.

All in all, we have identified several unofficial student narratives that are impactful for understanding their experiences in traversing the actor-networks of sophomore level math courses. While it is tempting to bury our heads in the sand and toe the party line in believing the official policies regarding homework, exams, and content in classes, looking at the unofficial and hidden activities of students demonstrates a significant divide between what is institutionally desired and what actually happens. Giving credence to the perspectives of students and valuing their perspectives as valid brings up new questions regarding the purpose and effectiveness of our durable educational artifacts and technologies, encouraging us to envision alternatives and initiate new conversations around understanding these unofficial student narratives.

6.3 Translations Into Engineering

While we identified that the math courses of sophomore year enable sophomore students to become *translated* into juniors, we question if these math courses assist in the larger transition process of *translating* students into engineers. Earlier findings sections demonstrated the divide between math and engineering, and the corresponding lack of content and skills *mobilized* between the two disciplines. Most students have difficulty *mobilizing* their abstract math content knowledge for application towards practical engineering problems. While the math classes are undoubtedly challenging and rigorous, packed full of valuable content, most students do not seem to retain the content or feel that the math classes prepare them for engineering.

The interlude described how the American turn towards engineering science shifted the entire engineering profession from an applied, experiential discipline to a more theoretical, mathematical, science-based activity (Seely, 1999). Marked by the construction and continued existence of the Engineering Center building, engineering science has permeated our undergraduate engineering program, evident through the focus on math and prerequisite requirements in physics and chemistry for undergraduate engineering degrees. Yet simultaneously, design is also supposed to be a central activity of engineering though it only appears in a select few places during the undergraduate curriculum. Somehow in four years the engineering degree programs are expected to instill a scientific foundation of knowledge in students and provide ample experiences with engineering design while also preparing students for modern engineering practice and technologies. Unfortunately these aspects of the engineering curriculum are usually separated in time and space, and rarely all integrated together in the same course or project. For example, the project assignments in the engineering math courses studied incorporated modern software and the application of mathematical concepts, but left out engineering design and practical engineering considerations. This separation is partially a consequence of organizational distinctions, as math and science faculty cannot be expected to teach students about engineering design, but it manifests in a program of undergraduate education which is internally inconsistent and disconnected. Even students who excel at math may be underprepared for the realities of engineering, while students who suffer through math may quit engineering before they get to the bulk of their engineering coursework. How is this un-integrated educational system supposed to foster innovation and creativity?

In addition, the reliance on the chalkboard in the math courses observed precluded the use of technology in demonstrating mathematical concepts in a more modern way. The lecture instructors used computers on very rare occasions, only once in Calc 3 and twice in Diff Eq on days that were observed through the entire semesters of class. Technology and software are undeniable tools for contemporary engineers, yet they were hardly present in these math courses. Occasionally, lecture instructors while sketching out vector fields or three-dimensional shapes on the chalkboard would comment that it would be easier to visualize and draw these diagrams on a computer. Yet, they would not personally employ computers in their lecture, sticking with the traditional teaching artifacts of chalkboard and chalk instead of utilizing modern visualization technologies. While students were required to use software programs and word processing applications to complete their project assignments, these computer-based tools were not demonstrated or included in the lecture.

The official activities of lecture remain immune to the passage of time and advancements in technology, despite the need for engineering students to become fluent in various programming languages and comfortable with using many software programs. Chalkboards and chalk are not the typical tools of modern engineers, while computers and email are the currency of contemporary engineering practice. The reliance on traditional artifacts during lectures seems outdated to students who have grown up with computers and digital technology for their entire lives. Mobilizing the abstract mathematical knowledge from the lecture chalkboard to the engineering workplace requires not just a translation between math and engineering, but a seismic shift away from old traditions to new technologies. Current students are already familiar with computers and most are adept at using modern technology, yet we insist on making them learn through historical artifacts that are unrelated to their future work as engineers. How can we prepare engineering students for careers in the modern world when we teach them using the methods of the past?

Chapter 7 – Recommendations, Limitations, Future Work, Conclusions

So what do our findings and discussion mean for engineering educators, administrators, and students? While we have mapped out actor-networks of sophomore mathematics, what does that tell us about improving the activities and environments of engineering today? Though we do not have a single solution or actionable recommendation, we have a variety of suggestions for further investigation and discussion. Instead of seeking to make a drastic change or do something to shift the organization of these classes, we encourage viewing our findings and discussion as initial forays into conversations exploring the motivation behind our durable classroom artifacts and their effectiveness in teaching current students. In the Questions to Initiate Conversation section below, we wish to initiate reflection and examination of our current system before intervening further, we hope to discuss the unintended consequences of institutional choices that were made decades ago. This chapter also includes a discussion of limitations to the analysis and opportunities for future work, continuing and expanding this research in a variety of directions, before concluding with some final comments about this study.

7.1 Questions to Initiate Conversation

We have included a bulletized list of conversation-starting questions around the central topics of our study in the hopes that these aid in easing into some contentious issues of undergraduate engineering education. Both a short question and a longer discussion of the question are included with each bullet, and the questions are grouped by topic.

Lectures:

1) Are lecture resources inherently unbalanced and does it matter for our students?

   Meaning, consider if the tiered lecture hall is a political artifact. How can we distribute the limited resources of the lecture hall equally among the students in attendance? Students in the front rows undoubtedly get access to the instructor and chalkboard on a different level than the students in the back. What would happen if seats were assigned, or randomized each meeting? Does it matter?

2) How can we integrate together chalkboards, chalk, computers, and e-mail to make class traditions and modern engineering practice more cohesive?

   Consider while the chalkboard and chalk remain useful artifacts for teaching mathematics, is there any potential to incorporate new technology into the traditional lecture? In addition to the active learning techniques already employed by some faculty members, weigh the possibility that displaying visualizations of the mathematical phenomena under study could reach more of the students in the room.

<u>Homework:</u>

3) What is homework really for? How can we make it more useful for all parties involved?

   Consider the different interpretations of homework evident among the students as well as faculty and graduate TAs. Is homework meant to provide practice for students, a task for TAs to grade, feedback for students and professors about levels of understanding in the course, etc. Is it something for students to cheat on to maintain a façade of enrollment or caring about learning in the course?

4) On what basis should homework be graded? Are there any alternatives to getting the right answer?

   Under the current homework grading scheme, students perceive some TAs to be harsh graders and others as lenient graders, significantly impacting the trend for a homework grade over a semester. How much does effort matter for homework grades? Discuss with TAs, students, and instructors the options for grading and the constraints of the system.

5) How should we treat cheating on homework and how much should we care?

Academic honesty is discussed briefly on the first day of classes, but students still cheat and find unauthorized and unexpected ways to access resources and justify their actions. Though some students may have survived Calc 1 and Calc 2 by cheating their way through, it may not work for them through Calc 3 and Diff Eq. Conversations with students about the purpose of homework, the options for help late at night, and the relatively small impact of homework on the final grade may alleviate some of the pressure they perceive as forcing them to cheat. Acknowledging that homework can be turned in incomplete and imperfect may also allow students to take a broader view of their education and efforts on their assignments. Encouraging students to be reflective about their personal ethics and motivations for learning may help put the onus on them to follow the honor code and not cheat.

<u>Projects:</u>

6) What are projects for, and how can they be graded to include room for teamwork and creativity?

   Does the stated purpose of projects align with their outcomes? Is it fair for some students to work alone on the projects while others work in groups of three? How can we convince students like Aurora to reach out and find a teammate the week the project is due? Investigate if there is room for teamwork be acknowledged and included in the assessment of the projects.

7) How have the projects added more work for the entire course ecosystem, and is it worth it?

   The addition of the projects and the accompanying 1-credit lab course can be seen as valuable new pedagogies or as extraneous decorations added onto already-full courses. Are the resources required to support projects in these courses justified?

<u>Teaching Assistants (TAs) and Recitation:</u>

8) Can greater awareness of social and cultural issues be covered in TA training?

   TAs are crucial for maintaining these large courses, serving as logistical coordinators and supporting students through recitations, office hours, review sessions, etc. In addition to the current focus on board work and *organization, is there room in the TA training to discuss how issues of access and equity affect learning? Can we attune our graduate student TAs to the experiences of their students, to be appropriately sympathetic and supportive?*

9) Is the amount of power TAs have appropriate?

   TAs are the backbone of these courses, as their grading, teaching, and coordination efforts enable the "machine" to keep running. As initiated back in 1963, recitations allow instructors to teach large sections of lecture courses while still giving students a chance to ask questions in a smaller recitation section once a week. We heard from our student interviewees that a TA can adversely or positively affect a course experience, possessing the power to significantly impact homework grades, project grades, exam grades, and understanding of content as well. Is their power over student trajectories through these courses and through engineering undergraduate programs appropriate?

<u>Exams:</u>

10) What benefits students in the aftermath of exams?

    Currently in the aftermath of exams, the recitations or lecture periods are largely focused on going over the exam problems to clarify what the right approach and right answers were in order to earn full credit. Do students want to go over the content right after seeing their grade? In addition to content review, is it possible to discuss and support the emotional reactions of students to their exam grades? How can TAs and professors help students contextualize their grade and consider what will help the students learn through the rest of the semester?

11) Does informing students of the historical exam trends beforehand imply that student math abilities are fixed instead of incremental?

    While the student exam scores from Calc 3 and Diff Eq have demonstrated certain stable trends from exam to exam, is there a way for the data to be presented to the students that does not imply that their performance on subsequent exams is determined by their first exam score? In conjunction with the research literature *comparing growth mindsets to fixed mindsets, particularly with regards to math skills, is it possible to convince students that math ability is not an inherent trait, but a developed skill (C. S. Dweck, 2010; C. Dweck, 2008)? Striking a balance between encouraging students to succeed and being realistic about their exam performance may be tricky, but important for allowing students to believe that they can pass the courses, that their grades are not predetermined or fated – that the 3rd exam and final are actually graded, not just predicted.*

12) What could we do without the online exam archive?

    The online exam archive is the primary resource for students in studying for their tests. Instead of looking at the solutions immediately, how can we get the students to struggle with the practice test problems in the same way they struggle on the actual test problems? What kind of preparation will help students when they are isolated away from their computers and friends in real testing environments? Without the exam archive to set expectations and serve as a baseline, how would the exam process be different or the same?

13) How much time should each exam take?

    Students describe how exams organize their entire day, sometimes their entire week. As there are reviews in advance, the exam itself, the grading party with TAs and instructors, and the aftermath, can we reconsider how many hours of exam-related activity are necessary and appropriate for learning? As orals and other exam-related activities become more common, more and more hours are going towards preparing for these events. Is it too much or not enough?

<u>General Questions:</u>

14) How will continued growth impact the TAs, instructors, and students in these courses?

    Considering the rapid growth in the number of students taking these courses each semester, the system may need to be streamlined in order to make it sustainable. The logistics of supporting the fall 2015 class will be staggering, as grading the exams and projects will take longer than ever before. Will the growth of the student body strain the current system past its breaking point? Are there any ways to streamline the class assignments *or processes, to reduce the workload of the instructors, TAs, and students while maintaining the high standards for academic achievement?*

15) Accepting that we have to use GPAs in our college system, how can we inform students of the impact of GPAs on their academic trajectories and the GPA's flawed nature?
The durable and nonsensical artifact of the GPA is embedded in our educational systems and institutional processes. If we discuss with administrators and students alike how the GPA system affects their progress, and how its calculation is illogical, will the students better understand the levers that control their movement through the engineering curriculum?
16) How can our current educational system respond to new developments in technology, culture, and society?
Identifying the local history that led to the construction of the building, the curriculum, and the lecture/recitation model, can we envision a new future that builds on our past but takes us in a new direction? Viewing the engineering math curriculum through the lenses of history allows us to see that specific individual actors are to thank for the courses and formats we have today. Can that empower people in the system to create new formats for courses and content that align with our current reality instead of the Cold War?

Note that these questions are not intended to be prescriptive solutions or directly actionable results. Instead these questions are meant to be entry points in initiating official conversations around contentious topics, to illuminate and understand the bigger picture of student experiences, durability, and change in sophomore mathematics courses.

7.2 Limitations to the Analysis

Our study is limited in that intensive observation of courses was conducted over only two semesters: one fall and one spring. It is possible that this sophomore cohort under observation could be unique or anomalous in some way from their older or younger groups. However, these classes of Calc 3 and Diff Eq have a great deal of history and tradition in their format and administration, and it is likely they will be taught in similar ways by similar instructors in the future. So while the student cohort may be unique and distinct in some ways, the environment they encounter and create in these sophomore level gateway classes has some staying power institutionally and structurally through the required curricula of engineering majors.

Furthermore, it is important to note that our data collection and findings focus on what is happening during public lectures, in the public arena of the lecture hall or recitation classroom. Aside from a few occasions in which the research team was able to observe students as they worked on projects informally in the computer labs and in one dormitory on-campus, there was not much visibility or fieldnote record of unofficial course events taking place in more private settings. Also, the students who were selected for interviews were known by the research team because they attended class at least occasionally – in this way, the selection was biased towards students who were physically present during the same lectures the participant observer from the research team attended. Students who did not attend lectures but were enrolled in the class had a different experience of classroom culture, and their voices are not represented here. As we are primarily concerned with the expression of actor-networks within the public classroom, we feel justified in focusing on the observable events of lecture and recitation. Interview data from students, TAs, and instructors regarding working styles, locations, and access to resources helps shed light on the private class-related events that the research team was not able to observe. We acknowledge that part of the student experience of navigating these courses includes working privately, and save the intensive study of these out-of-class events for a different project.

Our interview subjects are not representative of all available majors in the college of engineering, with mechanical and aerospace overrepresented among the students interviewed. We are more concerned with how students of all majors interpret the environments and experience the cultures of the gateway mathematics courses they are enrolled in, and not with the disciplinary cultures of individual engineering majors. Consequently, the common ground of taking Calc 3 and Diff Eq is our primary interest. Additionally, the nine students interviewed are, by appearance, Caucasian. It is not our intent to focus on the experiences of white students, but due to the demographics of the students in the courses and recruitment of interviewees the experiences of minorities are unfortunately not represented in our data. Of the nine student interviewees, four are women and five are men, an overrepresentation of women in our interview population as compared to the overall student population.

While mathematics is a cornerstone of the engineering curriculum, it is just one corner – physics and technical major specific requirements constitute the rest. We chose to focus on engineering mathematics due to the detailed curricular flowcharts which establish Calc 3 and Diff Eq as prerequisites for subsequent technical coursework, and because mathematics is frequently considered a barrier preventing student progress towards graduation. Engineering mathematics courses, while severely impactful on student trajectories through engineering, may not be representative of physics or other technical major coursework. We understand this limitation of our work and look to identify the cultural norms specific to gateway mathematics courses, not all of engineering undergraduate. Also keep in mind that this is a single-site study in that we are looking only at one campus here in the Rocky Mountain region. Boulder is a distinctive location that attracts people for a wide variety of reasons, so we acknowledge that the cultural and social environments of our study may be specific to our campus.

7.3 Future Work

This project has illuminated the durability of our current engineering mathematics courses and has raised questions regarding the intentions and consequences of curricular artifacts like recitations, homework, exams, TAs, and more. In addition to initiating conversations around contentious topics, we also have opportunities to further explore and expand our understanding of these actor-networks of sophomore mathematics and their impact on undergraduate engineering education.

7.3.1 Extending Conversations About Durable Networks in Engineering Education

The leaky pipeline was once the dominant metaphor for discussing attrition in STEM education (Chen & Soldner, 2013; Portland Metro STEM Partnership, 2012). The incoming freshmen are the fluid in the pipe, leaking out along their semesters of undergraduate, after graduation, and upon entering the workforce as well. While this image communicates the volume of people lost along the way, it does not include much nuance or understanding of the conditions at the leaks, or the fluid itself. Instead of the leaky pipeline, researchers are now beginning to talk about learning ecologies, and the diverse support networks essential for student success at the undergraduate level (Sullivan et al., 2015). Our research can join these conversations, offering yet another way to visualize how students enter the systems of undergraduate engineering, the challenges they encounter along the way, and the pathways that lead towards staying in engineering or leaving entirely.

Our study sees students as adaptable, relatively flexible entities that encounter the intensely durable traditions of the required mathematics courses in engineering sophomore year. To succeed and pass these challenging courses, students must navigate the actor-networks of sophomore math, comprised of the faculty, TAs, traditions, assignments, exams, and environments. Students who learn through lectures and connect to professors and TAs become integrated into the movements of the actor-network of sophomore math, engaging with math content and completing homework and project assignments. If these students can study for and pass exams, their membership within these networks will be confirmed and they will be able to mobilize their success in the form of a passing letter grade on an official transcript. Students on the periphery of the network, who don't pay attention during lectures or choose to cheat on their homework may have more difficulty moving through the actor-networks of sophomore math, as assignments will be obstacles and exams may be impassable. If these students do not connect to any of the resources of the official math actor-network including TAs, professors, office hours, or textbooks, they may not be able to pass the course and their mobility through the engineering curriculum will be compromised since their grades will not satisfy the prerequisite or college requirements.

Student interactions with the actor-network of sophomore math are representative of their encounters with the actor-networks present in all levels of engineering undergraduate, as each class is an actor-network, each major is an actor-network, the whole college is an actor network, etc. Individuals join these networks in the hopes of becoming translated into engineers, and along the way they are necessarily translated from sophomores into juniors, from freshmen into mechanical or other engineering majors, from enrolled students to alumni. Examining the organization of the actor-network at the level of sophomore math classes has illuminated the impact of non-human artifacts on student progress through the courses, as well as the official and unofficial ways students traverse the required course tasks. This approach has merit for understanding why some students succeed in these courses and others are held back, for viewing students at the centers of the actor-networks as well as on the periphery.

Going forward we plan to introduce this metaphor of students encountering durable networks as an alternative to the currently dominant imagery of leaky pipelines and chilly climates in engineering (Persaud, Salter, Yoder, & Freeman, 2006). As we search for a catchy phase that encapsulates the meaning and impact of durable actor-networks on individual student progress through engineering undergraduate programs, we plan to broadly circulate our study and start conversations in the engineering education community about shared curricular structures and artifacts that have remained largely unchanged for decades. As prior metaphors describing engineering education have led to the development of funding streams and research agendas, we humbly propose that our work has potential to result in similar outcomes and new ways of conceptualizing engineering education research.

As one of the first studies to explicitly and extensively apply Actor-Network Theory from the field of Science and Technology Studies towards engineering education, we hope that this precedent is followed by many more studies that adapt theories and findings from social science research towards engineering education research. While researchers from Science and Technology Studies have long examined engineers at work to formulate ideas and models for understanding our modern world, we feel it is time for our field to further learn from this research and expand its utility in exploring engineering education in addition to engineering practice (Latour, 1993). As Actor-Network Theory has greatly assisted our investigation and interpretation of the durability of our engineering mathematics curriculum, we look forward to uncovering other taken-for-granted aspects of undergraduate engineering education that are similarly durable and impactful to our students.

7.3.2 Uncovering Levers for Change Within Durable Engineering Actor-Networks

At every step of our analysis, we have identified durable curricular artifacts and structures within the actor-networks of sophomore math. By noting what actions are required to keep these items durable and in place, we can begin to understand what actions would be required to transform our curriculum and break from our durable traditions. Our historical interlude described how our Engineering Center building was designed and erected in less than five years, how recitations were instituted after one year of experimentation, and how the ongoing turn towards engineering science inspired revision of the engineering curriculum and mathematics sequence here at CU. Understanding the national environment and drivers of those changes in the 1960s era helps us envision what types of national events and movements may be required for change today. Do we need a new Sputnik or Cold War to motivate curricular transformation now? Is external and powerful rhetoric required to shift engineering education and our beliefs about what engineering training should look like?

The rapid makeover of engineering education at CU was punctuated by the new building that set in place more space for research, and specific rooms for teaching and learning under the ideology of large lectures and smaller recitations. As engineering at CU has grown in the intervening years and engineering disciplines and departments have begun to move out of the Engineering Center into new buildings, there are renewed possibilities for change. Will these new spaces inspire new models for teaching and learning, or will they continue to rely on the past traditions? Aside from remodeling the building to create new physical surroundings, how else can we inspire innovations in our engineering curricula?

While we once were able to react quickly to the needs of our nation and institute programs for research, change takes longer now as many administrators, faculty, staff, and students are bound to the current model. In exposing the curricular artifacts that have remained durable for decades, we hope to encourage institutional actors to reconsider their ties to past traditions and envision possibilities for new educational models and environments. There is no time like the present to begin addressing the limitations of our current implementation of undergraduate engineering education, as we need to be proactive in responding to future societal needs instead of being reactive in trying to maintain our institution's relevance in a changing world. Within each of the durable artifacts we have identified in the actor-networks of sophomore mathematics, we see potential for change and innovation. The mainstays of our curriculum are each levers for potentially transformational change in engineering education.

7.3.3 Network Analyses in Engineering Education Research

Recent scholarship in engineering education has taken a quantitative view of classroom networks, analyzing student interaction frequencies during class meetings, measuring student network connections on surveys of ethics and trust in teamwork, and even applying graph theory algorithms to visualize and draw classroom networks (Feister, Zoltowski, Buzzanell, Torres, & Oakes, 2015; Hilpert & Holliday, 2015; Sheridan, Kinnear, Evans, & Reeve, 2015; Simon, Finger, Krackhardt, Siewiorek, & Smailagic, 2015). Our study visualizes networks in a much different and more qualitative sense, not seeking to measure or quantify networks but instead to describe and map them out. While the networks in these quantitative studies are comprised of students connecting to other students, professors or TAs, our networks include important non-human actors like exams, syllabi, grades, GPAs, lecture halls, and buildings along with the relevant humans. Including the non-human artifacts that are embedded within our curriculum in our analysis offers a unique point of view and illuminates many of our taken-for-granted habits that were once actually a new idea.

As social networking programs continue to proliferate, arranging the everyday activities of modern life in new ways, network-based analyses may gain more popularity and acceptance broadly. While the quantitative approaches to modeling networks are novel and visually exciting, the qualitative work to map out these diverse networks and understand interactions and connections within them remains important and should not be lost or overlooked in the shuffle. Studies like ours can advance along with the research employing quantitative network measurements to illustrate networks from a different perspective, informed by Actor-Network Theory and including non-human elements. Networking is now a common buzzword referring to building professional connections among influential human actors, so there is great potential for analyzing these networks and including their non-human elements in arenas even outside of engineering education.

7.3.4 Opportunities for Extending the Research and Venues for Publishing

As we go forward with this research, we see potential both at this institution and beyond to further illustrate the usefulness of our approach and extend the significance of our findings for a broad audience interested in contemporary American engineering education. While we focused on examining the math classes of engineering sophomore year, we could expand our research by studying other cornerstones of the engineering curriculum, including the required science classes like physics and chemistry or looking into the discipline-specific engineering classes distinct for each major. We could also compare and contrast our findings and our curriculum with newer colleges of engineering, including Harvey Mudd College and Olin College of Engineering, to determine if these more recently founded programs include similarly durable curricular artifacts or if their newer classes feature newer ideas and models for teaching and learning engineering. By studying more than one institution, our research program would be able to identify the range of durability present in different amounts at various locations of undergraduate engineering, and perhaps determine how newer ideas and methods impact student trajectories just as much as the durable structures of our study.

We also wish to include more diversity in terms of students, TAs, and faculty interviewed, in order to extend the spectrum of student experience we describe and learn from in our work. While this study uncovered ranges of students who cheat and do not cheat, we are also interested in understanding how membership in nontraditional engineering populations affects the activity and mentality of students as they traverse through these required mathematics courses and are translated towards engineering. Students from underrepresented minority groups as well as underserved high schools would be valuable as research subjects to shed light on how our durable curricular structures impact these populations as well.

From this dissertation study, we plan to write several journal articles that explain aspects of our research to the engineering education community. One article is planned as part of a special issue of *Advances in Engineering Education* under the theme of engineering education in the middle years, and will focus on differing interpretations of exams among students, TAs, and faculty. Other articles will follow, explaining our method as well as elements of our findings. We plan to submit to the *Journal of Engineering Education,* the *International Journal of Engineering Education,* and to present our work at the *Frontiers in Education* and *American Society for Engineering Education Annual Conference and Exposition* in the coming years. We hope to find resonance in the engineering education community with our findings and our method, and locate potential collaborators and sites for further investigation of our research questions and durability in undergraduate engineering.

7.4 Conclusion – Connecting Back to Retention

Our findings have included examination of the durability of the sophomore mathematics actor-networks as well as the durability of the engineering curriculum and our local building. While we studied the history of our local site to identify durable course structures and artifacts, there are similar histories at land grant universities throughout the nation that faced comparable organizing conditions for their engineering programs during the Cold War. The concepts of durability and stability in the engineering science curriculum are thus transferable to other schools and colleges of engineering, which have traditions and legacies parallel to ours.

Examining our history has also enabled us to consider how our system has remained so durable in terms of demographics. Retention and recruitment in engineering remain difficult, especially for women and nontraditional groups, as we have been unable to move the needle in increasing the percentage of these populations in our engineering colleges or workplaces. Identifying the durability exhibited in our engineering curricula and environments suggests that our system has scarcely evolved in the last fifty years. Significant change and revision of these durable, traditional artifacts in engineering may be needed before we see changes in our demographics and population as well.

Throughout our research, we witnessed the full spectrum of engaging and mind-numbing lecturers, motivated and participatory students and ones who completely zoned out. While our study could have focused on the differences between the lecture sections and students observed, we chose instead to take a different view in investigating the ecology of learning that surrounds the math classes of engineering sophomore year. Employing Actor-Network Theory to study our history, students, and systems has allowed us to identify and locate diverse artifacts and actors along trajectories of participation and exclusion in actor-networks. This unique approach to examining engineering education has yielded new perspectives on durability and the potential for change within our foundational math courses and supporting institutional structures. With continued efforts and buy-in from our administration, faculty, TAs, and students, we can begin to envision new possibilities for our courses and curricula, finally separate from the durable legacies of Cold War engineering.

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Appendix A: Actor-Network Glossary

4 Moments of Translation: "A heuristic or sensitizing concept adapted to make sense of complex observations. Analysts of educational reform need not slavishly impose four steps and expect a linear process, but appreciate that translation is ongoing, iterative, and disorderly" (Fenwick, 2011 p. 122). "Translation is a process before it is a result" (Callon, 1986 p. 81).

Actor, Actant, Node, Knots: Used interchangeably in contemporary post-ANT scholarship, "actor" once referred to human elements of an actor-network while "actant" was reserved for non-human elements or nodes of the network. For our purposes, "actor" is a serviceable word and we can keep in mind that each "actor-network" is comprised of not just the nodes and linkages between each actor, but also the spaces in between. "Spaces exist as an unrepresented other to the network… a space outside the attention of the network" (T. Fenwick, 2011 p. 127). "An 'actor'… is not the source of an action but the moving target of a vast array of entities swarming toward it"(Latour, 2005 p. 46).

Actor-Network: "an actor network is simultaneously an actor whose activity is networking heterogeneous elements and a network that is able to redefine and transform what it is made of" (Callon, 1987 p. 87). The emphasis is that the network is constantly changing, not that it is fixed or stable in any way. Some authors consider using terms like "action nets" to communicate this ephemeral entity, but generally actor-network remains workable. "Actor networks obtain a fractal quality because each actor can itself represent an actor network" (Roth & McGinn, 1998 p. 405).

Actor-Network Theory: A novel social theory pioneered by Latour, Callon, and Law, which provides a set of sensitizing concepts which differ significantly from traditional sociological theory and practice. Sometimes considered an approach or set of tools for sociological analysis that focuses on "tracing associations" or "following the actors" instead of identifying the precise recipe or ingredients that enable certain social actions, causes, or effects. "ANT claims that it is possible to trace more sturdy relations and discover more revealing patterns by finding a way to register the links between unstable and shifting frames of reference rather than by trying to keep one frame stable" (Latour, 2005).

Black Boxes: "Objects that are taken for granted as completed projects, not as messy constellations. The accumulation of black boxes is crucial for what is considered progress in science and engineering" (Sismondo, 2010 p. 85).

Boundary Objects: "Relatively stable things… that are part of and mediate between heterogeneous practices, actors, communities of practice, and social worlds… Boundary objects sustain multiple overlapping social worlds… [they] can serve as tools to detect different social worlds" (Roth & McGinn, 1998, p. 403-404). "A central aspect of actor-networks is that actors who exchange boundary objects define each other in terms of the boundary object and the exchange" (Callon, 1991 cited in Roth & McGinn, 1998, p. 413).

Circulation: Useful idea for ANT studies - instead of spreading reforms, changes, or translations "top-down", they are "circulated" through many heterogeneous elements including inscriptions, intermediaries, actors, etc.

Controversy: "All the manifestations by which the representativity of the spokesman is questioned, discussed, negotiated, rejected, and so forth" (Callon, 1986a).

Displacement: Related to mobilization, something must be displaced and later reassembled in order to mobilize. Some authors prefer to discuss displacements and the "ease" of displacement as a complement to mobilization and translation.

Durability: How an actor-network becomes ordered and persists "through time" (Fenwick, 2011 p. 121).

Enrollment (3rd Moment): 'How to define and coordinate the roles', "The issue here is to transform a question into a series of statements which are more certain… it designates the device by which a set of interrelated roles is defined and attributed to actors who accept them. Interessement achieves enrollment if it is successful" (Callon, 1986a). "Every enrolment entails both a failure to enroll and a destruction of the world of the non-enrolled" (Star, 1990 p. 49).

Immutable Mobile: "an inscription that itself represents a translation of a series of events and actors and that has achieved sufficient durability to circulate across far-reaching space-times" (Fenwick, 2011 p. 120). E.g. textbooks.

Interessement (2nd Moment): "Describes the efforts of actors to encourage others to adopt their views and is a form of buying into a point of view" (Roth & McGinn, 1998, p. 405). "The process of translating the images and concerns of one world into that of another, and then disciplining or maintaining that translation in order to stabilize a powerful network" (Star, 1990 p. 32). "How the allies are locked in place" (Callon, 1986a). "To interest other actors is to build devices which can be placed between them and all other entities who want to define their identities otherwise" (Callon, 1986a).

Intermediary: "An actor that can translate thinking and behavior" (Fenwick, 2011 p. 120). "Powerful representations that contribute to the construction of Self and Other" (Roth & McGinn, 1998 p. 401). "What transports meaning or force without transformation: defining its inputs is enough to define its outputs" (Latour, 2005 p. 39).

Mediator: "Mediators transform, translate, distort, and modify the meaning or the elements they are supposed to carry… their input is never a good predictor of their output; their specificity has to be taken to account every time" (Latour, 2005 p. 39). The distinction between intermediaries and mediators is akin to the distinction between "traditional" schools of sociology and ANT approaches (Latour, 2005 p. 40).

Mobility: How an actor-network becomes ordered and persists "through space" (Fenwick, 2011 p. 121).

Mobilization (4th Moment): 'Are the spokesmen representative?', "To mobilize is to render entities mobile which were not so beforehand" (Callon, 1986). Nespor discusses mobilization a bit differently, as he believes "much of what it means to be a student involves *being mobilized"* already (Nespor, 1994 p. 14). Nespor delineates *material* (relatively immobile) and *representational* (more mobile) productions of space-time in order to describe how these differently enroll students into disciplines and enable the "mobilization of practice and practitioners" (Nespor, 1994 p. 15). Nespor's definition of *mobilization* is consistent with Fenwick's definition of *mobility*, above.

Object, Inscription, Artifact: a material or representational element which embodies "the ideologies and agendas of their designers, and…they are active elements that shape the relationships of people to each other and with settings" (Roth & McGinn, 1998, p. 401). Latour (1987) introduced concept of "inscription" to "make a distinction between the traditional cognitive science notion of representation – which connotes mental imagery and mental processes" (Roth & McGinn, 1998, p. 402). Nespor, meanwhile, uses "representational spaces" in reference to mobile artifacts that include textbooks, solution manuals, equations, and problem-solving practices (1994). "Inscriptions gain power as the information they summarize grows and the work it takes to deconstruct them increases" (Latour, 1987 as cited in Roth & McGinn, 1998 p. 403).

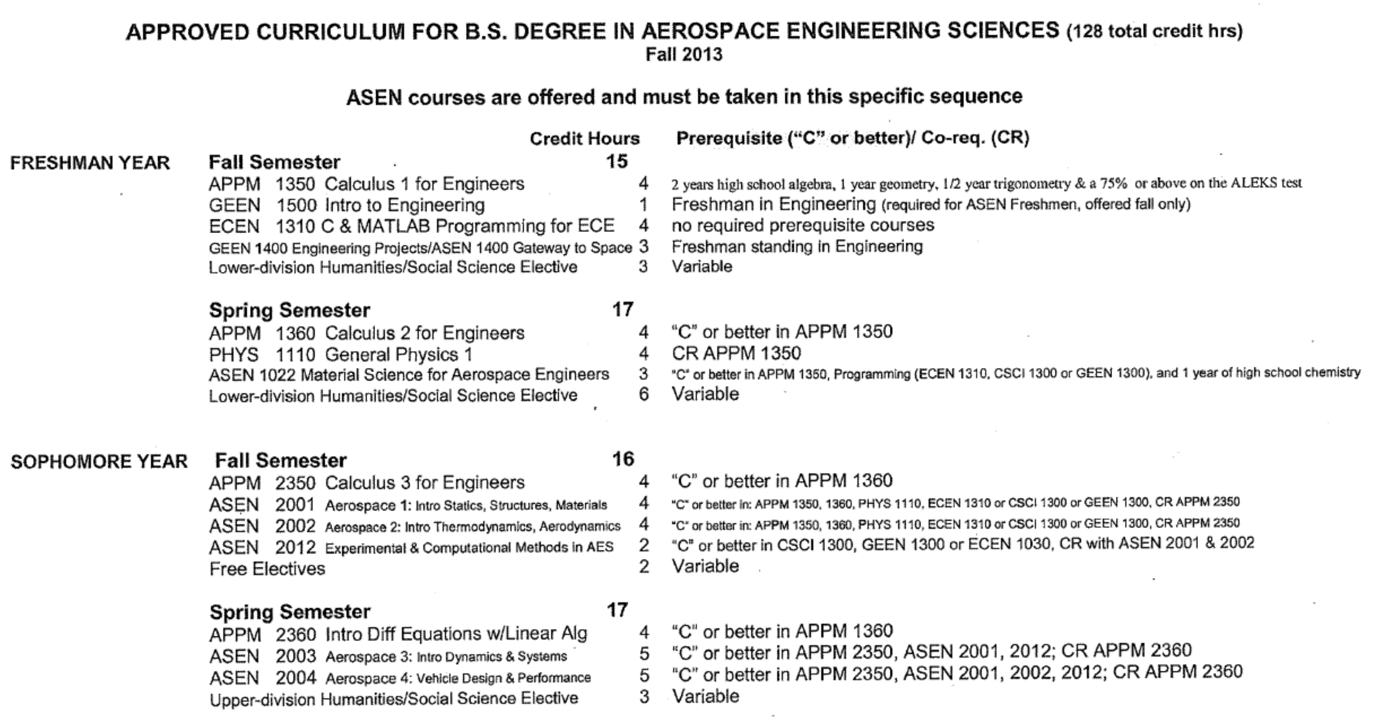
Obligatory Point of Passage (OPP): Closely related to Problematization – how network-builders define a set of allowable identities that in turn instills a certain event, artifact, or entity as a gatekeeper in a position of power. For Callon's scallops and fishermen, the OPP was the researchers coordinating everyone's efforts and transit through the network. For our study, the OPP could be the math courses required en route to an engineering undergraduate degree. OPPs are "Central assemblages through which all relations in the network must flow at some time" (Fenwick & Edwards, 2010).

Problematization (1st Moment): "the ways network builders define allowable identities and interests for people such as students" (Nespor, 1994 p. 13). Or, how to become indispensable by establishing oneself as "an obligatory passage point in the network of relationships" being built (Callon, 1986a).

Symmetry/Symmetrical Analysis: "A principle which holds that the material and non-human elements of any network should be treated analytically in the same way as the social and human elements" (S. Fox, 2005; Law, 1992b).

Translation: A process wherein "an entity, human or nonhuman, becomes selected, enticed, persuaded and partially or fully changed in ways that mobilize it to join the network's movements" (Fenwick, 2011). The central work-process of ANT in which "one element stands in for another or many others, just like a word in one language stands in for another, or a symbol stands for many strings of symbols. When one thing stands for others, the others are 'black-boxed,' that is, in a sense they are 'forgotten' about, assumed, or presumed" (S. Fox, 2005). "A way to think about how things come to be and how they change" (Fenwick & Edwards, 2010).

Appendix B: College of Engineering and Applied Science Curricular Prerequisite Requirements – Aerospace Engineering, Architectural Engineering, Civil Engineering, Mechanical Engineering



APPROVED CURRICULUM FOR B.S. DEGREE IN AEROSPACE ENGINEERING SCIENCES (128 total credit hrs)

Fall 2013

ASEN courses are offered and must be taken in this specific sequence

		Credit Hours	**Prerequisite ("C" or better)/ Co-req. (CR)**
FRESHMAN YEAR	**Fall Semester**	**15**	
	APPM 1350 Calculus 1 for Engineers	4	2 years high school algebra, 1 year geometry, 1/2 year trigonometry & a 75% or above on the ALEKS test
	GEEN 1500 Intro to Engineering	1	Freshman in Engineering (required for ASEN Freshmen, offered fall only)
	ECEN 1310 C & MATLAB Programming for ECE	4	no required prerequisite courses
	GEEN 1400 Engineering Projects/ASEN 1400 Gateway to Space	3	Freshman standing in Engineering
	Lower-division Humanities/Social Science Elective	3	Variable
	Spring Semester	**17**	
	APPM 1360 Calculus 2 for Engineers	4	"C" or better in APPM 1350
	PHYS 1110 General Physics 1	4	CR APPM 1350
	ASEN 1022 Material Science for Aerospace Engineers	3	"C" or better in APPM 1350, Programming (ECEN 1310, CSCI 1300 or GEEN 1300), and 1 year of high school chemistry
	Lower-division Humanities/Social Science Elective	6	Variable
SOPHOMORE YEAR	**Fall Semester**	**16**	
	APPM 2350 Calculus 3 for Engineers	4	"C" or better in APPM 1360
	ASEN 2001 Aerospace 1: Intro Statics, Structures, Materials	4	"C" or better in: APPM 1350, 1360, PHYS 1110, ECEN 1310 or CSCI 1300 or GEEN 1300, CR APPM 2350
	ASEN 2002 Aerospace 2: Intro Thermodynamics, Aerodynamics	4	"C" or better in: APPM 1350, 1360, PHYS 1110, ECEN 1310 or CSCI 1300 or GEEN 1300, CR APPM 2350
	ASEN 2012 Experimental & Computational Methods in AES	2	"C" or better in CSCI 1300, GEEN 1300 or ECEN 1030, CR with ASEN 2001 & 2002
	Free Electives	2	Variable
	Spring Semester	**17**	
	APPM 2360 Intro Diff Equations w/Linear Alg	4	"C" or better in APPM 1360
	ASEN 2003 Aerospace 3: Intro Dynamics & Systems	5	"C" or better in APPM 2350, ASEN 2001, 2012; CR APPM 2360
	ASEN 2004 Aerospace 4: Vehicle Design & Performance	5	"C" or better in APPM 2350, ASEN 2001, 2002, 2012; CR APPM 2360
	Upper-division Humanities/Social Science Elective	3	Variable

AREN Block Diagram

Sem	CR						
8 SPR	17	**Tech Elective-3**	**Tech Elective-3**		**AREN 4317-5 #** AREN Design (ARCH 4010*)	**ARCH 3214-3 #** History & Theories of Architecture II	**HSS Elective-3**
7 FALL	17	**Concentration II** AREN/CVEN XXXX-3	**Tech Elective-3**		**ARCH 4010-5 #** Arch. Design (Open to AREN SR's only)	**ARCH 3114-3 #** History & Theories of Architecture I	**HSS Elective-3**
6 SPR	15	**Concentration I** AREN/CVEN XXXX-3	**Tech Elective-3**	**Proficiency I** **CVEN 4545-3/4555-3 **** Struct. Des. **AREN 4110-3 #** HVAC Design **AREN 4570-3 #** Electrical Systems **CVEN 3256-3** Const. Equip./Methods		**Proficiency II** **CVEN 4545-3/4555-3 **** **AREN 4110-3 #** **AREN 4570-3 #** **CVEN 3256-3**	**WRTG 3030-3** Writing on Science/Society (Jr. standing) OR **HSS Elective*****
5 FALL	15		**AREN 3540-3 #** Illumination 1 (GEEN 1300)	**AREN 3010-3 #** Mech. Systems Bldgs. (AREN 2050, 2110, 2120)	**ECEN 3030-3 #** Electrical Circuits (APPM 2360)	**CVEN 3525-3** Structural Analysis (CVEN 3161)	**Free Elective-3**
4 SPR	16	**APPM 2360-4** Introduction to Linear Algebra & Differential Equations (APPM 1360)	**GEEN 1300-3** Engineering Computing	**AREN 2120-3 #** Fluid Mech. & Heat Transfer (APPM 2350, AREN 2110, co-req. APPM 2360)	**CVEN 3246-3** Introduction to Construction (4th-semester standing or instr. consent)	**CVEN 3161-3** Mechanics of Materials I (CVEN 2121, co-req. APPM 2360)	
3 FALL	17	**APPM 2350-4** Calculus III for Engineers (APPM 1360)	**PHYS 1120-4** Gen. Physics II (PHYS 1110, co-req. APPM 1360)	**AREN 2110-3** Thermodynamics (PHYS 1110, co-req. APPM 1360)	**AREN 2050-3 #** Building Materials and Systems (Sophomore standing)	**CVEN 2121-3** Analytical Mechanics I (PHYS 1110, co-req. APPM 2350)	
2 SPR	17	**APPM 1360-4** Calculus II for Engineers (APPM 1350)	**PHYS 1110-4** Gen. Physics I (co-req. APPM 1350)		**CVEN 2012-3 #** Introduction to Geomatics (APPM 1350 or equiv.)	**GEEN 1400-3** Engrg. Projects OR **GEEN 1410-3** Social Innovation and Design	**HSS Elective-3** OR **HUEN 1010-3** Intro to the Humanities***
1 FALL	14	**APPM 1350-4** Calculus I for Engineers (2 yr. HS alg., 1yr geom., ½ yr. trig.; or approval)	**CHEN 1211-3** Gen. Chem. for Engineers**** (1 yr. HS chem. or CHEM 1021, HS alg., co-req. CHEM 1221)	**CHEM 1221-2** General Chemistry Lab for Engineers	**AREN 1316-2 #** Introduction to Architectural Engineering	**AREN 1027-3** Engineering Drawing OR **AREN 1037-3**	

Fall 2012/revised August 2013

 # Course is offered only once per year (FALL or SPRING as shown)

( ) Prerequisite and co-requisite requirements for course listed

*** Other prerequisites: AREN 3010, AREN 3540, CVEN 3246, CVEN 3525**

**** CVEN 4545 Steel Design offered spring semester only; CVEN 4555 Reinforced Concrete Design offered fall semester only**

***** Freshmen (in their first two semesters of college) may take HUEN 1010 to fulfill the writing requirement. Students who choose this option will take another HSS elective in place of WRTG 3030.**

****** CHEN 1211 and CHEM 1221 must be taken concurrently**

SEM	CR	CVEN BLOCK DIAGRAM					
8TH SEM (SPR)	14	**CVEN XXXX-3** **Proficiency IV**	**CVEN XXXX-3** **Concentration II**	**Technical Elective-2**	**Technical Elective-3**		S-H Elective-3 **(upper-level)**
7TH SEM (FALL)	16	**CVEN XXXX-3** **Proficiency III**	**CVEN 3602**-3 Transportation Systems #	**CVEN XXXX-3** **Concentration I**		**CVEN 4899**-4 Senior Design Project (SR standing) #	S-H Elective-3 **(upper-level)**
6TH SEM (SPR)	15	**CVEN 3227**-3 Probability Statistics & Decision for Civil Engrs. (Restricted to JRs/SRs) #	**CVEN XXXX-3** **Proficiency I**	**CVEN 3111**-3 Analytical Mechanics II (CVEN 2121, co-req APPM 2360) #	**CVEN XXXX-3** **Proficiency II**		**WRTG 3030**-3 Writing on Science & Society (JR standing)
5TH SEM (FALL)	15	**CVEN 3246**-3 Intro. To Construction (JR standing or instructor consent)	**CVEN 3323**-3 Hydraulic Engineering (CVEN 3313) #	**CVEN 3525**-3 Structural Analysis (CVEN 3161)	**CVEN 3414**-3 Fund. of Env. Engr. (CHEN 1211, APPM 1360)	**CVEN 3708**-3 Geotechnical Engineering I (CVEN 3161)	
4TH SEM (SPR)	16	**APPM 2360**-4 Introduction to Linear Algebra & Differential Equations (APPM 1360)	**CVEN 3313**-3 Theoretical Fluid Mechanics (CVEN 2121) #	**CVEN 3161**-3 Mechanics of Materials I (CVEN 2121, co-req. APPM 2360)	**CVEN 3698**-3 Engineering Geology #	**GEEN 1300**-3 Intro Engr. Computing (co-req. APPM 1350 or equiv.)	
3RD SEM (FALL)	18	**APPM 2350**-4 Calculus III for Engineers (APPM 1360)	**PHYS 1120**-4 **PHYS 1140**-1 Gen.Phys II/Lab (PHYS 1110, co-req APPM 1360)	**CVEN 2121**-3 Analytical Mechanics I (PHYS 1110, co-req. APPM 2350)		**AREN 2110**-3 Thermodynamics (PHYS 1110, co-req. APPM 1360)	S-H Elective-3
2ND SEM (SPR)	17	**APPM 1360**-4 Calculus II for Engineers (APPM 1350)	**PHYS 1110**-4 Gen. Physics I (co-req. APPM 1350)		**CVEN 2012**-3[*] Introduction to Geomatics (APPM 1350) #	**AREN 1027**-3[*] Engineering Drawing	S-H Elective-3
1ST SEM (FALL)	17	**APPM 1350**-4 Calculus I for Engineers (2 yr. HS alg., 1yr geom., ½ yr. trig.; or approval by faculty advisor)	**CHEN 1211**-3 Gen Chem for Engineers $ (1 yr. HS chem. or CHEM 1021, HS Alg, co-req. CHEM 1221)	**CHEM 1221**-2 General Chemistry Lab for Engineers $	Basic Engineering Elective/ **GEEN 1400-3**[**]	**CVEN 1317**-2 Introduction to Civil & Environmental Engineering #	S-H Elective-3

Fall 2012/ revised April 2013

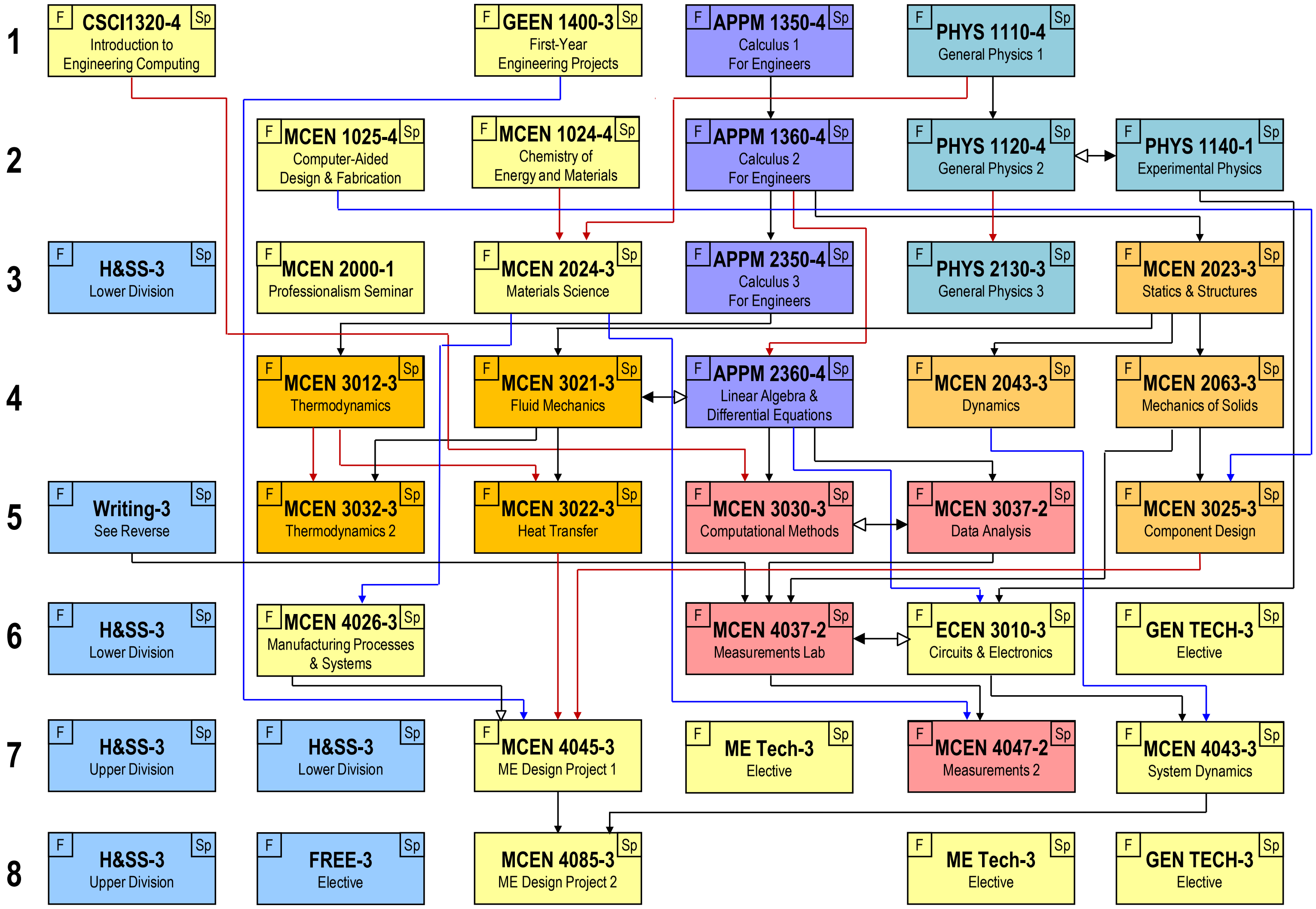
- \# **Courses marked thus are offered only in *SEMESTER* shown (fall or spring).**
- $ CHEN 1211 & CHEM 1221 must be taken concurrently.

[*] Both CVEN 2012 and AREN 1027 may be taken earlier or later in the program

[**] See curriculum description for acceptable courses

MECHANICAL ENGINEERING CURRICULUM (4-Year Plan)

F Sp = Semester usually taught



Prerequisite ⟶ Co-requisite ⟷ First course, if not taken as co-requisites ◁⟶ Second course, if not taken as co-requisites

Blue Version - Effective Fall 2015

Appendix C: Semi-Structured Interview Protocols – Students, Instructors, Teaching Assistants, Focus Groups

Fall 2013 Student Semi-Structured Interview Protocol:

1) Tell me about your semester.

- classes, difficulties, struggles, fun, challenges, satisfaction?

2) How hard do you work as a student / have you always worked the same amount?

  - did you find any of the material cool and why? Or what?

3) What did you expect coming here? Is it what you expected?

4) Which subjects are most important to being an engineer? Why?

5) Are there any students you are impressed by in engineering? Why?

  - Tell me what a good student is like in engineering.

6) Do you think there are people in the classroom that are well-respected? Why?

  - Are any of your peers well-respected? As a person, as a student, as an engineering?
  - Describe what they do to get that status.

Spring 2014 Student Semi-Structured Interview Protocol:

1) Tell me about your semester.

- What stands out to you?
- Did you find any of the material cool and why? Or what?
  - highlights
  - low lights
  - favorite classes
  - least favorite classes

2) What concepts or skills are most important to being an engineer? Why?

3) How did you like Diff Eq?

- workload
- lectures
  - do you go to lecture?
  - What do you usually do during lectures?
    - if on your phone – why? What do you look at? Who do you text? What do you notice?
    - How did you feel about the Diff Eq lectures (useful or not, engaging or not, etc.)

4) How did you do the Diff Eq projects?

- computer lab? Lab course? Personal laptop?
- What kind of laptop and phone do you have?

5) If you need help on your homework, where would you turn?

- office hours, internet, peers, upperclassmen, Facebook, Chegg, etc. or something else

6) Who do you trust to give you advice about engineering and why?

- Instructor, family member, advisor, peer?

Student Focus Group Protocol Fall 2014:

Opening Question: Tell me what APPM course (and who instructed it) you're currently in or the last one you completed, your major, and how many years you've been here at CU.

* How was that? - "I heard some not so happy noises — tell me about that. What was your experience?
—> * Tell me a little about your last math class. "need a loosening up question".

Topic A: Engineering Center Spaces
- How do you navigate the engineering center?
- Where are your favorite spaces?
- Where do you prefer to work, and why? (ITLL vs. E Lobby vs. Computer Labs)

Topic B: What's the purpose of Lecture?
- What do you take notes on?
- How do you take notes?
- How do you use phone, tablets, laptops, etc.?
- How do you ask questions?

Topic C: Think back to your last APPM Math homework: How did you do it?
- Solutions Manual
- Chegg
- Office Hours
- Peer Help
- Workspaces

Topic D: Lecture vs. Recitation, Instructors
- How do you ask questions in Lecture vs. Recitation?
- Do you feel more or less comfortable with recitation TA vs. lecture instructor?
- What do you think of the grading?

Topic E: What did you learn from doing the projects?
  - How did you find people to work with on the projects?
  - Where did you work?
  - What do you remember of working on the projects?

Topic F: Exams
  - What did you think of the exams?
  - How did you prepare for them?
  - What do you remember about taking them?

Ending Question: If you had a chance to give advice to students entering Diff EQ/Calc 3 with the same instructor that you had, what would you say?

Is there anything you want to talk about that you didn't get a chance to say today?

Instructor Semi-Structured Interview Protocol:

1) How did your classes go this semester?
    - anything different than when I observed?
    - anything unchanged from when I observed?
    - are the students any different?
    - are the logistics any different? More students etc.
    - are you any different?

2) If you could start from scratch – and teach these courses any way you wanted, what would they look like?
    - What would your ideal system be like?

3) How were your TAs this semester?
    - What are the most important qualities or actions for a TA to have/do?
    - what is most important thing a TA does to impact sophomore learning?
    - Can you imagine teaching this course without TAs? How would it be different?
    - Are there any other tasks you wish the TAs would do so you don't have to?
    - Are there any tasks that you wish you did instead of the TAs?

4) Part of the theory I am using includes the idea of tracing the impact of single artifacts. As exams come up a lot with the students, let's talk about a particular exam and how it affected students. For instance, the 1st midterm for Calc 3 this Fall 2014.
    - What do you remember from the exam?
    - Do you remember how students reacted to the exam? Can you share anything of what you heard from students?
    - How do you think that exam has affected the students in the class?

5) How do you handle students who are not passing?
    - Is it different in a smaller vs. larger class?
    - Have you spoken to any this semester?
    - How many, on average seek you out for counsel?
    - How often do you have students who repeat your course taking your course?
    - Do you talk to them about it?
    - How much do you think a student should work on material related to this course per week to pass the course?

6) Let's talk about grade breakdowns and how the curve works – again. Because I am curious about your opinion of the grade distribution for the last 5 years (see document) – can you shed some light?
    - how would you describe the variation from year to year?
    - Is there a trend? Where do you think this is headed?
    - would you share this information with students? Why/ why not?
    - in the meeting I sat in with you last week, you mentioned a desire to use the whole 0-100 scale, not just 60-100. Can you tell me more about this?

7) What do you think of the variety of support opportunities for Calc 3 (workgroups, lab courses, recitations, office hours)?

Instructor 2 Semi-Structured Interview Protocol:

1) Tell me about Diff Eq in the spring semester.
   a) Did any students or events stand out to you?
   b) Did you have much attendance at office hours?

2) How did you get involved in Teaching Diff Eq?
   a) How is the course structured (textbooks, exams, projects, homework, lecture) and why?
      - How were the point breakouts for each course element determined? (1000 points, 150 for HW, 50 each for projects, 150 for each of 3 exams, and 250 for final)
      - How was the 55% cut-off for exam scores chosen?
      - Does this change from year to year or remain constant? What causes it to change?
   b) How was the textbook for the course chosen?
      - How long has this particular book been in the rotation?
      - What are the trade-offs with the textbooks you've seen?
      - Do you think electronic textbooks will be an option in the future? Why/not?

3) How long have you been teaching here in the applied math department at CU?
   a) Where/what rooms on campus have you taught in - which were your favorite and why?
   b) Where and what will you teach next year?

4) You taught an "honors" Diff Eq when I observed – do you teach non-honors classes as well?
   a) What do you think of the students, honors or otherwise?
   b) How is the atmosphere in the lectures?
   c) Do you notice students on their phones? When/why?

5) General Diff Eq questions:
   a) When/how did the projects come about?
      - Who writes them?
      - How much do they change from year to year?
      - What is your desired learning outcome from these projects?
      - How did you choose teams of 3 or fewer students?
      - Why Matlab vs. Mathematica or something else?
   b) How do you choose homework problems to assign?
      - Why no standard problems?
      - What are the homeworks graded on?
   c) How do you feel about solutions manuals and online solutions services?
      - Is there a difference in the content students can get from the textbook vs. watching a YouTube video?
   d) How do you plan your lectures/is there a specific style or ideology that you employ?
   e) Do you have much interaction with the recitation instructors/TAs?

    - How often are re-grades for exams requested, and do these go to the instructors or the TAs?

  f) What if anything will you do differently next time you teach the course?

Teaching Assistant Semi-Structured Interview Protocol:

1) How long have you been here at CU?
    - a) How many semesters have you been a TA?
    - b) Which APPM courses have you taught?

2) Tell me about being an APPM TA.
    - a) Pros/cons?
    - b) Did you choose which courses you've TA'd or were you assigned? Why?
    - c) Grading parties?
        - i) How do you feel about the grades and grading policies in APPM?
    - d) Office Hours / APPM Help room?
    - e) Training seminar – what kinds of things did you learn/do you remember? What do you think is important to know for teaching the APPM fundamental courses?

3) How do you balance your TA responsibilities with the rest of your workload?
    - a) How much time does being a TA take?

4) How do you prepare for your workgroups/ recitations?
    - a) Tell me about running workgroups/ recitations.
    - b) do you have office hours? Where do you hold them, how do you prepare for them?

5) Tell me about your interactions with CU students.

6) What are your favorite things about being a TA in APPM?
    - a) Do any concepts stand out to you/matter to you?
    - b) Do remember any lessons, courses, cohorts, recitation sections, etc.?

7) What do you think of the exams?
    - a) Let's talk about the first midterm, specifically (see document).
    - b) Do you remember how the students reacted to the midterm?
    - c) Do you think the tests are fair? Why?

8) Grade distributions in Calc 3 over the last 5 years – does this surprise you? How or why?

Appendix D: Actor-Network Code Book

Category	Code	Abrv	Definition	Example
ANT Connections: Centered on Students	Students and Professors	**STU-Prof**	Ways in which students and instructors do or do not forge connections	Scott asks a question in class, Instructor responds and they have dialogue. Or, student asks question in class and instructor discourages them from asking a follow-up.
	Students and Students	**STU-Stu**	Ways in which students and students do or do not connect	Finding partners for a project, working together vs. not getting along with a roommate, not working well with other students, or comments about "social life" and friends.
	Students and TAs	**STU-TA**	Students connecting (and not connecting) to TAs	"actually had a good TA", or "TA didn't know anything"
	Students and Software	**STU-software**	Ways in which students and software do and do not connect (Matlab and Mathematica)	If a student learns or does not learn these software packages, how they either connect or do not connect to these as resources/skills. How an instructor views students connecting to these resources or not.
	Students and Mobile Technology	**STU-MobTech**	Ways in which students and mobile technologies connect or do not connect	Mobile technologies include phones, laptops, tablets, etc. and how students use them or don't use them in different settings and times.
	Students and Content	**STU-Content**	Students connecting (and not connecting) to classroom concepts/content	Content include the mathematical skills and concepts that instructors want students to know/ test them on exams. Students connecting means they remember them, not connecting means they don't remember.
	Students and Material spaces	**STU-Material**	Students connecting and not connecting to Material Spaces	Material spaces include classrooms, buildings, dormitories, fraternities, the large-scale areas that students occupy, connect to, or dislike being in.
	Students and Homework	**STU-Hmwk**	Students connecting and not connecting to Homework – including the resources enlisted in order to do homework	Homework includes the homework assignment itself, office hours, solution manuals, Chegg.com, anything that is enlisted (or not utilized) in the process of doing a homework assignment.
	Students and Exams	**STU-Exams**	Students connecting and not connecting to Exams – including the resources enlisted to do the Exam	Exams includes the exam itself, the studying leading up to it and the potential for a re-grade after it, the review sessions and crib sheets that are used or not used by students.

	Students and Grades	**STU-GPA**	Students connecting and not connecting to course structures like GPAs in engineering programs	Course Structures include GPA, minimum passing grades for prerequisites, curves, standard deviations, etc. – this can connect to feelings of competition as well.
ANT Connections: Centered on Faculty/ Instructors	Faculty and Faculty	**PROF-Prof**	Faculty connecting to other faculty, or not	Course coordination meetings, discussions of other faculty from one faculty, comparisons of faculty/teachers by students.
	Faculty and TAs	**PROF-TA**	Faculty connecting to TAs, or not	How do faculty and TAs connect? Or disconnect?
	Faculty and Software	**Prof-software**	Ways in which faculty and software do and do not connect (Matlab and Mathematica)	If a faculty uses these software packages, discusses them in class, or does not talk about them. How students view faculty using software or not.
	Faculty and Mobile Technology	**Prof-MobTech**	Ways in which Professors and mobile technologies connect or do not connect	Mobile technologies include phones, laptops, tablets, etc. and how Faculty use them or don't use them in different settings and times.
	Faculty and Content	**Prof-Content**	Professors connecting (and not connecting) to classroom concepts/content	Content include the mathematical skills and concepts that instructors want students to know/ test them on exams. Faculty connecting means they present the concepts, value them, or disvalue them and ignore them. Most lectures will exhibit faculty connecting to content through the medium of a chalkboard.
	Faculty and Material spaces	**Prof-Material**	Professors connecting and not connecting to Material Spaces	Material spaces include classrooms, buildings, offices, the large-scale areas that professors occupy, connect to, or dislike being in.
	Faculty and Homework	**Prof-Hmwk**	Faculty connecting and not connecting to Homework – including the resources offered in order to do homework	Homework includes the homework assignment itself, office hours, solution manuals, Chegg.com, anything that is enlisted (or not utilized) in the process of doing a homework assignment.
	Faculty and Exams	**Prof-Exams**	Professors connecting and not connecting to Exams – including the resources enlisted to do the Exam	Exams includes the exam itself, the studying leading up to it and the potential for a re-grade after it, the review sessions and crib sheets that are encouraged or ignored by teachers.
	Faculty and GPAs	**Prof-GPAs**	Professors connecting and not connecting to course structures like GPA in	Course Structures include GPA, minimum passing grades for prerequisites, curves, standard deviations, etc. Connecting could be enforcing, commenting on, etc.

			engineering programs	
ANT Connections: Centered on TAs	TAs and TAs	**TA-TA**	TAs connecting to other TAs, or not	Do TAs work together? When, why? Or do they work in isolation? How does scheduling contribute to this?
	TAs and Software	**TA-software**	Ways in which TAs and software do and do not connect (Matlab and Mathematica)	If a TA uses these software packages, discusses them in class, or does not talk about them. How students view faculty using software or not.
	TAs and Mobile Technology	**TA-MobTech**	Ways in which TAs and mobile technologies connect or do not connect	Mobile technologies include phones, laptops, tablets, etc. and how TAs use them or don't use them in different settings and times.
	TAs and Content	**TA-Content**	TAs connecting (and not connecting) to classroom concepts/content	Content include the mathematical skills and concepts that instructors want students to know/ test them on exams. TAs connecting means they present the concepts, value them, or disvalue them and ignore them. Most recitations will exhibit TAs connecting to content through the medium of a chalkboard.
	TAs and Material spaces	**TA-Material**	TAs connecting and not connecting to Material Spaces	Material spaces include classrooms, buildings, offices, the large-scale areas that TAs occupy, connect to, or dislike being in.
	TAs and Homework	**TA-Hmwk**	TAs connecting and not connecting to Homework – including the resources offered in order to do homework	Homework includes the homework assignment itself, office hours, solution manuals, Chegg.com, anything that is enlisted (or not utilized) in the process of doing a homework assignment.
	TAs and Exams	**TA-Exams**	TAs connecting and not connecting to Exams – including the resources enlisted to do the Exam	Exams includes the exam itself, the studying leading up to it and the potential for a re-grade after it, the review sessions and crib sheets that are encouraged or ignored by TAs
	TAs and GPAs	**TA-GPA**	TAs connecting and not connecting to course structures like GPA in engineering programs	Course Structures include GPA, minimum passing grades for prerequisites, curves, standard deviations, etc. Connecting could be enforcing, commenting on, etc.
ANT CONCEPTS AND NON-HUMAN CONNECTIONS	Time and Temporality	**TIME**	Heterogeneous connections to time – of all kinds	Students could talk about running out of time, or not having enough time. Exams are time-limited, and connected to time.
	Competition	**COMPETE**	Heterogeneous connections to Competition	What is "competition" and how does it arrange human activity? Grading on a curve, students discussing beating each other, are enlisting and connecting to "competition".
	Cost and	**MONEY**	Heterogeneous	How is Money related to activity? Students talking about

	Money$$	**$$**	connections to Money, Cost of Goods, Value	going to lecture because it costs them $100 each time, etc.
	Gender	**GENDER**	Heterogeneous connections to gender	How do students and teachers talk about it? Do material spaces organize them certain ways by gender (e.g. seating in room?)
	Majors	**MAJOR**	Heterogeneous connections to major departments, disciplines	How are students, faculty, and TAs connected to disciplinary majors? How are non-human spaces connected to majors?
	Engineering Discipline	**Engineering**	Heterogeneous connections to “engineering”	Engineering as a concept, discipline, actor-network in itself. How are humans connected to “engineering” and how are non-humans connected to “engineering”?
	Post-Graduate / Jobs/ Industry	**Post-Grad**	Heterogeneous connections to postgraduate activity	What happens after school? How do people talk about, how do they connect to future activity, etc.
	Durability	**DURABLE**	How long (in time) has something existed?	Anything relating to persistence through time of an actor-network
	Stability	**STABLE**	How resistant to disruption?	Anything relating to stability in terms of ability to resist disruption, and how something resists a given disruption.

Appendix E: Walther & Sochacka Q3 Framework, 2014

Questions of Quality in Interpretive Research

Validation: Do the findings appropriately capture & represent relevant aspects of the social reality observed?

Do we get to see what we think we see?

Are our interpretations grounded in the participants' social realities?

Are our findings relevant and meaningful beyond our study setting?

Theoretical Validation concerns the fit between the social reality under investigation and the theory generated

- What is, in terms of scope and nature, the specific social reality we want to investigate?
- How will we be able to see / what could prevent us from seeing the full extent of this social reality?
- How can we ensure that our interpretations do justice to the complexity of, but capture patterns of coherence within the social reality?
- How do I know that the findings make a meaningful contribution to the relevant body of theory?

Procedural Validation concerns features of the research design that inherently improve the fit between the reality studied and the theory generated

- What are appropriate means by which we can 'see' the social reality under investigation?
- What features can we build into the inquiry to mitigate threats to an authentic view of the social reality?
- What features can we design into our process of interpretation to mitigate the risk of mis-constructing the social reality of our participants?

Communicative Validation concerns the integrity of the interlocking processes of social construction with the relevant communication communities

- How can we authentically co-construct meanings of participants' social realities on their own terms?
- How can we maintain the meaning constructed in the communication community throughout our analysis?
- What are robust ways of co-constructing interpretive meaning in a communication community with other researchers?
- How can we construct our findings within the meaning conventions of the relevant research community?

Pragmatic Validation concerns the compatibility of theoretical constructs with empirical reality

- What theoretical constructs do we bring to the study?
- What theoretical assumptions do we make about the nature of the reality under investigation?
- How do we know whether these assumptions 'survive' the exposure to the social reality in the field?
- What assumptions about the structure of the social reality does our research approach make?
- How meaningful are our interpretations for the social reality under investigation? (Insight, resonance, change...)
- How meaningful are the theoretical constructs we generate for social realities similar to the one under investigation? (Insight, affect, attention, utility, change...)

Ethical validation concerns aspects of integrity and responsibility throughout the research process

- What are our motivations and intentions for investigating this social reality?
- What are the impacts of our interests, biases, preconceptions or intentions on this investigation?
- How can we ensure legitimate and responsible decisions to inform our interpretations?
- How can we meaningfully and equitably engage all members of the research team?
- Do our findings do justice to the lived realities of our participants?
- What are impacts of our research for the social reality investigated and for similar social realities?

Process Reliability concerns the mitigation of random influences on the research process

- How can we mitigate, as far as possible, random influences on our process of seeing the social reality under investigation?
- How can we capture & record the constructions of participants' social realities in a dependable way?
- How can we foster consistency of our process of interpretation?
- How can we document and authentically demonstrate the dependability of our entire process of investigation?

Walther, J., Sochacka, N. W., & Kellam, N. N. (2013). Quality in interpretive engineering education research: Reflections on an example study. *Journal of Engineering Education, 102*(4), 626-659. doi: 10.1002/jee.20029

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Appendix F: De-Identified Syllabi from Calc 3 and Diff Eq

APPM 2350 Calculus III

Course Objective: This course extends the ideas of single–variable calculus (eg. differentiation, integration, optimization) to functions of several variables. Topics include vectors and vector operations, curves in space, multi–variable functions, partial differentiation, multiple integrals, line integrals, Stokes's Theorem and Gauss's Theorem. These concepts form the mathematical basis for many areas in the Sciences and Engineering.

Text: Chapters 10–13 of *Essential Calculus* 2nd edition, by James Stewart.

Recitations: Recitations meet for 1 hour on Thursdays. The purpose of the recitation is partly to help you with the homework. More importantly, the recitation is intended to further clarify the Calculus III concepts.

Homework: There are two types of homework problems in this course. On-line problems associated with each lecture will be due prior to the next lecture. Hand written problems will be due, each Friday at 4 PM, under your TA's office door. Late homework will **not** be accepted or graded. Graded work will be returned during the next recitation, and the solutions will be posted on the course web page.

Exams: There are three midterm exams and a comprehensive final. The midterms are on Wednesdays (Sep 25, Oct 23, and Nov 20) from 5:00–6:30 PM. The final exam is Wed, Dec 18, from 7:30–10:00 AM. There will be **no** make–up exams or early exams. If you are sick during a midterm, please bring a note from your doctor verifying your illness. Your course grade will then be determined by the rest of your course work. Please bring your CU ID to each exam. Electronic devices are not allowed during the exams. If you have questions about exam grading, within one week of the exam submit to your instructor a detailed written explanation addressing the specific grading errors.

Computer projects: To give you experience solving larger, more difficult problems involving multiple concepts, there will be three computer-based projects assigned during the semester. Suggested software is Mathematica, although MatLab and Maple may be used. Further details about the projects will be posted on the course web page. These projects are required of all students registered in APPM 2350.

APPM 2450: This is an optional, 1 credit Pass/Fail lab–based course in which one can learn more about Mathematica. This software is useful for visualizing functions and solving multi–variable problems. Students wanting additional help on their 2350 projects are also encouraged to sign up for this lab.

Grade determination: There is a total of 800 points for the course. The points are distributed over homework (100 points), recitation assignments (50 points), three projects (50 points each), three midterm exams (100 points each), and a cumulative final exam (200 points). You must earn a C- or better on your exams to earn a grade of C- or better in the course. After the final exam, if your exam scores average to something less than a C-, it is not possible to earn a C- or better in the class.

Dropping the course: Advice from the Dean's office and your department advisor is recommended before dropping any course. After Nov 1, dropping the course is possible only with a petition approved by the Dean's office.

Course web page and D2L: (*http://amath.colorado.edu/course-pages/*) It is your responsibility to check the course web page and D2L, on a regular basis, where you will find detailed information about homework assignments and solutions, past exams, tutoring options, pre–exam review sessions, exam rooms and times, and office hours. In addition, these sites contain policies on illness, academic honesty, and special accommodations for religious holidays and documented special needs.

Blue books: Each student is required to purchase **five** 8.5×11 blue books and give them to the TA by the second recitation (Sep 5). These will be used for the exams, so please do not write anything on the front of the books.

Academic Honesty: Students are encouraged to work in groups, however **all work turned in must be your own.** Violation of the CU Student Honor Code (*http://www.colorado.edu/academics/honorcode*) or the College of Engineering's Academic Honesty Advising Guidelines (*http://www.colorado.edu/engineering/ar_ugradadvising.html*) will result in a final grade of F in this course.

APPM 2360 Differential Equations with Linear Algebra

Course Goals: To learn the concepts and techniques of ordinary differential equations and linear algebra. Topics include qualitative methods, linear and nonlinear ODEs, and first and second order systems.

Text: *Differential Equations and Linear Algebra*, by Farlow, Hall, McDill, & West (2nd edition). **No**, the first edition won't work as the problems are different.

Course web page: You will find useful information on the course web page, such as homework assignments and solutions, practice exams with solutions, and where to go for deeper understanding of course material (such as office hours and tutoring options).

Recitations: Recitations meet for 1 hour on Thursdays. The purpose of the recitation is only partly to help you with the homework and labs. More importantly, the recitation is intended to further clarify APPM 2360 concepts. There are no recitations the day after an exam.

Office Hours: Instructors will be in their offices during their posted office hours. TA office hours will normally be in ECCR 211. During the weeks that the projects are due, they will hold office hours in ECCR 143.

Grade determination: There are a total of 1000 points for the course. The points are distributed over homework assignments (150 points), three projects (50 points each), three unit exams (150 points each), and a cumulative final exam (250 points). Note that your grades for exams, homeworks, projects, and final will be available on **desire2learn**.

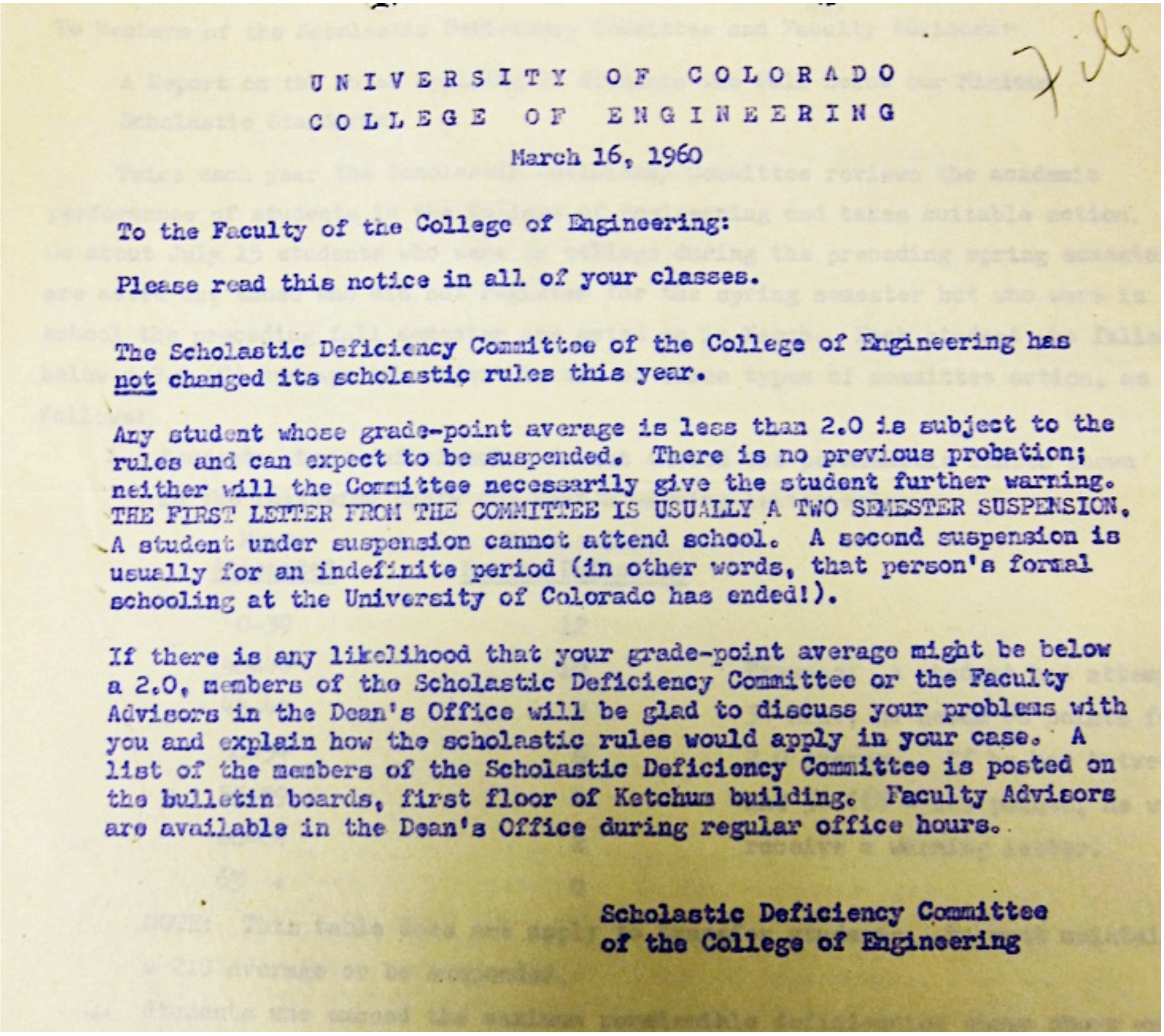
You must earn an average of 55% or better on your exams (midterms and final) in order to earn a D- or better in the course. After the final exam, if your exam scores average to less than 55%, you will earn an F in the course regardless of your homework and lab scores. After the final exam, if your exam scores average to 55% or better, then your homework and lab points will be factored in to determine your course grade. (Note: it is possible to have a 55% average on the exams and still earn a D or F in the course if your homework and quiz scores are low.)

Homework: To do well in this course, attend the lectures and do (and understand) the homework. Ask questions. Homework is due in recitation on Thursdays, except during exam weeks, when they are due the following Monday in class. Late homework will **not** be accepted or graded; you must show all your work in your homework. **Homework problems and due dates are available on the course webpage (under the "schedule" tab).** The problems listed are those that are to be turned in for credit; however, it is your responsibility to do as many problems as is necessary to understand the material and know how to do the graded problems.

Projects: You will turn in three projects for APPM 2360. Projects and due dates will be posted on the course web site and you will submit a **pdf copy on desire2learn** by **5pm** on the day it is due. You may work in groups of **3 people or fewer** and you can work with students in **any section** of this course. If you work in a group, only one pdf needs to be submitted for the whole group. All group members will receive the same grade; the instructors will not arbitrate on internal group disputes. Late projects will **not** be accepted or graded. In the projects, you will investigate certain topics in differential equations in more detail, perform some of your analysis in a computer software package (Mathematica, Matlab, or MVT), and turn in a write-up of your results. **Pay special attention to your writeup and the "good" and "bad" examples on the website.** The majority of lost points are due to directions being ignored.

APPM 2460 This is a one-credit course http://amath.colorado.edu/courses/2460 specifically designed to help you with the projects and use of mathematical software. While not required, you are encouraged to sign up for APPM 2460. Please direct questions about APPM 2460 to the coordinator,

Appendix G: Notice from the Scholastic Deficiency Committee, March 16, 1960



File

UNIVERSITY OF COLORADO
COLLEGE OF ENGINEERING

March 16, 1960

To the Faculty of the College of Engineering:

Please read this notice in all of your classes.

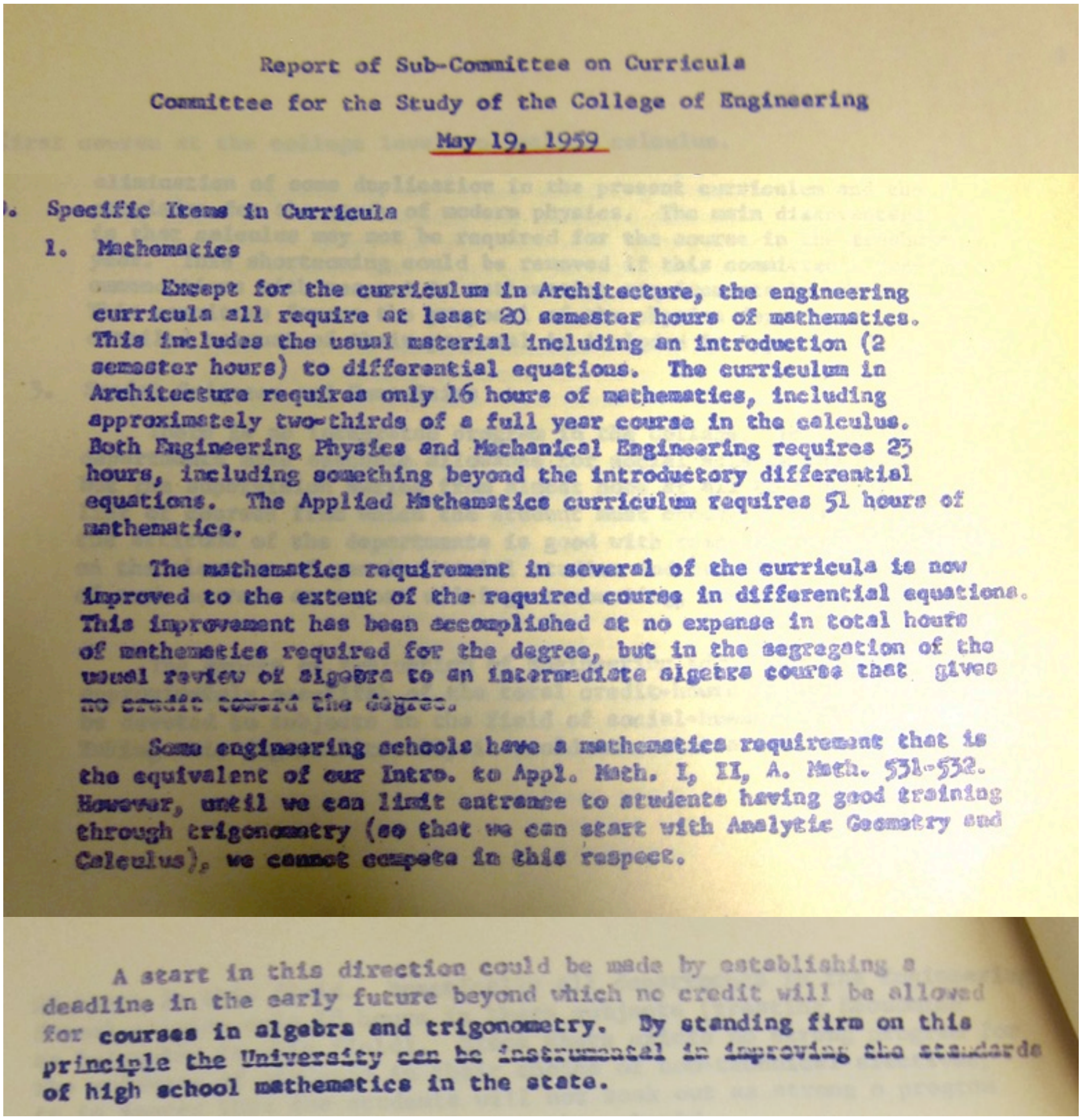
The Scholastic Deficiency Committee of the College of Engineering has not changed its scholastic rules this year.

Any student whose grade-point average is less than 2.0 is subject to the rules and can expect to be suspended. There is no previous probation; neither will the Committee necessarily give the student further warning. THE FIRST LETTER FROM THE COMMITTEE IS USUALLY A TWO SEMESTER SUSPENSION. A student under suspension cannot attend school. A second suspension is usually for an indefinite period (in other words, that person's formal schooling at the University of Colorado has ended!).

If there is any likelihood that your grade-point average might be below a 2.0, members of the Scholastic Deficiency Committee or the Faculty Advisors in the Dean's Office will be glad to discuss your problems with you and explain how the scholastic rules would apply in your case. A list of the members of the Scholastic Deficiency Committee is posted on the bulletin boards, first floor of Ketchum building. Faculty Advisors are available in the Dean's Office during regular office hours.

Scholastic Deficiency Committee
of the College of Engineering

Appendix H: Sub-Committee on Curricula Report Detailing Mathematics, May 19, 1959



Report of Sub-Committee on Curricula

Committee for the Study of the College of Engineering

May 19, 1959

. Specific Items in Curricula

1. Mathematics

Except for the curriculum in Architecture, the engineering curricula all require at least 20 semester hours of mathematics. This includes the usual material including an introduction (2 semester hours) to differential equations. The curriculum in Architecture requires only 16 hours of mathematics, including approximately two-thirds of a full year course in the calculus. Both Engineering Physics and Mechanical Engineering requires 23 hours, including something beyond the introductory differential equations. The Applied Mathematics curriculum requires 51 hours of mathematics.

The mathematics requirement in several of the curricula is now improved to the extent of the required course in differential equations. This improvement has been accomplished at no expense in total hours of mathematics required for the degree, but in the segregation of the usual review of algebra to an intermediate algebra course that gives no credit toward the degree.

Some engineering schools have a mathematics requirement that is the equivalent of our Intro. to Appl. Math. I, II, A. Math. 531-532. However, until we can limit entrance to students having good training through trigonometry (so that we can start with Analytic Geometry and Calculus), we cannot compete in this respect.

A start in this direction could be made by establishing a deadline in the early future beyond which no credit will be allowed for courses in algebra and trigonometry. By standing firm on this principle the University can be instrumental in improving the standards of high school mathematics in the state.