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Learning to Conduct "Team Science" through Interdisciplinary Engineering Research

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Learning to Conduct "Team Science" through Interdisciplinary Engineering Research

Abstract

Today's science and engineering graduate students will likely work in collaborative settings and interdisciplinary teams in their future careers. The solutions to the greatest scientific global challenges rest on the productivity and success of diverse teams of specialists working together. Recent work has begun to explore the optimization of collaborative interdisciplinary efforts, paying attention to factors such as interpersonal dynamics and teaming. This emerging field has been dubbed "Science of Team Science" and has been studied mainly in professional research settings. This exploratory study seeks to understand how graduate students learn to conduct team science across institutions and disciplines. Participants consisted of graduate students that differed in a variety of characteristics, including time in their graduate program, focus within materials science engineering, and level of experience with independent laboratory research. Senior graduate students were responsible for facilitating an interdisciplinary research project and delegating research work tasks to teams of other students. We present findings from a mixed methods study which evaluates individual and team successes in collaborative multi-institutional and interdisciplinary research. Implications of this work include helping programs develop competencies for their graduate students that include "team science" and collaborative skills.

I. Introduction

To solve complex, ill-structured engineering and science problems in an advanced technological world with societal challenges, new tools and approaches to research and education need to be developed[1-3]. The solutions to the greatest scientific challenges rest on the productivity and success of diverse teams of specialists working together. In order to best educate future professionals, the higher education and professional education research communities need to understand the ways in which the skills needed for conducting collaborative research can best be developed[4]. The "Science of team science" (a term which can be shortened to "SciTS"—pronounced "sights") is a relatively new field that researches the knowledge and skills required to conduct effective cross-disciplinary research and how teamwork and research outcomes in this context can be effectively implemented, managed, and evaluated. Exploratory studies of these issues at the graduate level in engineering and science disciplines will facilitate teaming and training strategies so future practitioners and researchers are prepared to operate effectively in high-performing cross-disciplinary teams.

II. Literature Review

A. Attributes and Definitions of Effective Teams

According to Katzenbach and Smith[5], ill-structured problems require strong *teams* of interdependent collaborators. The idea of a team extends beyond a group of people who happen to be working on the same project, emphasizing the importance of shared commitment and purpose with performance goals to which they hold themselves and each other accountable. Similarly, Kozlowski and Ilgen[6] argue that the primary difference between working groups and teams is the distributed expertise and collective knowledge that is shared between the members. In a team, although there may be leaders or members with more experience, it is acknowledged that each individual can and should contribute to the knowledge of the team. In order to leverage each individual's technical expertise and experience, effective communication and teamwork practices are essential. An effective team is comprised of individuals with complementary technical and problem-solving skills as well as adequate interpersonal skills[5]. These skills are necessary to navigate the phases of team formation that are independent of the specific shared goal or task. All teams go through stages of formation, whether they are brand new collaborations or existing projects that have an influx of new members. Describing these stages, Tuckman[7] proposed the "forming, storming, norming, performing (and adjourning)" model to describe the interpersonal dynamics that face teams, even those that seem to be "dream teams" at the beginning.

B. Challenges in Conducting Team Science

Challenges facing interdisciplinary teams are both individual and cognitive, and social, as group members share knowledge in order to most effectively solve a problem[8].Team effectiveness can be influenced by a number of characteristics including level of trust and social cohesiveness, size of the team, physical environment, leadership traits and behaviors, team goal setting and communication, and alignment of team, task, and outcome interdependence[2].

Most immediately critical to a team's success is the social elements of effective communication. This aspect of team science cannot be understated in order to transition into high-performing phases of teaming. Organizational behavior scholars have found face-to-face team communication to be the preferred mode for team success, as the ability to share emotion may not be translated through more disconnected venues[6,9]. For example, in Pentland's[9] organizational behavior studies, team members' communication patterns including tone of voice, body position, and body language was found to be the most critical factor for team success regardless of the expertise and skills of individuals in the topic at hand. Success was also facilitated when team members sought connections with each other outside the project[9].

As teams become more geographically dispersed, deliberate communication strategies are required in order to foster successful collaborations. Remote collaborations are especially sensitive to technologic, environmental, socio-cognitive, and emotional factors[2]. After face-to-face communication, Pentland[9] found videoconferencing and phone to be the next most valuable forms of communication, but their effectiveness decreases as more people participate. E-mail and texting were found to be least valuable. Therefore, virtual teams need to be attentive to how they aim to communicate and foster team interaction using less-than ideal communication venues. In addition to the time required to navigate team formation and other interpersonal issues, logistical issues such as time zone and cultural differences add additional complexity.

Especially within team science contexts, Stokols et al.[2] recommend that teams explicitly discuss research outcomes, timelines, and expectations with the understanding that teams tend toward conflict, since "[u]nrealistic expectations for complete cooperation and harmony, along with ambiguity of goals and intended outcomes, can impede the teams' collaborative efforts. Members must be aware of the collaborative constraints, disagreements, and conflicts that they are likely to encounter over the course of the project and be prepared to dedicate considerable time and effort toward establishing common ground both intellectually and socially" (p. S105). Conflicts may also arise in the later stages of team science: Publications in team science often involve several authors. In fields where first-author and/or single-author publications are most highly valued, it may be difficult to achieve consensus over author order, or buy-in on large projects[10]. In order to overcome these issues, Bennett and Gadlin[11] stress the integration of workload between team members, regular meetings, and clear individual and group expectations as criteria for success in collaborative settings.

C. A Call for Rigorous Team Research: Introducing the "Science of Team Science"

The Science of Team Science (SciTS), a title coined in October 2006 during a conference organized by the National Cancer Institute, is a relatively new niche in the sciences[12]. Originally intended to address the need to evaluate and study large scale transdisciplinary research, SciTS is an emerging field of study that "...aims to develop fundamental knowledge about [team science] and translate that knowledge into evidence-based strategies for success"[13] (p. 1). The SciTS community is charged with conducting rigorous and systematic studies of collaborative scientific efforts, rather than relying on anecdotal strategies for team success. A groundbreaking study conducted by Falk-Krzesinski et al.[14] quantified current team scientists' ideas on the areas on which future team science research should be performed. Statistical results indicate several main themes where research progress is needed: definitions and models of team science; disciplinary dynamics and team science; structure and context for teams; institutional support and professional development for teams; management and organization for teams; characteristics and dynamics of teams; and, most suggested, was ways to measure and evaluate team science.

In itself an interdisciplinary field of study, SciTS literature draws from contributions of practitioners with experience in conducting or overseeing these interdisciplinary team projects as well as concepts and methods from various knowledge domains exploring teams (e.g., psychology, management, communication, public health, computer science). The methods used to study team science are also interdisciplinary: A variety of methods have been employed in both SciTS, which stem from various research paradigms including quantitative, qualitative, and mixed methods (i.e., research designs employing both quantitative and qualitative methods) approaches. With the prevalence and prestige of quantitative research, especially within the sciences, predictive models exploring factors of successful teams and Likert-type scale surveys are common. However, Börner et al.[15] advocate the use of mixed methods research designs in order to develop robust evaluative tools and explore the nuances of interpersonal and communication dynamics within complex interdisciplinary collaborations.

D. Opportunities to Study the Training of Scientists in SciTS

Most of the SciTS research studies practitioners and generally fails to provide recommendations for students or young professionals *learning* to conduct team science. Fiore[8] proposes that i*nterdisciplinary research as teamwork* is a learned skill rather than an innate attribute, and promotes several recommendations in order to better prepare scientists to work in teams, including accurately assessing team competencies and team training (cross training, teambuilding, crew resource management, and leadership training). Most relevant to the present study, however, is Fiore's recommendation that scientists engage in interdisciplinary education in order to understand and engage with diverse disciplines while solving problems[8]. Stokols et al.[2] echo this call: Preparation and practice of collaborative research are essential in forming future productive teams. Much of this training revolves around becoming aware (through experience) of the factors that foster or inhibit strong collaborations, which requires deliberate reflection as teams succeed or fail in their initiatives.

A number of programs have funded educational initiatives that intend to prepare graduate students to be future leaders in interdisciplinary research. One of these projects is the Integrative Graduate Education and Research Traineeship (IGERT), supported by the National Science Foundation[16]. Awarded IGERT proposals seek to train the next generation of engineers, scientists, and scholars in disciplinary grounding, integration, teamwork, communication, and critical awareness[1]. Although these skills are similar to those recommended to be studied in the SciTS literature, studies evaluating and assessing IGERT programs typically focus on curricular structure and content, descriptive analyses (e.g. number of scholarly activities such as publications and presentations, time to degree, demographics etc.), and career trajectories[1,17-19]. However, we propose that evaluation of *authentic* learning through IGERT collaborations can yield insight into the dynamics of conducting interdisciplinary work at the graduate level, the training support and experiences required to achieve particular outcomes, and how outcomes can be assessed.

This study aims to explore teamwork and communication processes towards this end within one particular geographically diverse IGERT project—The Integrative Graduate Education and Research Traineeship in Magnetic and Nanostructured Materials (IGERT-MNM) with virtual interdisciplinary research teams. A mixed methods study (employing longitudinal survey data and content analysis of team communications) of graduate student teams learning to conduct authentic interdisciplinary research tasks will provide a) new suggestions for Team Science and interdisciplinary science training programs and b) work toward developing piloted tools for the evaluation of graduate student Team Science across institutions and disciplines. Therefore, the research questions this study seeks to answer are as follows:

> *Research Question 1: How do the characteristics for effective virtual teaming manifest in email communications supporting a graduate student-led multi-institutional and interdisciplinary research project?*
>
> *Research Question 2: What are the most critical criteria of successful multi-institutional and interdisciplinary research projects? What are the most critical barriers that must be overcome?*

This paper presents an analysis of the first phase of a larger research project studying interdisciplinary team science in graduate students. This phase was conducted over four weeks in Fall 2015. The analysis of survey results and content analysis of email communications during this time period is described below.

III. Methods

A. Participants

Graduate engineering and science students that are part of IGERT-MNM were recruited for the study. As a part of the IGERT traineeship, all affiliated graduate students participate in an extracurricular interdisciplinary research project which extends through the calendar year in addition to regular graduate research and coursework responsibilities. Interdisciplinary research teams were formed based on interest, each comprised of students from at least two of the three IGERT-MNM-affiliated universities. Team leads are advanced graduate students that act as research project managers and are responsible for communicating with advising faculty and facilitating group progress. This educational environment, where graduate students can practice leading research teams and conducting interdisciplinary team science, is highly unique, as discussed in the literature review. All IGERT trainees in this collaboration were recruited to be part of our study, after IRB approval was obtained. Of the 15 trainees in this IGERT, 13 opted to contribute to the study. These participants represent three interdisciplinary research teams with independent research goals, timelines, and outcomes (Table 1).

Table 1: IGERT Student Team Descriptions

Team	Number of Team Members	Broad Subject Area
A	5	Actuation of soft robotics for human use
B	5	Nanostructure synthesis and characterization
C	3	Development of SPASER technology

For this study, we employed a mixed methods research plan which included survey data and content analysis methods. The surveys employed are evaluative rather than predictive, and required trainees to rate their performance and their team's performance in a number of different categories. The surveys were compiled from important elements of teamwork as found in literature. The same survey was sent to participants each week for four weeks, so short-term longitudinal data on the same criteria is collected. The survey protocol is given in Appendix A.

As a method of understanding how graduate researchers learn to communicate in interdisciplinary settings, we also collected the email threads between team members. Content analysis methods were used to analyze these data. Codes by which to analyze the data were based on the attributes required for effective virtual team efforts described by Stokols[2] and adapted to include new themes emerging from the data. This coding schema is shown in Table 3. In this study, we are holding a constructivist view of the science of team science within the learning environment. Rather than all students subscribing to a positivist truth, each student understands their part within the group as an individual. This lens affects the ways in which the team science is conducted. Through our data analysis, we, as researchers look for the ways in which students are constructing their own methods for leading and/or conducting interdisciplinary team research.

IGERT trainees who declined to participate in the study were deleted from the email correspondence transcripts before data analysis begins: Although this leaves an incomplete view of the conversations via email communication, this limitation occurs because of respect for those declining to participate in the research. In addition, many groups met on other venues to discuss research, such as Skype, Google Hangouts, or on the phone. These modes of communication were not studied in this project. However, the team leader from Group A estimated they conducted 95% of team business over email; the leader from Group B estimated 90%, and Group C estimated 30% of their communication was through email and the rest through Skype. No groups reported that texting or other "abbreviated" forms of communication were significant for conducting large amounts of team science.

IV. Results

A. Longitudinal Survey Results and Qualitative Coding

The results for this mixed methods study will be presented by team. The data analysis and coding schema are presented in this section, and the following sections will combine the quantitative and qualitative results for all the teams, understanding that team context is valuable in understanding the learning of interdisciplinary team science in our graduate student participants. The Likert-type response data were transformed into a new numerical scheme centered around "0" (Neutral/Neither agree nor disagree), with positive values implying agreement and negative values implying disagreement with the statements in the survey (Table 2). As described above, individuals filled out the same survey each week to provide longitudinal data.

Table 2. Corresponding values to survey results

Survey Response	Quantitative Value
Not Applicable	--
Strongly agree	2
Agree	1
Neither disagree or agree	0
Disagree	-1
Strongly disagree	-2

Each individual's responses were summed over the weeks to give a holistic understanding of the individual ratings on each of the survey items, which were probed from three perspectives: individual proficiency with the item, team proficiency, and the importance of the item to project success. The individual values for the members of each team were then summed to provide an indication of how the team as a whole perceived the overall effectiveness of the team pertaining to each question. As an example, the following responses were given by each member of Group A on a weekly basis for the first question-setting weekly goals: Member 1: 3,5,4; Member 2: 5,4,5; Member 3:1,5,4; Member 4:2,5,2,5. Note that only one member responded to all surveys sent out. After coding the values became: Member 1: 0,2,1; Member 2: 2,1,2;Member 3:-2,2,1; Member 4:-1,2,-1,2. Summing all of these coded values leads to 11 (0+2+1+2+1+2-2+2+1-1+2-1+2).Therefore, the closer the summed individual coded responses are to the summed team responses, the more aligned individual and team performance might be. For example, a team member could agree that both they and their team did well at setting goals over the observed time period. Misalignment between individual score and the team score would indicate conflict within the team in that particular dimension of their teamwork and project. The closer the summed importance value is to the summed individual and the summed team responses, the more likely that the team members agree on the importance of the trait probed by the question. The magnitude of the value indicates agreement of the team: If a team's scores are close to zero, it is an indication of contradictory responses and may indicate team tension on the trait probed. Optimal team productivity results when the team members are in agreement with how they are performing as a team, and all feel that the tasks (which were all derived from literature) are important.

In the presentation of the survey data, we highlight negative values (< 0) in the Team Alignment Score and Importance Alignment Score columns (shown in boldface) because these numbers indicate that the individual team member perceptions of individual achievement were higher than their perceptions of the team's success, and the importance of the skill was less than the teams' perception of their success on the item, respectively. There were some weeks in which several participants did not complete survey data, resulting in missing data values.

The qualitative data was coded through the construction of directed content analysis methods[20]. A codebook of final themes and definitions was compiled through iteration with the team of researchers. The finalized codebook describes ten themes that recur through email communication in the three virtual teams studied in this research. The initial coding schema was based on the topics discussed by Stokols,[2] who described six critical virtual teaming factors: Intrapersonal, Interpersonal, Physical Environment, Societal and Political, Technologic, and Organizational components. The elements were re-organized and expanded upon through our qualitative analysis to represent the ten themes in the codebook, with the associated definitions, shown in Table 3.

Table 3: Codebook for Qualitative Coding

Theme	Definition	Corresponding Example
Familiarity and Social cohesiveness	Quality of interaction between members	• Showing recognition of personal situations/events, informal communication about non-technical subjects • Consideration for individual needs over the needs of the team
Leadership Traits Exhibited	Demonstration of responsibility	• Taking initiative to delegate tasks and motivate progress • Lack of delegation or poor project management
Goals	Setting or referencing milestones	• Keeps the overarching team goal in mind • Seems to be unclear on the long-term goals of the project
Tasks	Setting or referencing short-term output	• Completing tasks within the long-term goal • Failure to complete a deliverable
Technological Factors	Relation to technology usage ("How")	• Indicates use of a technological mode of communication (e.g. Skype) • Issues related to the use of technology for meetings (bad connections, etc.)
Logistics	Coordination of team activities ("Where/ When")	• Organization of plans and timeline of due dates • Missing plans or meetings

Distribution of Power	Role of individual within group	• Show respect for hierarchy and ownership of responsibilities • Does not complete a designated role in the group
History of Collaboration	Referring to past experiences	• Mention past projects and strategies related to team projects
Organization Support	Resources to support project	• Advisors, Financial (through IGERT), Finding resources
Communicating Expertise	Translation of disciplinary knowledge	• Imparting scientific knowledge, sharing journal articles or literature

The themes are defined to be neutral, such that both positive and negative versions of enacted themes can be coded within. Examples of positive and negative manifestations of the codes are given in the codebook table. In the interpretations of the data, the noteworthy findings from the quantitative survey results will be further contextualized using email communication evidence. The data are discussed by team in order to build an understanding of the different ways in which teams manage their deadlines, their science, and the interpersonal aspects of virtual and interdisciplinary research.

B. Analysis of Group A: Soft Robotics Project

Group A is composed of five team members from two universities. The team leader, a few team members, and the project have continued from a previous year. The summed survey scores, calculated as discussed above are presented in Table 4.

Table 4: Quantitative Survey Results for Team A

Team A: Soft Robotics					
Survey Items	**Individual Proficiency[1] (Ind.)**	**Team Proficiency[2] (Team)**	**Importance of Task[3] (Imp.)**	**Team Alignment Score** *(Difference between Team and Individual Score:Team-Ind.)*	**Importance Alignment Score** *(Difference between Importance and Team Score Imp.-Team)*
1. Set goals for week	11	15	16	4	1
2. Demonstrated effective communication about research tasks	0	8	9	8	1
3. Worked to build relationships with group members outside of research tasks	-6	3	-1	9	**-4**
4. Demonstrated Trust	8	10	7	2	**-3**

and respect of group members					
5. Completed tasks in a timely manner	2	7	9	5	2
6. Demonstrated accountability (holding self and others responsible for their goals)	4	11	16	7	5
7. Met group deadlines	6	11	10	5	**-1**
8. Conducted research tasks	12	9	16	**-3**	7
9. Conducted non-research tasks that support research	2	6	1	4	**-5**
10. Communicated with faculty about project	-8	5	0	13	**-5**
11. Communicated with people outside of the group about project	-5	1	-5	6	**-6**
12. Reflected on weekly progress	5	13	11	8	**-2**
13. Managed interpersonal dynamics	1	10	6	9	**-4**
14. Leveraged strengths of group members	0	11	5	11	**-6**
15. Demonstrated openness to constructive criticism	5	14	7	9	**-7**

[1]Individual: I feel that I did this item well this week
[2]Team: I feel that my team as a whole did this item well this week
[3]Importance: This aspect of team science was very important this week

Goal Setting: There is a high level of agreement between the responses to the question of setting weekly goals across the board. Individuals felt successful in their ability to set weekly goals (evidenced in the individual proficiency column). Team members felt the team as a whole was also good at setting weekly goals (also very positive, Team proficiency column). It is not surprising that the members also felt that the setting of weekly goals was extremely important (also highly positive importance sore). The Importance Alignment Score for this facet may imply that the importance placed by each member on setting of weekly goals as a team was a driving force for this team.

Here is an excerpt that identifies an example of positive goal-setting regarding an upcoming written deliverable:

> “How would you like to proceed with the writing tasks. […]I think we should break it down into making an outline (which we have done already) and the pulling pieces from each text that best meet the outline requirements.
>
> Do we want to appoint two leads to make the outline and then have the rest of the group focus more on synthesis? Or would you prefer for everyone to be involved at this point. We should probably have the outline done in the next day or two so we will have enough time for the writing.”

In this way, the team managed the goals of their project well throughout; however, there were times when communication mishaps affected the goal-oriented nature of the team, such as in the next example.

Effective Communication about Research Tasks: The value of zero for the individual coded responses (2nd column) is interesting. It implies that team members had opposing (both positive and negative) feelings towards their individual effectiveness to communicate about research about research tasks over the weeks of the survey. On contrary as a team (as seen in the Team Alignment Score column), they seem to have the feeling that the communication of research tasks was effective. The discrepancy between the responses from the Importance Alignment Score column imply that there was great emphasis placed on the need to communicate effectively, which may be the reason why their team as a whole felt good about their communication skills at a team level, even though individual team members may not feel confident about their communication skills.

The following excerpt demonstrates this tension. The team leader admits to dropping a task and missing deadline, but takes responsibility for actions and rallies the team to perform at a higher level in the future.

> “Hi all, I want to apologize for the fact that we seemed to miss the assignment today. I was not there last week and so I didn’t understand [the deliverable]. [Team member], you’ve been great on leading the way.
>
> As far as the work goes, if you are behind in your Gantt chart (which I know I am), please try to make a new adjusted timeline or reach out for help to address the problems[…]”

Therefore, the team is working to improve the communication that impeded their weekly project and resulted in missing a deliverable.

Leveraged Strengths of Group Members: This is a very interesting aspect that sheds light on the nature of the teamwork. The 2nd column (a value of 0) suggests that at an individual level, team members did not require the strengths of other team members. This could imply that the interdisciplinary collaboration was not that integrative in nature; i.e. the sum of the individual talents did not result in something greater than the whole. The value at the team level (3rd column) contradicts that at the individual level (5th column) and is very positive in nature. However, the importance placed on this aspect was low. This may suggest a misunderstanding at the team level about the nature of their collaboration (as demonstrated by the very positive numbers in the Team Alignment Score and the negative numbers in the Importance Alignment Score).

> "Hi all,
> Here is an incomplete "task breakdown" of what I think is necessary to get a paper from this project. Feel free to add/edit it as needed or start a whole new document if you'd like. The task breakdown should detail every experiment we need to do and should help show how the labor is divided. We can make sure too much work isn't on any one persona and [Team Member] can step in to help out as needed."

General Trends: Questions 3 (Build relationships), 4 (Trust and respect), and 9-15 (tasks dealing with managing non-research components of the project) were noteworthy in that the Importance Alignment Scores column for all of these questions were negative. This means that less importance was placed on the traits being probed by these questions, despite the fact that at the team level they performed quite well. This could either imply that the team has gotten good at say, managing interpersonal dynamics, or at taking constructive criticism. It could mean that the group is in the norming or performing phase. However, it could also mean complacent behavior within the team on these matters. Questions 1, 5, and 7 help to gauge the ability of the team to perform successfully. The values were all generally positive, indicating that the group as a whole placed great importance on completing their tasks and carrying out their weekly duties. However, the negative value (though quite small) in the Importance Alignment Scores column may imply that the group placed less emphasis on this task despite consistently meeting milestones and deliverables. This could imply that the group is truly working as a team or that they are not being challenged enough.

Team A met mostly via virtual conferencing, so the emails that were analyzed generally occurred immediately before a deadline, and therefore, were quite task and logistics oriented (setting up a time to meet, an online venue, or delegating tasks to be done for upcoming research updates.) Most of the emails were exchanged between the same team members, who seemed to "drive" the project and when meetings were held. Interestingly, one of the team members who was not the project lead exhibited considerable leadership in terms of task delegation and project management through the course of the project, keeping the members aware of upcoming deadlines.

C. Group B Analysis: Nanostructure Synthesis Project

Group B also is comprised of five members from two universities. This group was newly formed in the beginning of the 2015 academic year, and therefore it was anticipated that the team would allocate time differently than the other groups, especially in the project planning and implementation stages. The longitudinal quantitative data for this group is shown in Table 5.

Table 5: Survey Data from Group B

Group B (Topic: Nanostructure synthesis)					
Survey Items	**Individual Proficiency**[1]	**Team Proficiency**[2]	**Importance of Task**	**Team Alignment Score** *(Difference between Team and Individual Score:Team-Ind.)*	**Importance Alignment Score** *(Difference between Importance and Team Score Imp.-Team)*
1. Set goals for week	12	11	13	**-1**	2
2. Demonstrated effective communication about research tasks	7	8	10	1	2
3. Worked to build relationships with group members outside of research tasks	-2	2	1	4	**-1**
4. Demonstrated Trust and respect of group members	7	12	11	5	**-1**
5. Completed tasks in a timely manner	9	8	15	**-1**	7
6. Demonstrated accountability (holding self and others responsible for their goals)	5	5	17	0	12
7. Met group deadlines	9	8	16	**-1**	8
8. Conducted research tasks	12	8	16	**-4**	8
9. Conducted non-research tasks that support research	7	7	1	0	**-6**
10. Communicated with faculty about project	-2	4	-1	6	**-5**
11. Communicated with people outside of the group about project	2	10	1	8	**-9**

12. Reflected on weekly progress	8	7	1	**-1**	**-6**
13. Managed interpersonal dynamics	6	8	7	2	**-1**
14. Leveraged strengths of group members	6	10	12	4	2
15. Demonstrated openness to constructive criticism	8	10	10	2	0

[1]Individual: I feel that I did this item well this week
[2]Team: I feel that my team as a whole did this item well this week
[3]Importance: This aspect of team science was very important this week

Goal Setting: The individual responses in this group were slightly more positive than the group values, which led to a negative reading in Team Alignment Score column. This is an indication that the individuals in this group were confident about their ability to set goals but had a slightly less confidence about their team. The very positive value in the Importance column and the very low value in the Importance Alignment Score column may suggest a general agreement among team members over the significance of setting weekly goals. These values may signify that the team is in a forming or norming stage.

> "As a follow-up, what are your thoughts on this biweekly update? Should we have one person spearhead this or would it make more sense for us to collaborate somehow. I believe we need to present some kind of progress this week. If that is the case, I think we can spin "determined an expedient and efficient method to perform a crucial experimental step of our project" into a very impressive sounding accomplishment haha. But we should obviously work towards actually performing said "crucial experimental step" as our first priority."

Communication about research; developing trust and respect: The team appears to have very little cohesiveness and camaraderie as indicated by the negative value in the team score column and the small positive importance value. This also reflects in their method of communication: The familiarity codes are outweighed by the knowledge translation occurrences across the email correspondences. The team as a whole agreed well on their ability as a team (and on a personal level) to communicate effectively about research tasks. However, the qualitative email data suggests there may be an imbalance of knowledge within the group, because there is usually one main person that is looked to for technical expertise in the group.

The first of these email excerpts that may demonstrate this tension is from the team leader, checking in on the progress of the group. The first question is interesting coming from a team leader, rather than checking in on the most immediate step of the project, the overall status of the project is seemingly unknown:

> "Hi all,
> How are we doing on the research project?
> Would it help you to meet via Skype sometime next week?"

Similarly, the following email correspondence was sent to the team leader (with the rest of the team members copied on the email), and it shows the discrepancies in knowledge between the leader and the other team members, which may be the reason why most of the communication is highly technical in nature.

> "[Team member], we were hoping you might be able to present the motivation slide of the pitch seeing as you know much more about that than any of us here."

Conducted non-research tasks: The fact that the values for non-research tasks that support the project were quite high may be an indication that the group is in the initial stages of its work and is still trying to figure out how to proceed. However, the low values on the importance placed on this category may suggest a level of frustration with the project, since a lot of time is spent on work that does not produce tangible results. This could greatly affect the morale of the team. The high negative value in the Importance Alignment Score column is an indication that the team does not agree on how important this value is despite the fact that they perform well at this task.

Many of the deliverables of this team are spearheaded by a single team member, rather than being a collaborative effort on the part of the group. This may demonstrate the differences in "importance" that the various members feel about the tasks that are peripherally related to the research project. For example, in this excerpt, one of the most junior members of the team has prepared an update for the next day:

> "I have come up with the following presentation for tomorrow's presentation pitch. I suggest that [Team Member] and/or [Team Member] could talk about slides 2 and 3 (in [Team Member's] absence). [Team Member] could do slide number 4 and I will do slide 5. If you have anything else to add, please do so."

In addition, some of the emails offer "apologetic" language for focusing on non-research tasks, here, talking about making a PowerPoint (pp) presentation:

> "I know that we have time to make our pp on Thursday but I think it is better to get some ideas before, fisrt *(sic)* we should think about one application for this project, it should be very interesting and general, then we should build the rest of pp around it with nice and fun pictures. Pease informe *(sic)* the group with your cool ideas."

This excerpt indicates an apology for thinking about a non-research task ahead of time, which both applies to the "goal-setting" findings and time spent on "non-research tasks."

General Trends: Questions 3, 4, and 9-13 show negative values in the Importance Alignment Score column, which suggests that the team feels quite good at performing the tasks despite placing little significance on the importance of each of the tasks. The ones with a strongly negative value indicate a discrepancy between the level of importance and the team performance. This could also suggest complacency within the team, completing the tasks without valuing their importance to the project.

Team B spent many of their emails communicating scientific and engineering expertise among the group. Especially because their experiment required the purchasing of supplies, the interactions of the group often focused on support, accessing financial resources, and working with faculty members to ensure their efforts were promising. In addition, members updated each other readily with the status of experimental results, and planned to meet over breaks far in advance in order to not work last-minute over holidays—an element of strong leadership and project management. The code frequencies for their team emails were oriented on the logistics and goals near the beginning of the project, which potentially yielded fewer "task" type emails in the days before major milestones and deliverables.

D. Group C Analysis: SPASER Development Project

Team C consists of three members from two universities. The two senior members of the group (one being the project leader) hold longstanding working relationships, even though the project was new to the team members. In this team, we were particularly interested in understanding the established communication patterns held by a team that had potentially undergone the first stages (forming, storming, norming) and potentially moved into the fourth stage (performing), according to Tuckman's[7] model of teams. The longitudinal survey data is presented in Table 6.

Table 6: Survey Data from Group C

Group C (Topic: SPASER Project)					
Survey Items	**Individual Proficiency[1]**	**Team Proficiency[2]**	**Importance of Task**	**Team Alignment Score** *(Difference between Team and Individual Score: Team-Ind.)*	**Importance Alignment Score** *(Difference between Importance and Team Score Imp.-Team)*
1. Set goals for week	2	4	7	2	3
2. Demonstrated effective communication about research tasks	2	7	11	5	4
3. Worked to build relationships with group members outside of research tasks	-3	-3	-9	0	**-6**
4. Demonstrated Trust and respect of group members	8	8	2	0	**-6**
5. Completed tasks in a timely manner	-1	5	5	6	0
6. Demonstrated accountability	5	8	8	3	0

(holding self and others responsible for their goals)					
7. Met group deadlines	3	7	7	4	0
8. Conducted research tasks	-4	3	6	7	3
9. Conducted non-research tasks that support research	4	6	10	2	4
10. Communicated with faculty about project	-3	-2	-11	1	**-9**
11. Communicated with people outside of the group about project	-6	-2	-13	4	**-11**
12. Reflected on weekly progress	0	2	4	2	2
13. Managed interpersonal dynamics	-3	1	-5	4	**-6**
14. Leveraged strengths of group members	4	6	-1	2	**-7**
15. Demonstrated openness to constructive criticism	2	3	-6	1	**-9**

[1]Individual: I feel that I did this item well this week
[2]Team.: I feel that my team as a whole did this item well this week
[3]Importance: This aspect of team science was very important this week

Building relationships, Demonstrating trust and respect: This team is quite different than the other two teams with respect to their level of relationship and cohesion. The qualitative results indicate a team with great cohesiveness. The highly negative value placed on the importance of this cohesiveness may indicate lack of self- awareness by the team about their cohesive structure. It may also mean that they are so cohesive that it has become second nature to them, and not a feature of interest. The cohesion of the team is also reflected in the "trust" item. The scores for trust among team members were generally high at a team level, and valued by them as well, and there was great agreement on these matters at an individual and at a team level, as shown in the Team Alignment Score column. The strong negative values found in the Importance Alignment Score column is again a strong indication that this trait has become second nature and has little significance to their progress as a team.

Although the team did not rank these traits as highly important, the tenor of the emails exchanged between team members differed drastically from those exchanged by other teams. Many emails started with a social nicety, or a comment showing investment in the collaborators as friends (e.g., asking about major doctoral milestones and exams, summer plans, etc.). The usage of non-verbal emotional cues (emoticons (e.g. smiley faces (☺), etc. in the email) and exclamation points, or other informal language cues pointed to the collaborative and relaxed community that had been built among the group members. This use of non-verbal language in emails helps to clarify and soften tone in email correspondence, especially when delegation of tasks occurs, such as in these emails:

> "Hey [Team Member],
> When is your A exam? Is that similar to a qualifier or a proposal?
> I know right now you are strapped for time so is there is anything I can do to help with IGERT please let me know. (Though as my advisor said, I don't have any magical skills to make experiments work☺)"

Later in the email thread, the same team member wrote:

> "Ooh that's right around the corner. Best of luck!! I am writing my proposal now and presenting next month so I will most likely be a nutcase towards the end of this month ☺. Sounds great about the gold nps [nanoparticles]!! Just let us know when you would like to meet, or if you would like I can start the ball rolling on determining a meeting time for all. Let me know which is best. Have a great day!"

The candor with which these team members understand that the interdisciplinary science exists *within* the framework of a full life with outside obligations means that the discussions of personal things and the team-oriented things are held in the same discussion. None of the other emails from the teams talked in this much detail about personal things coming up, nor did the team members indicate a willingness to take on a team members' tasks in order to help them accomplish other immediately important milestones (like doing a preliminary exam/proposal, in this case.)

General Trends: The working style of team C was radically different, not because of the rigor of the project, but in the style of communication between the team members. The "familiarity and social cohesiveness" theme appeared at least once in every email. The group sought consensus on most issues: If the team leader asserted an opinion or a plan of action, she also added that if other members had different ideas, they should share them so the group could make the best decision. This project had continued from previous years of the IGERT collaboration, and this was potentially one of the reasons for the relaxed atmosphere. "Task" and "role" codes were assigned heavily before deliverables in this group as well, but the "goal" codes did not surface after the beginning of the project, again, potentially a result of a pre-existing collaboration. In addition, the Team Alignment Scores are all positive, which indicate that the team feels that they are "better than the sum of their parts"—that the team working together outscores the individuals' perceptions of their own contribution. This is one of the facets of a productive team, as noted by Katzenbach and Smith[5].

Contextual factors may also contribute to this team's working and leadership style. Firstly, this is the only team that conducted most of their business through Skype online videoconference, rather than through email. In addition, two of the members worked together before, indicating some level of comfort and established expectations regarding working relationships. Lastly, this was the only team that was led by a female student, and two of the three members were women.

Although this study did not seek to look at the gendered nature of team leadership within science and engineering collaborations, the trend toward consensus could result from either or both personal leadership style and/or reflection of socialized expectations for strong female leaders.

V. Discussion

The characteristics probed in this study of interdisciplinary, virtual teams focused on aspects of team science that were emphasized in the literature concerning professionals. However, we were interested in studying the ways in which these concepts manifested for graduate students learning how to conduct team science in a collaborative and authentic environment. The survey component of the study indicated differences in the ways in which individuals viewed their contributions and the contributions of the team as a whole, as well as a numerical difference between the tasks and their importance. Although the three teams are part of the same collaboration and are all graduate students, the ways in which they interacted with these concepts are quite different, representing different leadership styles and experience with project management in an interdisciplinary and virtual setting.

The "team science" literature discusses the importance of effective leadership within these groups. At the graduate student level, we probed aspects of leadership within the survey itself (such as effective communication, establishment of trust and respect, management of deadlines), but did not ask participants to rank themselves as "leaders" or to evaluate the team lead on the project. The differences between the teams are likely due to a combination of the maturity of the project, the personal investment in the project by the team members, and the leadership styles and traits of the senior graduate student team leads. The systems are in flux, because as the team leaders are adjusting to positions of leadership and decision-making, the team members are learning about projects in a (potentially) new discipline, and the project is becoming more defined. This can cause issues: If team leaders have only ever experienced well-defined projects with other students who have similar academic backgrounds, then it is easy to assume that each member of the team can "see" the logical next steps of the team (assuming a leader as "guide" role). While the idea of allowing team members to "own" parts of the project to increase investment is a well-established team leadership principle, in reality, undefined projects with novice team members may need stronger authoritative leadership, since the novice graduate students potentially have too little prior knowledge to intuitively deduce the next steps of the project without careful guidance. In this case, a transformative leadership style would be more effective, starting out with extra structure to guide and teach novice team members, and gradually allowing more freedom, ownership, and choices over the course of time.

From the quantitative data, across the three teams we studied through this project, the ways in which the teams differed most were in their ideas on communication, in goal setting/meeting, and in building team trust and respect. These themes were echoed in the qualitative email communication discourse analysis, through which we saw the three teams using different communication styles over email, indicating various leadership and role-oriented traits as some of the most frequently occurring in the data, both in positive and negative ways, across the three teams' communications.

The opportunities for graduate students to learn to conduct team science in authentic, yet protected environments allows for opportunities for students to develop their own leadership skills. The IGERT Traineeship did incorporate some elements of leadership training, based on case studies and responsible conduct of research, but in a "real life" project instead of a case study, managing peers and an extracurricular project reveals the true challenges of virtual teams and interdisciplinary science.

Any engineering educators seeking to form opportunities for graduate students to conduct team science should consider rigorous leadership training and discussion throughout the team science experience. No two groups will be the same, because of interpersonal dynamics, working styles, power dynamics, seniority, and differences in prior knowledge of team members (especially in interdisciplinary research settings like the one presented here). In this case, it is best for the team leaders to work to understand the prior knowledge of their team members in order to best communicate with them, identify and leverage strengths, and establish rapport. Engineering educators facilitating these authentic learning environments should also stress the "soft", or professional skills necessary to be an effective leader: These manifest in team communications in the "trust" and "relationship-building" items that are readily ignored during highly technical projects. However, the establishment of rapport can open doors to more effective team communication and management of conflict before it occurs.

Finally, the work of engineering leadership, to which attention is being paid at the undergraduate level, should extend into the graduate curriculum, either through formal or informal experiences. Project management should be included as students progress through their graduate careers, so that they can be an "apprentice" manager of a project or a virtual team, gradually gaining leadership confidence and experience to manage projects at a successful level as future thought leaders in interdisciplinary science and engineering.

E. Future Research Opportunities

Future opportunities for team science research include the addition of focus groups and interviews to more deeply understand the dynamics within each of the teams. Further survey data will continue to be taken to achieve a longitudinal assessment of the actions of graduate students conducting and leading interdisciplinary team science with colleagues at multiple institutions. We hope to assess the impact that a particular factor of team science has on a successful project outcome, which can be assessed at the end of the academic year. Ultimately out of this research, the researchers hope to build a new model for interdisciplinary team science that can be an aid to graduate student project managers learning to lead and conduct a team science project.

Other engineering educators can contribute to the conversation in how to build leadership and teamwork training into the graduate engineering education curriculum in authentic and knowledge-building ways. A balance must be found between letting student-led teams negotiate their struggles in order to learn effective teamwork, and unproductivity or paralysis that can come if the leaders are not prepared to manage a long-term interdisciplinary and/or virtual project. Therefore, research-based educational interventions and tools will be of utmost importance, as will continued research on graduate-level "team science" learning.

V. Conclusion

Through a mixed methods research design, we longitudinally assessed three interdisciplinary, virtual teams as they work on a long-term engineering project. The teams are led by senior graduate students, and are comprised of graduate students with varying levels and types of expertise. Through this experience, we see multiple teams where there is a mismatch between the attitudes of an individual and the attitudes of the group as a whole, as well as mismatches between how effective a group feels at some element of the "team science" process and how valuable they think the tasks are. Optimal team productivity results when the team members are in agreement with how they are performing as a team, and all feel that the tasks are important. Further, following the email communication patterns of the teams reveals three different discourse strategies for the teams. Our findings indicate that engineering educators need to build explicit leadership and project management training for virtual and interdisciplinary teams into (formal or informal) graduate educational experiences, teaching students to be adaptable leaders that can meet the needs of diverse team members.

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Appendix A

Weekly Team Science Evaluation

Directions: Please rank your opinions on each statement as they relate to you as an individual in the team, your team as a whole, and the important with which you regard each statement.

NAME:			
Item	**I feel that I did this item well this week (1= strongly disagree, 5= strongly agree)**	**I feel that my team as a whole did this item well this week (1= strongly disagree, 5= strongly agree)**	**This aspect of team science was very important this week (1= strongly disagree, 5= strongly agree)**
1. Set goals for week	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
2. Demonstrated effective communication about research tasks	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
3. Worked to build relationships with group members outside of research tasks	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
3. Demonstrated Trust and respect of group members	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
4. Completed tasks in a timely manner	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
5. Demonstrated accountability	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5

(holding self and others responsible for their goals)			
6. Met group deadlines	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
7. Conducted research tasks	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
8. Conducted non-research tasks that support research	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
9. Communicated with faculty about project	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
10. Communicated with people outside of the group about project	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
11. Reflected on weekly progress	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
12. Managed interpersonal dynamics	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
13. Leveraged strengths of group members	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5
14. Demonstrated openness to constructive criticism	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5