NAVIGATING A DISCIPLINARY CHASM: THE STATISTICAL PERSPECTIVES OF GRADUATE TEACHING ASSISTANTS

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ABSTRACT

Graduate Teaching Assistants (GTAs) carry a substantial instructional role in introductory courses for many mathematics and statistics departments. As a result, many GTAs have first-hand influence on the initial impressions of statistics for students from a range of disciplines. But as simultaneous learners of the discipline themselves, GTAs in statistics are still forming their perspectives of statistics and statistics instruction. Using multiple case study design, I conducted a longitudinal study with four, first-year statistics GTAs aimed at capturing their experiences and notions related to statistics. This paper highlights several disciplinary perspectives and tensions expressed by the GTAs. I also discuss noteworthy connections between the participants' statistical perspectives and their pedagogical views for introductory statistics. Findings reveal that the GTAs in this study struggled to reconcile how authentic statistical practice could be translated to the introductory curriculum. I close with implications and ideas for training statistics GTAs in light of these findings.

Keywords: *Statistics education research; Disciplinary beliefs; Pedagogical beliefs; Graduate teaching assistants*

1. INTRODUCTION

Disciplinary perspectives can greatly influence teachers' pedagogical decisions (Abd-El-Khalick et al., 1998; Speer, 2008; Thompson, 1984). At a very practical level, disciplinary understanding can be framed as subdimensions under knowledge for teaching (e.g., curricular knowledge or pedagogical content knowledge; Groth, 2007; Hill et al., 2008). Beyond these more concrete categories is a more abstract, metacognitive perspective of the discipline that probes questions of nature and practice (Capps & Crawford, 2013; Mason & Davis, 2013). Mason and Davis (2013) described this metacognitive perspective in mathematics as one's mathematical being, which becomes the basis for the in-the-moment pedagogical choices made by the teacher. In other words, teachers imagine the mathematical ideas they teach within a larger, personal framework of mathematics. These perspectives, in turn, influence pedagogy.

Similar disciplinary discussions are found in the statistics literature. Perspectives have been articulated on the topics of what it means to do statistics (Cobb, 1999; Wild et al., 2018), what ideas are central to a sophisticated conception of statistics (Justice et al., 2020), and what beliefs characterize the statistical epistemologies of disciplinary experts (Diamond & Stylianides, 2017). Wild and colleagues (2018) argue that presenting a wider view of statistics, emphasizing investigation and meaning-making, should be central in the learning process, even for beginners. Achieving this curricular emphasis naturally begins with understanding the statistical perspectives of teachers and instructors.

There has been some research on how the disciplinary perspectives of statistics teachers may directly influence pedagogical choices (e.g., Chick & Pierce, 2008; Eichler, 2008). For example, Eichler's (2008) study of German secondary teachers identified different beliefs about the usefulness or purpose of statistics that influenced these teachers' curricular enactment. Little is known, however, about the disciplinary perspectives of instructors or professors of statistics, and how those perspectives interact with curricular and pedagogical decisions in university courses.

This study complements existing research findings by exploring these questions as they relate to graduate teaching assistants (GTAs). The experiences of graduate students in university teaching vary across international contexts, but there are certainly commonalities. GTAs are typically at a critical point in their statistical learning, with many taking theoretically-advanced courses. Some are also involved in the direct teaching of undergraduate students, including introductory courses. The limited research on statistics GTAs shows that many often struggle to articulate introductory level concepts, even while being

very fluent with introductory level procedures and even excelling with graduate level content (Dolor, 2017; Green, 2010; Noll, 2011).

In this paper, I document the statistical perspectives of four, first-year statistics department GTAs in a U.S. context. I explore how their perspectives influenced (or failed to influence) their pedagogical views toward the introductory statistics course they were teaching. I also consider their first-year experiences and to what extent their perspectives evolved throughout this period. I address these matters through the following questions:

1) What key statistical conceptions and epistemic views characterized the perspectives of four, first-year statistics GTAs?
2) How did the participants' statistical perspectives interact with their pedagogical views for introductory statistics?

2. PREVIOUS RESEARCH ON STATISTICS GTAs

Justice's (2020) review of literature on GTAs echoed a common cross-disciplinary challenge: many GTAs lack adequate knowledge, preparation, and support. Several survey studies of GTAs in mathematics, statistics, and biology found that most like the idea of active learning, but few have seen these strategies enacted well in their own courses. Instead, many GTAs are more comfortable enacting transmission-style instruction and computationally-centered worksheets (Deshler et al., 2015; Justice et al., 2017; Pentecost et al., 2012). Without direct experience with constructivist learning environments, GTAs are also more likely to over-emphasize the importance of general aspects of teaching (e.g., lecturing clearly, giving enough practice problems) rather than thinking deeply about the nature of the content itself (DeFranco & McGivney-Burelle, 2001; Gardner & Jones, 2011; Kung & Speer, 2007).

While the solutions to these issues are complex, there are some interesting themes in the literature on statistics GTAs. In particular, there is a question as to how well statistics GTAs express cohesive disciplinary perspectives across both introductory and advanced coursework. By surveying 68 statistics GTAs and conducting think-aloud interviews with five others, Noll (2011) found that most GTAs demonstrated mastery of procedures and theoretical properties for the topics of distribution and sampling variability. She also discovered that many GTAs consistently struggled with more conceptual components. Noll explained, "These GTAs may have compartmentalized their theoretical knowledge of statistics, creating difficulty in applying that knowledge when working with empirical data" (p. 69).

From a curricular perspective, Green's (2010) focus group research with first-year statistics GTAs also suggested a disciplinary disconnect between content taught in graduate courses and the foundational introductory concepts. She reported that many GTAs were aware of their own lack of knowledge about introductory statistics curriculum, with several expressing difficulty in picking out key ideas from the textbook around which to build their lessons. Green concluded these statistics GTAs found it challenging to think about problems from the perspective of an introductory student.

Speer's (2008) case study of Zachary, a mathematics graduate student teaching Calculus, revealed a similar mismatch from a metacognitive perspective. Zachary described mathematics as beautiful and somewhat flexible, but struggled to connect these views to the context of the course he taught. Zachary described the content of Calculus as a foundational set of procedures and techniques—he was not sure how to integrate the beauty of mathematics into a course that focused on the fundamentals of mathematics. While Speer's study is specific to mathematics, it is not hard to envision how a similar mismatch could exist in statistics.

In synthesizing these studies, we see a suggestion that GTAs may not hold a unified disciplinary perspective across all levels of content and may be prone to viewing introductory content with a more procedural lens rather than with a conceptual one. It leads to an important question of how statistics GTAs think about the discipline of statistics, and whether their perspectives on introductory content are cohesive with their overall disciplinary understanding.

3. FRAMING STATISTICAL PERSPECTIVES

In this paper, I use the term *statistical perspective* to represent broadly the views and conceptions one may have about statistics. These perspectives include some examination of one's disciplinary conception and epistemology for statistics (Diamond & Stylianides, 2017; Justice et al., 2020), as well as views about

what it means to engage in statistical work (Wild & Pfannkuch, 1999; Wild et al., 2018). To better understand the perspectives of the GTAs in this study, I first provide some frame of reference by discussing expert perspectives on statistics.

3.1. PERSPECTIVES ON THE NATURE OF STATISTICS

To understand the nature of statistics, it is important to also unpack the nature of mathematics. Statistics draws much from mathematics, and naïve views of the two disciplines may simply note that statistics *is* mathematics or a branch of applied mathematics (Diamond & Stylianides, 2017; Justice et al., 2020), but such descriptions discredit the true nature of both mathematics and statistics (Cobb & Moore, 1997; Skemp, 1976; Wild et al., 2018).

Mathematics is dynamic—it serves to enlighten, codify patterns, and provide a language for quantitative manipulations (Ernest, 1991). Skemp (1976) explained that mathematics is often mistaken to be nothing more than a system of procedures in which learners are pushed to develop what he terms instrumental understanding. Instead, Skemp believed mathematics should be viewed as a system of objects to be conceived and manipulated at the discretion of the user; a goal he termed, relational understanding. Furthermore, mathematics is a system that rests on assumptions (i.e., axioms); changing these axioms changes the nature of the system and the theorems that proceed.

Statistics and mathematics share much overlap, as statistics works with the language of mathematics, necessitates assumptions at times, and requires a blend of procedural and conceptual elements (Cobb & Moore, 1997; Lindley, 2000; Wild et al., 2018). Statistics would most clearly be distinguished in its aims to acknowledge and measure uncertainty, focus on meaning-making, and make reasonable—but not necessarily perfect—explanations from incomplete data (Cobb & Moore, 1997; Davidian & Louis, 2012; De Veaux & Velleman, 2008). The following model (see Figure 1) from Wasserman (2013) demonstrates how statistics as a field both includes and transcends mathematics. Probability is more closely related to mathematics in its aims to quantify likelihood given assumptions, while inference and data mining (data mining used in the general sense of drawing insights from data) are more distinctly statistical activities that ask what could be true given what we have observed.
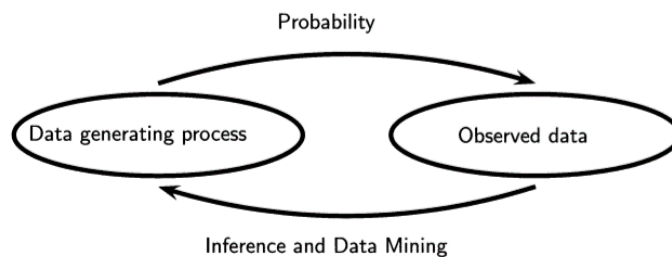

Figure 1. Probability and inference (Wasserman, 2013)

Wild and colleagues (2018) also bring attention to a wider view of statistics, which involves the contextually-rich process of learning from data and making judgments. That is not to take away from the structural landscape of statistics, namely the theorems, rigorous definitions, and methodologies that undergird disciplinary practice. Statistics still rests on principles that are intended to bring objectivity to data analysis. Wild et al. (2018), however, argued that the wider view more clearly represented the mission of statistics and provided a holistic landscape for this process to work within.

3.2. PERSPECTIVES ON THE PRACTICE OF STATISTICS

To understand the practice of statistics, one may start with recognizing what characterizes experts in the field. At a domain-general level, experts perceive information through conceptual frameworks or schemas to make sense of processes and ideas, in contrast to simply recalling disconnected facts (National Research Council [NRC], 2000). Because of this deep, conceptual knowledge, experts are well-positioned to answer ill-defined problems and propose flexible and creative solutions within their work (Cobb & Moore, 1997; NRC, 2000). To provide a metaphor, experts know how to cook, while novices depend more on recipes (Garfield et al., 2015; Schoenfeld, 1998).

De Veaux and Velleman explained, "Navigating through and making sense of [statistics] requires not just rules and axioms, but life experience and 'common sense'" (2008, p. 2). In drawing a contrast between statistics and calculus, De Veaux and Velleman noted that after solving for the rate of change in the water level of a cone, the calculus student probably does not need to use data to investigate whether the container into which the water is being poured is *really* a cone.

In proposing the construct of *statistical thinking*, Wild and Pfannkuch (1999) argued that seasoned analysts understand their work not simply as a set of practices to complete, but as applying a sophisticated mindset that cannot always be boiled down to discrete steps. For example, many statistical investigations may be framed in terms of a cycle that includes 1) defining a problem that can be addressed with statistics, 2) planning the investigation, 3) collecting the data, 4) analyzing the data, and 5) interpreting the results to form a conclusion. Beyond carrying out these practices, experienced analysts are continually seeking explanations, making strategic decisions based on practical constraints, and reasoning contextually with competing statistical models. These analysts also enact productive dispositions—skepticism, imagination, curiosity, openness, and perseverance.

From these discussions, themes emerge regarding the nature of doing statistics. Statistical work involves grappling with questions—sometimes ill-defined—that do not have deterministic answers (Cobb & Moore, 1997). While inference should be appropriately grounded in probabilistic arguments, statistical problem-solving also requires a deep understanding of the context and an inquisitive pursuit toward making meaning (Garfield et al., 2015; Nelder, 1986; Pfannkuch, 2011).

4. METHODS

This paper offers models that capture the disciplinary perspectives of four statistics GTAs and explores how these perspectives intermingled with their pedagogical views for introductory statistics. I address these aims by analyzing data collected across one full year. In this section, I briefly introduce the participants, methods of data collection, and methods of analysis.

4.1. SETTING

This study took place during the 2017-2018 school year at a large, U.S. public university. Participants were members of a new cohort of statistics graduate students who had received teaching assistantships. Of the 12 new GTAs in the cohort, 7 elected to complete entrance surveys and interviews. From those 7, I chose to continue research with the 4 GTAs who a) had no previous solo teaching experience and b) were on track to solo teach by the next summer. Table 1 provides information about the participants.

Table 1. Participants

Pseudonym	Nationality	Degree Program	Highest Degree
Kathy	American	PhD Biostatistics	BS Math & Health
Li	Chinese	PhD Statistics	BS Math
Mindy	American	MS Data Science	BS Math
Sahil	Indian	PhD Statistics	MS Statistics

Kathy was interested in becoming a pharmaceutical researcher. She also had experience working as a course assistant in her undergraduate university's general education health class, where she led a small discussion section each week. Li expressed interests in machine learning, but he also greatly enjoyed theoretical and philosophical discussions in statistics. He had tutored high school students privately on occasion. Mindy aimed to work in sports statistics. She completed a data science internship the summer prior to starting the MS program, where she gained experience coding and completing basic statistical projects in R. She also worked as a tutor for mathematics in the University's learning center. Sahil's statistical background was primarily academic and theoretical. He expressed interest in becoming a professor at a research university in the future. Like Li, he had also tutored high school students privately on occasion.

As part of the PhD program, Kathy, Li, and Sahil took the same courses during their first year. This included a two-semester sequence of applied methods (e.g., design, hypothesis testing, linear modeling),

two semesters of computational statistics (i.e., various machine learning topics), and a two-semester sequence of mathematical statistics (e.g., probability, distribution theory, estimation and inference). As part of the Masters in Data Science program, Mindy took the same applied methods sequence and the first semester of computational statistics. She also took a two-semester sequence of SAS programming and a Time Series course in the spring semester.

For fall and spring, Mindy and Sahil led discussions sections once a week for a large-lecture, introductory-level statistics course taught by the GTA Coordinator. This was a 200-level, algebra-based course that largely served psychology and business majors. Li worked for this course as well—grading in fall and leading discussion sections in spring. Kathy led discussion sections in fall and spring for a 100-level course on designing and analyzing survey data. This course was taught by another professor in the department and counted as a general education credit for the college. As was typical for discussion sections in the department, GTAs had one group meeting to become familiar with the course and received weekly activities/quizzes to administer. The GTAs facilitated these activities as they saw fit, however.

There was no pre-semester GTA training in this department, but all four participants completed the department's Teaching-in-the-Discipline Workshop during the spring semester. This workshop included 60-minute sessions weekly for six weeks. The workshop was led by the GTA coordinator, who had more than 10 years experience supervising the GTAs in the department and teaching large lecture introductory statistics courses for the department. The content of the workshop included a mixture of department-specific policy guidelines, as well as activities and discussions related to teaching introductory statistics (see Table 2).

Kathy, Mindy, Li, and Sahil were all selected to solo teach a section of the 200-level introductory statistics course that several of them had assisted with the previous year (in Kathy's case, this course was "new" to her, but included very similar content to the course she had assisted with). They were asked to base their instruction from the GTA Coordinator's materials, but they had general freedom to structure their assessments and lessons as they felt best. The course curriculum was fairly traditional in its coverage of introductory topics (descriptive statistics, random variables, normal distributions, one-sample inference, chi-square testing, and linear regression with up to two predictors). Computation was calculator-based, and most example problems were procedural, with occasional conceptual questions. The teaching model that the GTAs had seen for this course was largely lecture-based, but the course's discussion sections incorporated computationally-focused activities that all four planned to enact.

Table 2. Teaching Workshop Overview

Week	Segments and Small Group Discussions	Assignments
1	*Introductions activity:* GTAs asked to answer questions together in small groups. *Qualities of a Good Statistics Instructor*: In groups of 4, Students wrote down three qualities of a good introductory statistics instructor, with each group sharing one item with the class.	*Classroom Observations:* Students need to visit at least two different instructors' classes over the following weeks and answer a short observation protocol (e.g., "What did you like?" "What didn't you like?")
2	*Data Collection Activity:* Students recorded how many keys they had with them on class dotplot. Students then got in groups of 4 and reported average number of keys on second dotplot. GTA Coordinator used as example of active participation and use of real datasets. *Grading Components*: Students were provided a list of common assessments (e.g., exams, attendance, homework, projects, etc.) and asked to think through how they would structure their grading components across various options. Short discussion followed.	*Read "The 10 most common teaching mistakes:"* Students assigned to read 5-page essay about promoting quality instruction at the undergraduate level.
3	*Administrative Details:* GTA Coordinator discussed department and university teaching policies. *Pacing Schedule Activity:* In groups of 4, Students filled in 30 class periods of content using the GTA Coordinator's pacing schedule as a guide, including assessments and activity titles. *Email Courtesy:* GTA Coordinator provided handout with tips on writing courteous and appropriate emails. In groups of 4, Students had opportunity to think through response to sample student emails.	*Write Syllabus*: Students asked to write a syllabus aligning with one of the introductory courses. Include grading components and classroom management policies.
4	*Syllabus Grading:* Students swapped syllabi and completed checklist for required elements. *FSU Policies Quiz:* In groups of 4, Students completed a multiple-choice quiz on proper policy for different teaching scenarios and student issues. Students asked to think about how well their syllabus addressed many of these issues.	
5	*GAISE Report*: GTA Coordinator discussed the Executive Summary, sharing examples of how to address each of the six guidelines. *Question Writing Activity:* In groups of 4, Students were provided list of data points with corresponding boxplot and histogram and asked to write conceptual questions they could ask using this information. Briefly discussed together. *Grading Activity:* In groups of 4, Students discussed how they would grade a sample student quiz. At the conclusion, the GTA Coordinator briefly discussed how she would grade the quiz	
6	*Mindfulness scenarios:* GTA Coordinator opens up segment asking students what they would do if no one is talking or listening. After short discussion, handout is passed around with four questions about keeping energy, how to prepare when you do not want to go teach, and what they like (or is least unlikeable) about teaching. Students discuss in groups of 4.	

4.2. METHODOLOGY AND DATA COLLECTION

This study was based in multiple case study design (Yin, 2009). Consistent with this approach, I gathered data from a variety of sources to make sense of the participants' experiences and views. The year-long data collection period also allowed me opportunity to reflect extensively on the data, giving me space to memo, reorient my data collection as necessary, and follow up with participants to explore ideas further (Corbin & Strauss, 2008).

I also strove for more informal relationships with each participant, rather than strictly professional. "It is not distance that qualitative researchers want between themselves and their participants, but the

opportunity to connect with them at a human level" (Corbin & Strauss, 2008, p. 13). I noticed after the first interview that engaging in casual conversation before and after the interview opened the participant to talk about several experiences they did not discuss while the recording device was on. After the first interview, I made it a habit to begin each subsequent interview with space for casual conversation, delving into each person's story with open curiosity so long as they were willing to share.

Below, I outline the various data collection methods used.

Pedagogy Survey. The GTAs completed a survey before their first and last interviews (see Appendix A). This survey was comprised of likert-scale items related to curricular and instructional decisions for introductory statistics. I consulted both the Statistics Teaching Inventory (Zieffler et al., 2012) and the Graduate Student Statistics Teaching Inventory (Justice et al., 2017), using or adapting many items from each that were relevant to my goals. I also wrote several of my own items to address areas that were lacking (e.g., items assessing the aims and content of an introductory statistics course; items about general pedagogy, such as the perceived effectiveness and prominence of lecture, etc.). I used the survey responses as a medium for follow-up and discussion during the interviews rather than for quantitative measurement.

Interviews. As part of the data collection process, GTAs completed four interviews (descriptions in Table 3 and full interview protocol in Appendix B). The interviews served several purposes. First, they allowed the GTAs opportunity to reflect on their recent experiences. Second, they allowed me to ask questions to understand their statistical perspectives over time and how their ongoing experiences were shaping these views. Third, they allowed me to tap into their pedagogical views and note how these views evolved as they moved closer to the point of teaching their own introductory statistics course. While all interviews included different sets of questions or tasks, key ideas were revisited in most every interview.

Table 3. Data collection timeline

Timing	Data Collected and Measures Used	Purpose
September	Pedagogy Survey Interview 1: Entrance interview	Learning about participants' previous experiences, disciplinary views, and pedagogical views.
December	Interview 2: First-semester check-in	Documenting participants' first semester experiences as GTAs and graduate students; completing the Statistics Mind Map Activity.
January-March	Workshop artifacts Field notes	Documenting the workshop activities and assignments completed.
March	Interview 3: Post-workshop reflection	Exploring participants' workshop experiences and reflections; targeted questions on the nature and practice of statistics.
May	Pedagogy Survey Interview 4: Pre-teaching interview	Documenting participants' experiences planning for first solo teaching assignment.

In preparing for these semi-structured interviews, I consulted a range of sources (Baxter Magolda, 1992; Diamond & Stylianides, 2017; Justice et al., 2017; Liu & Liu, 2011; Stanic & Kilpatrick, 1989; Tsai & Liu, 2005). Interview questions addressed the following topics: the distinctness of statistics, the structure and context of statistical knowledge, the means of negotiating and justifying statistical knowledge, the characteristics of a statistical expert, and the nature of statistical investigations. I also asked questions that were specifically pedagogical; these were usually in direct response to pedagogy survey items. As part of the interviews, I also prepared occasional tasks for the participants to complete. Full interview protocols are included in Appendix B, but I will highlight one task from Interview 2 and a line of questioning from Interview 3 that were central to understanding the participants' perspectives.

In the statistics mind map task, I asked participants to visualize their conception of statistics (full protocol in Appendix B, Interview 2). This was carried out in three stages: 1) Asking students to list all words, terms, and phrases that came to mind when they thought about statistics, 2) Categorize similar terms/ideas together, and finally 3) Create a mind map that organizes these terms in a way that made sense to them.

In Interview 3, I provided a picture of the sample standard deviation formula (Figure 2, left) and asked, "Tell me what you think this formula represents. What is it measuring, and why is it constructed this way?" I also posed these follow-up questions: "How would you react to reading a peer-reviewed research paper that used mean absolute deviations instead of mean squared deviations in the formula? Do you think there is a context where that alteration could be ok, or is that wrong?"

Measures of variability have been a widely debated topic in the discipline's development (Gorard, 2006). Gorard explains that an alternative measure, the mean absolute deviation (Figure 2, right), was more common in practice decades ago and still has several advantages in particular situations. Probing participants' views about the validity of such an alternative measure was intended to probe the participants' views regarding what statistical formulas represent, how the statistics community comes to codify a formula or method, and how (or whether) choosing measures is related to problem context.

$$\sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \qquad \frac{\sum_{i=1}^{n}|x_i - \bar{x}|}{n-1}$$

Figure 2. Equations for Sample Standard Deviation (left) and Mean Absolute Deviation of a Sample (right)

Workshop artifacts. In addition to my tasks and questions, the GTAs completed several tasks and assignments as part of their participation in the department's teaching workshop during spring semester. I took field notes to account for interesting exchanges or moments as well as to describe the mood and general engagement of participants. During small-group discussions, I occasionally took notes of things they said. These notes were helpful as a source of triangulation when I asked the participants about their workshop experiences.

Memos. Throughout the year, I had ample time to memo, reflect, and synthesize each participant's responses. My memos took the form of case profiles of each GTA as I made sense of their views and experiences. Memos were helpful to chart my own incomplete perspectives about each participant as the study progressed; they also allowed me to bring up seeming discrepancies from earlier interviews to ensure I understood the participant's views, or if, perhaps, the participant's views were evolving.

4.3. DATA ANALYSIS

To address my first research question (conceptions and tensions about the discipline), I identified common themes of discussion across the participants' first two interviews related to this question (e.g., distinguishing mathematics and statistics, objectivity/subjectivity of statistical investigations). I next wrote category summaries for each GTA, which were used to synthesize into individual profiles. Interview 3 included the more comprehensive disciplinary questions. Building from their initial profiles, I attempted to reconcile Interview 3 statements with earlier statements to confirm (or clarify) earlier interpretations, or to identify views that were continuing to evolve.

To address my second research question (connections to statistics pedagogy), I focused primarily on discussions about the pedagogy survey from interviews 1 and 4. This variety of data sources helped with triangulation. My analysis began with exploring common perspectives and views across the participants (e.g., experiences in math or statistics classes, the aims of an introductory statistics course). Following the same process as described before, I drafted pedagogical profiles for each participant and revisited my initial claims as new findings challenged those notions. To link the participants' pedagogical and disciplinary views, I consulted their mind maps and subsequent discussions closely, in addition to the disciplinary profiles I wrote of each participant.

By meeting with these GTAs over the course of a year, I was able to use their direct feedback in constructing these statistical and pedagogical case profiles. I often shared my tentative explanations with each GTA and received confirmations or rebuttals based on their own perceptions. In such cases, I would often attempt to reword a GTA's reflection or view and ask if I was capturing their thinking. The GTA could then affirm or refine my statement. It was through a series of such interchanges that I was able to come to explanations about each GTAs' views and link experiences with fidelity.

5. EMERGING STATISTICAL PERSPECTIVES

In this section, I outline the perspectives articulated by the participants about both the nature of statistics and the practice of statistics. To do this, I share models I constructed to highlight differences in how these GTAs answered central disciplinary questions. These models are based primarily on the GTAs' responses from Interview 3. This interview included targeted questions about the nature of statistics and statistical knowledge (including whether or how it was distinct from mathematics) and the nature of doing statistics. See Appendix B, Interview 3 for a detailed protocol.

5.1. VIEWS ON THE NATURE OF STATISTICS

On the nature of statistics, all four participants believed statistics is centrally concerned with data and structurally related to mathematics. Differences emerged in how each participant described the relationship between statistics and mathematics, as well as how objective they perceived statistical theorems and formulas to be. I share three models that represent how the participants related statistics with mathematics, and unpack how these models emerged in different participants' thinking.

The Unified Model. The Unified Model (Figure 3) reflects two important beliefs about statistics—first, statistics is structurally a part of mathematics, and second, statistics is applied mathematics for data.
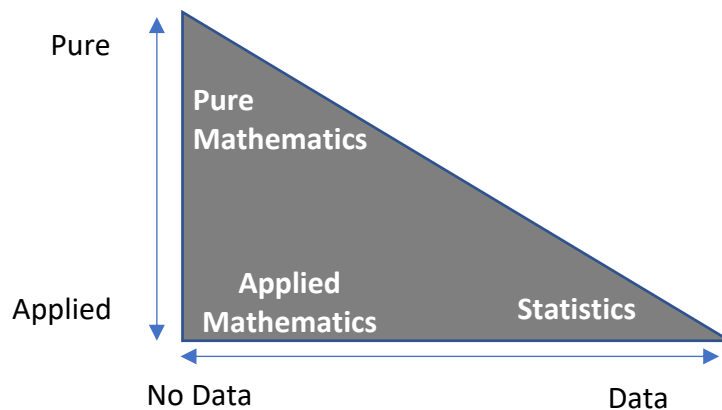

Figure 3. Unified Model

Kathy reflected this view by noting many similarities between statistics and mathematics; she described both as having assumptions and utilizing fixed methods, making them both "hard and fast sciences." To distinguish the two, Kathy said of statistics, "It's not just learning the equation, it's learning how to interpret the equation and what it means, and I think that's just as important as getting the right answer."

Despite her distinctions around application, Kathy viewed statistics as a part of mathematics, rather than as a separate discipline, or even an extension. Having completed a bachelor degrees in mathematics and public health, she frequently described statistics as "math," and would even refer generally to these computational disciplines as "a science" to denote rigidity and objectivity. In contrast, she talked about health and medicine (e.g., sleep, diet, exercise) as being ideas around which students constructed their own notions to further practical habits. For Kathy, such notions seemed inappropriate in statistics: "For [statistics], how do you feel about correlation? where do you see correlation? [chuckling] … It's just not as discussion-based." From Kathy's perspective, statistical content existed more as truths than as constructions, and the idea that different people would contribute to discussions around statistical content was difficult for her to envision.

The Extension Model. The Extension Model (Figure 4) provides more delineation between mathematical and statistical structures. While mathematical methods offer universal applicability, statistical methods are rooted in mathematics and offer only contextual applicability.
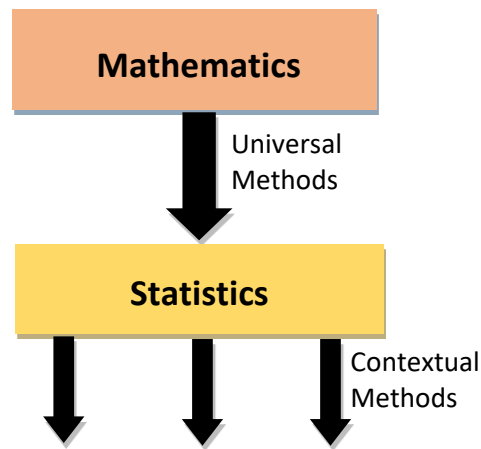

Figure 4. Extension Model

Mindy expressed this perspective best by noting that mathematics could be described better as an "exact science" involving certain formulas. As an example, she had a calculus project for which she had to calculate the water volume of the school pool—there was a correct approach and a right answer. In contrast, statistics is more situational. Statistical tests and methods require assumptions, whereas it seemed mathematics is more universally true. She said, "I'm sure there's assumptions behind all the math that you do, but it was never taught that way, whereas in stats, it's always that way."

Mindy also had experiences with statistics that reflected more subjectivity in decision-making. She described her summer internship experience, during which her team was using Twitter posts to predict and model social unrest in different cities. She explained there was not a correct method, or even a correct answer, but rather a construction of methods to draw insights. Similarly, in her Time Series class during spring semester, she reflected there were so many ways to create a model, where context and judgment determine the one that is most helpful. In this way, the Extension Model distinguishes itself from the Unified Model by representing statistical methods as more subjectively constructed and applied.

Like the Unified Model, the Extension Model positions the foundational elements and logic of statistics within mathematics. Mindy admitted having little understanding of the principles and theory on which statistics is based. She mentioned probability as a foundational idea for statistics, but she did not have a well-developed conception of what statistics is beyond the use of methods. Methodology represented a contextual strategy for making sense of a problem, but with objective rules and building blocks from mathematics undergirding these strategies.

The Divergent Model. The Divergent Model (Figure 5) proposes statistics and mathematics as taking diametrically opposed approaches. This model closely resembles the model shared by Wasserman (2013). Probability is more closely related to mathematics in its aims to quantify likelihood given assumptions, while inference and data-based sensemaking are more distinctly statistical activities that ask what could be true given what we have observed.
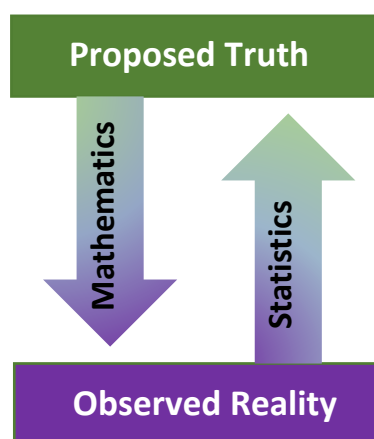
Figure 5. Divergent model

This model characterized the disciplinary conceptions of both Li and Sahil; Li's statements in particular offered clear and vivid imagery. Li recognized a paradigmatic difference in the approach of statistics as building methods and conclusions from data, while mathematics builds methods and theory from assumed truths. He explained that mathematics tries to "prove the truth" under starting assumptions. Statistics by nature cannot provide truth, but can instead offer a "reasonable story." Like Mindy, Li saw context playing an important role in the identity of statistics by believing statistics always starts from the data and the problem (bottom up). This has implications on the types of problems each discipline addresses, with both sharing a common aim in attempting to model the world—mathematics from pure, abstract logic and statistics through data-based sense-making.

Li consistently expressed a more constructed view of statistics. He explained that statistical proofs did not propose or reflect truth in themselves, but instead represented "direction." "[Statistics] has its own rules and assumptions." Context still dictates the usefulness of statistical theorems and formulas. This is in contrast to mathematics, which proposes theorems and formulas that are valid without the need to be useful—statistics is inherently interested in what is useful.

The objectivity of statistical formulas. When presented with the line of questioning on the formula for standard deviation, Kathy described standard deviation as "the best [formula] we know" for measuring variability, but that there was "always room for improvement."

> I think one of the reasons why stats in particular, but science as a whole, is advancing is because there's always this underlying disbelief that what we have is good, but it's not the be all end all. I'd be surprised if everyone took [the standard deviation formula] as the gold standard—something that could never be beat.

Kathy viewed this formula as an approximation of truth, much like the scientific community refines theories to better reflect objective truth. "Science is always moving forward, and just because this is what we use traditionally doesn't mean there's not some other standard that could be just as good or even better." At this point in her studies, Kathy may not have seen statistical formulas as having different contextual applications. The PhD students would have recently covered such topics as sufficient statistics and unbiased estimators, so she may have been compartmentalizing her graduate coursework from this more introductory-level conversation.

Li's discussion of measuring variability with a measure like standard deviation offered a helpful perspective of the divergent model. He compared using mean absolute deviation versus mean squared deviation as a relative choice:

> When we're working on some problem, our method should be flexible, so we can use absolute value or square value …There is a famous saying in statistics, 'all models are wrong but some of them are useful.' So there is no way to tell the square is better, square is true or absolute value is true. The only way to judge them is which one performs better in some case.

Li articulated a conception of statistics where *both* the theoretical basis and applicable methods it produced were driven by contextual need and usefulness. Sahil, like Li, also understood statistical formulas as contextually appropriate rather than universally correct. "[Mean absolute deviation] is also a measure of

spread. The idea is to measure how far the data varies from the center, so that is also an acceptable measure." He explained that standard deviation is usually more appropriate in cases of Gaussian, or at least symmetrically distributed data.

Mindy struggled more with the task and had less definitive answers. While she tended to think of formulas like standard deviation as more objective building blocks, she also seemed open to the idea that formulas are contextually appropriate:

> I'd be trying to figure out what exactly you're showing with [mean absolute deviation] since I've never seen that formula before. First, I wouldn't trust it right off the bat, but I'd be trying to figure out what your numbers are showing.

Summarizing perspectives on statistics. The standard deviation task revealed that Kathy viewed structures more objectively (consistent with the Unified Model), Sahil and Li viewed them more contextually (consistent with the Divergent Model), and Mindy had mixed thoughts. Mindy's articulation of the Extension Model might be a more transitionary conception of statistics that worked for her due to her limited background in mathematical statistics (she had only the first semester course, which did not include topics like sufficiency and bias). Without understanding the mathematical basis for statistical structures, mathematics was a placeholder in her conception.

5.2. VIEWS ON THE PRACTICE OF STATISTICS

Layers of flexibility. The participants had different views regarding the extent to which statistical work could be flexible. I outline three levels of views in Figure 6. The downward arrows symbolize that learners of statistics may be most likely to encounter statistics at the top level and gradually conceptualize lower levels of disciplinary practice with experience and exposure.
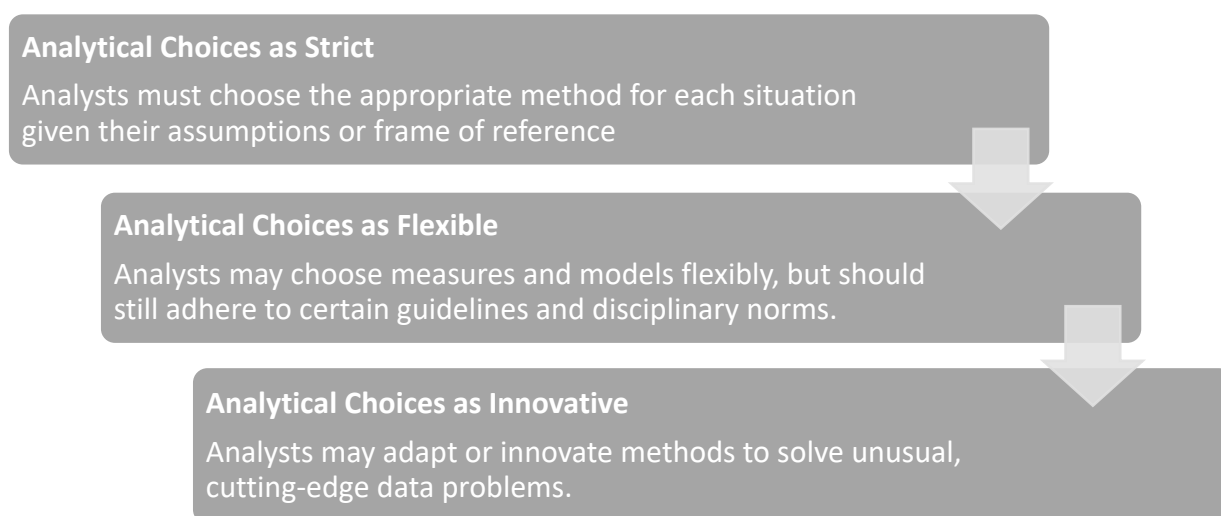

Analytical Choices as Strict
Analysts must choose the appropriate method for each situation given their assumptions or frame of reference

Analytical Choices as Flexible
Analysts may choose measures and models flexibly, but should still adhere to certain guidelines and disciplinary norms.

Analytical Choices as Innovative
Analysts may adapt or innovate methods to solve unusual, cutting-edge data problems.

Figure 6. Approaches to statistical problem solving

Kathy was one who viewed statistical work as rather strict and methodical, with standard statistical work being a process of choosing an appropriate method and applying it.

> I would classify [statistical work] more as a decision tree rather than a creativity process ... you have to follow the different pre-known procedures definitely. But I think there are different procedures that you can follow for each test, so that's where you get a little bit of individuality.

She also cited Bayesian versus Frequentist approaches as a choice statisticians may make in their analysis, but that within a particular paradigm, analysts should follow conventions closely.

Mindy shared similar ideas, but she was more comfortable using the word "creativity" to describe statistical design and analysis.

It takes creativity in designing your experiment, figuring out how you're going to test it, what is best to test, what is best going to give you the answers you're looking for, because there's so many ways to go about it and different data you collect, so that's where the creativity comes in.

Mindy described sports data as flexible, since she and the coach might simply identify the "top three," or seeing who is above the median. These were contextually-driven choices.

Mindy also saw a ceiling to creativity in statistical analysis. When discussing the Time Series course she was taking, she explained, "There's like 8 ways to run a model! ... [But] you still have to follow guidelines when you're being creative, so that you don't break your assumptions later." Having less experience with advanced statistical methods, she felt less confident in discussing this sector of work as anything more than guided choice.

Sahil and Li understood more advanced analysis as fertile ground for innovation. Sahil elaborated,

I think when you're solving like tricky difficult problems, what you think is like, we already know these methods, and these methods are not already matching with this problem, but…we have to use these methods to solve this one. So, the part where we know these methods, it's like [that]. When we have to write methodology, and when we are using these to solve this problem, that's where the creativity comes in.

In this excerpt, Sahil recognized that some problems cannot be solved with existing statistical methods, but new problems and existing methods could inspire new methods, and this generation of new methods may take creativity.

Skill versus experience. The participants' views about what characterizes an expert in statistics seemed to follow from their views about the nature of solving statistical problems. I represent these notions around statistical experts as a spectrum (Figure 7), where I argue in Section 3.2 that the right side of this spectrum aligns best with notions found in the literature discussed in section.
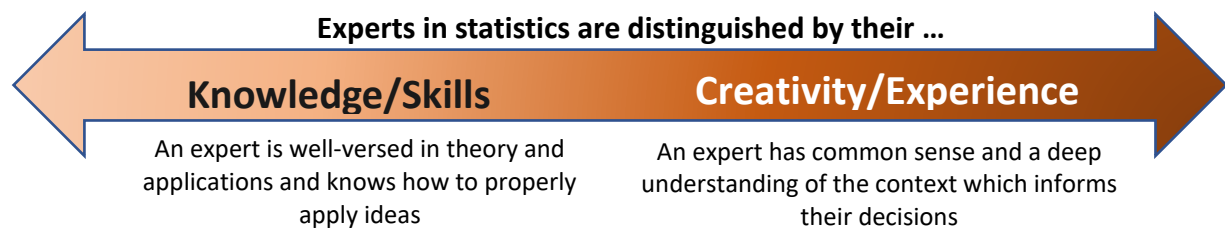
Experts in statistics are distinguished by their …

Knowledge/Skills
An expert is well-versed in theory and applications and knows how to properly apply ideas

Creativity/Experience
An expert has common sense and a deep understanding of the context which informs their decisions

Figure 7. Tensions surrounding the distinctions of an expert

Interesting perspectives on this topic emerged when the participants were each asked if statistical work might ever be thought of as "artistic" or "creative." Kathy responded to this question by stating:

I think that's a pretty liberal use of the word 'art'…I think statistics is more practically based, and there is more creativity, but I know just from a biological perspective, when you break it down, different sides of the brain, left brain, right brain, whichever one is art, whichever one is reasoning, that I am particularly reasoning brain focused. I'm a terrible painter, terrible artist, but I'm good at statistics, so I think that in terms of art and reasoning, it definitely is more reasoning than it is of art.

While she did not completely shut out the possibility that analysts could be creative or artistic in their work, that language did not seem to evoke any meaningful imagery for her. The "left-brain/right-brain" dichotomy also seemed to distance these two worlds and suggest that statistics could not reasonably include both of these perspectives substantively.

In contrast, Li and Sahil both viewed creativity and even individual expression as critical distinctions of statistical experts. Li explained this need well by stating, "[Knowledge of methods] can just let you know some shorter ways to handle these problems, but it can't help you with everything, so I think statisticians need more creations." For Li, statistical creations were not merely intellectual exercises— such activity intermingled with artistic expression:

Learning a skill, it doesn't matter if it's painting or learning the piano or whatever it is, it requires someone to feel the pulse of your own body to have the best performance on your work, and the result of your work is an art object. So, in this case, I think it's kind of statistics.

As someone who played the piano and did calligraphy, Li linked these activities with the kinds of emotions and approaches needed to solve novel statistical problems.

Sahil explained that a central goal of statistical analysis is trying to come up with the most "elegant" methods, "not overfitting, not underfitting." Furthermore, analysts might approach problems in strikingly different ways that express their creativity and individual perceptions:

I think whenever someone is trying to deal with a problem, they will have their own thought processes, right? ... There might be some similarity, since we all learn similar things, since it was built on us. So there will be some similarity. But where the creativity part comes into the picture, it will be different.

Sahil recognized something individualistic about how experts engage in problem solving. There are similar shared structures that analysts depend on, but analysts also engage their own thought processes when facing unique problems and exercise creativity.

Summarizing notions of statistical practice. Distinctions in how the GTAs discussed the nature of statistical practice hinged on past experience and exposure to the more creative and flexible aspects of statistical work. Kathy seemed to have the least prior coursework and practical experience in statistics, lending to her view that statistical work was more about following rules and conventions. Mindy had more exposure to the adaption of tools to the problem at hand, but without the theoretical background to understand the creation of brand new methods. Sahil and Li were able to articulate a more comprehensive view of doing statistics by sharing a more detailed understanding of theoretical development.

6. CONCEIVING INTRODUCTORY STATISTICS

At the beginning of their graduate studies, the four GTAs expressed different visions for an introductory statistics class. As the year progressed, these curricular and instructional visions began to converge around several shared themes. As members of the department community, the GTAs were immersed in the teaching practices and introductory curriculum of the department. While the GTAs tended to use first-person singular pronouns (e.g., I, my) during their first semester, they gradually started to use more first-person plural pronouns (e.g., we, our) to refer to introductory course curricular priorities and best teaching practices in second semester.

In this section, I outline each participant's early pedagogical views from their first semester, how they intermingled with their disciplinary perspectives, and how ongoing experiences added to (and in some cases, disrupted) their vision for introductory statistics.

6.1. KATHY: INTRODUCTORY STATISTICS AS A FOCUS ON "THE BASICS"

Kathy's pedagogical views toward statistics were deeply intertwined with her disciplinary perspectives. She described statistics as a "math-based class," and stated that when working on statistical problems, "there is a process and a right answer."

Kathy frequently contrasted pedagogy used in statistics to pedagogy she had used formerly as a discussion leader for a human health class. While her health class took the form of group discussion generated from guiding questions, her vision for statistics was founded on encouraging collaborative effort on more closed-form questions.

In the health class, one of the things you might discuss was "how you can better improve your time management by looking at a log filled out for a week." So pretty individualized. Whereas [statistics] would be everyone's working together to get the answer, kinda walking through step by step, making sure they all get it.

Kathy also described health as a topic to which students can bring in their own ideas and experiences to guide discussion, whereas statistical content is a "hard and fast science." She remarked,

> Being a stats TA doesn't require you to be as engaged with your students…when you get the material out, it's not as important to get student feedback immediately, except for just asking if they have questions.

Kathy viewed introductory statistics as needing to acquaint students with "the basics": summary statistics, graphs, and probabilistic calculations. Kathy was not opposed to projects or learning software in an introductory course, but she explained, "I maintain that you can't analyze data and do a full study if you haven't learned the basic procedures first."

Kathy's mind map (Figure 8) represented many of these curricular components, with the basics beginning on the top left, extending to hypothesis testing (with aid from probability), and then opening up possibilities in other more advanced bubbles. Kathy framed her mind map based on her ongoing coursework. She first represented the Survey class with which she assisted, where summary statistics (which she labeled as "the basics") were the ingredients for inference, and topics like probability and normality provided an important role as well. Since Kathy viewed statistics as fundamentally part of mathematics, it was important to her that students to master these basic mathematical elements before they could competently use more distinctly statistical activities. She associated these more advanced methods with her applied methods course. Her mind map acts much like a curricular flow chart from objective core content to optional extensions and applications. All mind maps presented here have been redrawn for readability, but original drawings are included in Appendix C.
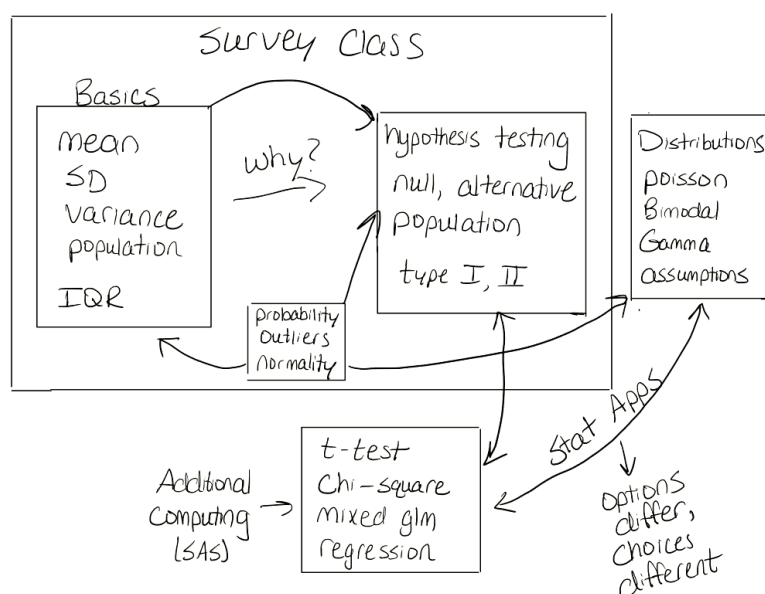

Figure 8. Kathy's Mind Map (redrawn)

6.2. SAHIL: INTRODUCTORY STATISTICS AS MATHEMATICALLY GROUNDED

With a background in graduate mathematics and statistics already, Sahil had a very theory-centric view of statistics. He remarked in the first interview that he thought the best way to teach students would be through motivating lectures. His experiences in the classroom over both semesters, however, helped him realize that not all students learn well with a theory-heavy approach:

> Intro statistics course, those are like the foundational statistics and the mathematics behind the methods. They worked out perfectly for me, but I have seen students who have found them difficult to deal with … I would very much like to say that mathematics is most important, but I think computational methods is also like equally important because … if you provide both of them, like not too much, both of them sufficiently … the student will be able to understand the idea of statistics, either by mathematics or by computational methods.

By the end of first semester, Sahil still held a relatively high view of mathematics in the introductory statistics curriculum, as evidenced in his mind map (Figure 9). When beginning the task, I noted the first word he wrote was "mathematics," suggesting an important relationship between the two disciplines. The

bubble on the left included general statistical terms with which he was not sure what to do. The sector on the top was described as "the backbone" of statistics, and included terms like "mathematics" and "probability." The terms in the middle represented "Inference." Finally, the bubble on the right was a "computational approach to inference," which contained specific statistical methods.
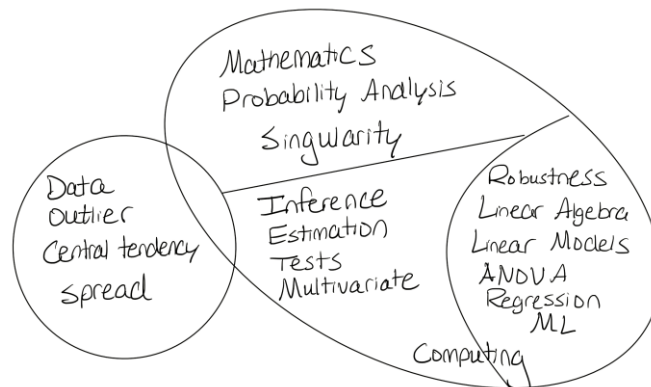

Figure 9. Sahil's Mind Map (redrawn)

When asked if he could relate his mind map to an introductory statistics course, Sahil said, "An introductory course starts from [the left bubble] … and goes through [Inference] with a little bit of help from mathematics." He also mentioned that in the context of a truly introductory course, the far-left bubble might also include things like summary statistics, boxplots, and histograms.

In terms of pedagogy, Sahil's views evolved noticeably across the year as his expectations for students began to drop. He explained that the students he interacted with in discussions typically asked only low-level questions and got easily confused over simple concepts:

> It's been very clear to me that most of the students are not from a statistics background, right? So, they need to learn stats to use it in their own way. So, in that case, I don't think learning the theory is that important …. Students need to know how the testing method works on data, but for an intro course, I don't really believe they need to know how we have *landed* into that method, and not any other type of method.

In relating Sahil's curricular vision to his disciplinary perspectives, it became clear he was separating introductory aims from more advanced coursework aims. Since Sahil found students struggling both in motivation and mathematical background, he was not sure how to engage students with theory to undergird principles. As a result, his vision for introductory statistics involved a focus on handwritten or calculator computation that emphasized correct procedures and the delay of instruction on undergirding theory or flexible statistical practice until later courses.

6.3. LI: INTRODUCTORY STATISTICS AS A "SHADOW"

Li's disciplinary perspectives connected to his pedagogical views for more advanced study, but he struggled to articulate a clear vision for introductory statistics. Li summarized high-quality statistics instruction by saying:

> For statistics, to figure out the direction is the strength of the statistics teachers. They can always tell you, we use this formula, or we use this algorithm to do this work, and after that, we can get this output, so that's pretty clear.

Li said one of the worst things he could do would be to throw too much information to students at once.
Li believed introductory statistics would be best taught as a general survey course:

> [Students] really should take some introduction courses to get some basic idea, and in the future when they face this question, though they still don't know how to solve it, they know … that's a question of statistics, and I need some partner who work in this field to solve this problem.

For similar reasons, he believed it was more important for a course to teach principles rather than over-emphasize details: "They will forget how to do the Chi-square or *z*- or *t*-test … but they will remember

there's a hypothesis test …. These details are practice to help them have a temporary understanding of this guy." Li seemed to believe that a focus on concepts, as well as limited practice with methods, would help students develop a broader statistical understanding.

When it came to the mind map task, Li struggled to describe the field conceptually (Figure 10). He separated his map into three sections: Math/theory, Programming and Statistical Learning, and Class Learned/Advanced methods ("class learned" was a reference to things he himself was learning currently). When asked whether his mind map resonated at all with the content of an introductory statistics course, Li responded, "The contents of the course are related as a shadow, because the course just introduces basic ideas, so something of probability, and mostly of distribution." He struggled to be more specific than that in explaining what exactly introductory students needed to take away from a first statistics course.
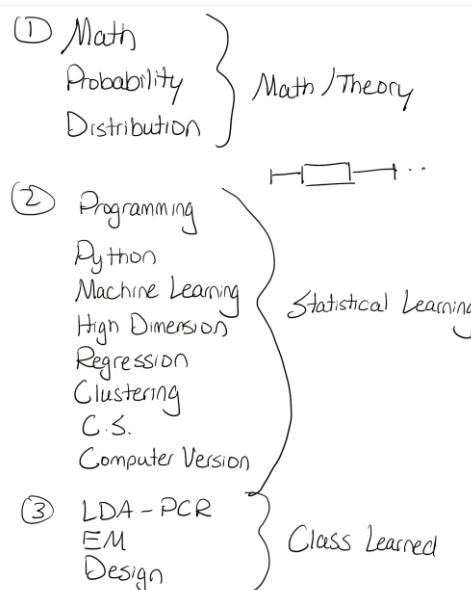

Figure 10. Li's Mind Map (Redrawn).

In semester 2, Li was noticeably influenced by his discussion section experience for introductory statistics. He had initially said that he wanted students to share their own informal thinking before introducing formal methods, but his faith in students began to fall:

> I found especially for non-statistics major students, it's impossible for them to get their own idea, like *t*- or *z*-test. They don't have the background here. So the ways to solve these problems are not trivial for them at all. Even to let them think is probably a waste of time. There are so many things before they need to learn.

He had begun to latch onto the more procedural tasks used in the activities he facilitated and adjust his curricular vision accordingly.

Li's broader notions of statistical thinking were overshadowed by more immediate concerns of student capabilities. In practice, he began to also adopt Kathy's "basics" approach to introductory statistics, where experience with procedures was a prerequisite to these higher-order perspectives. Like Sahil, he also needed to compartmentalize his more theoretical disciplinary perspectives and instead focus on teaching an objective canon of procedures.

6.4. MINDY: A DESIRE FOR SOMETHING BETTER

From the very first interview, Mindy clearly articulated a view that statistics curriculum should prepare students to apply the ideas they were learning to real-world problems. This view was rooted in her personal motivation toward studying statistics: "I [want] to be solving new problems every day, I guess, and found I want to be a sports analyst. [I] found that niche and realized that was a thing I could do." Mindy's internship experiences were also a big part of this perspective, as that gave her opportunities to think creatively and develop motivation to learn new methods to answer interesting questions. By the

end of first semester, however, Mindy began to experience curricular tensions about the introductory course, as shown in her Mind Map (Figure 11).
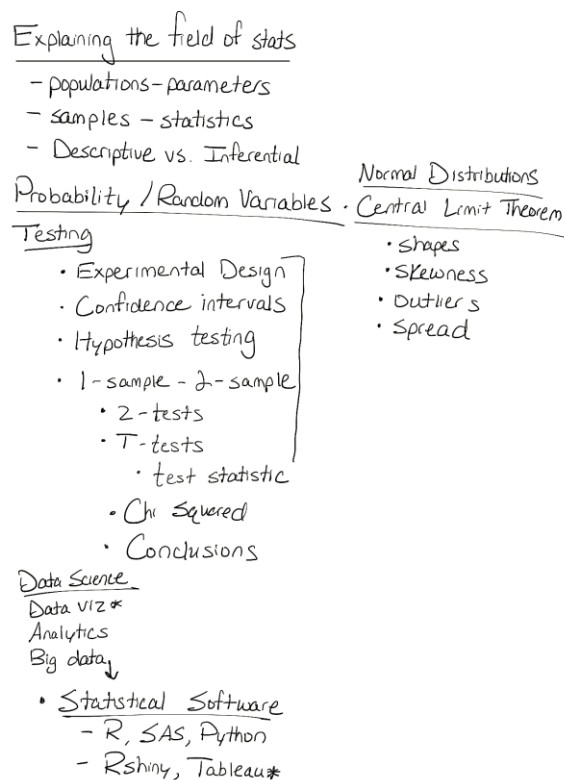

Figure 11. Mindy's Mind Map (redrawn)

Mindy first wrote a list titled, "Explaining the field of statistics." Her next inclination was to create a "Testing" category, but then felt she needed to bridge that gap:

Mindy:	And I know I'm missing all the stuff in the middle.
Interviewer:	What is the stuff in the middle?
Mindy:	I don't know, I can't think of it right now … or ok probability, and random variables would definitely need to be here. That was test 3 … They can't just jump to testing. They need to learn, obviously [Central Limit Theorem] was huge … learning the shapes of distributions, skewness. Umm, outliers, spread, etc. This was a rough one for them.

Mindy described "the stuff on the bottom" as the "fun" parts of statistics, but also described the "stuff in the middle" as the more necessary elements that students needed to learn first, even though she also thought it was the worst part of the curriculum for students.

In discussions across the year, Mindy seemed to be disappointed with what students were actually learning in the department's introductory courses. She thought that the traditional curricular elements did not align with the more flexible understanding of statistics students needed. "I want to help them understand why they're doing statistics and not be robots." This was in response to her observation that the department's introductory course tasks seemed rather procedural and required too much recall of memorized responses from a flow chart.

Mindy too was struck by the mathematical difficulties her students exhibited. When asked with what students often struggled, she explained, "Anything with numbers. Division, fractions, finding the mean … just critical thinking, unless they've seen this problem asked the same way." Consistent with her views of the discipline, she still believed it might be good for at least some of these students to be given data and asked an open-ended question. But she also believed that other students in that situation would get confused or flustered.

Mindy also voiced poignant dissatisfaction with the questions used in the introductory classes. She described the course as too much like a mathematics class, where students needed to demonstrate fluent

computational skills and run through an exorbitant number of different statistical tests. She did not believe her students were actually prepared to do any statistics by the time the class was over because they had only learned a lot of procedures that they would simply forget. The procedures were competing with the other curricular aspects that she enjoyed. Mindy lamented, "We can't teach the math and all the other things. We just don't have time to do that."

Mindy's disciplinary views were sidelined, but not necessarily abandoned. She recognized context mattered and that some manner of flexibility and choice had a place in statistical work. Yet, she felt restricted within a framework for statistics that seemed exclusively methodical and rule-based. Mindy wanted to engage students in problem-solving opportunities, but she was unsure how that might be possible if students needed to do all of the "stuff in the middle."

7. DISCUSSION

The goals of this paper were to document the disciplinary perspectives of first-year GTAs in statistics, consider to what degree these disciplinary perspectives intermingled with their visions for introductory statistics, and to ask how these findings should influence GTA training in statistics. While the GTAs expressed varying perspectives on the nature and practice of statistics, all seemed to conform to a similar pedagogy of introductory statistics that emphasized procedural fluency. But the sense of frustration expressed by Mindy (and to a lesser degree by Sahil and Li) provides optimism of what could be possible with the right training and resources. This study offers no clear success story or concrete solution, but I can offer theories of what might have changed these outcomes.

In this final section, I first highlight an observed phenomenon experienced by three of the participants that I see as a barrier to bridging a wider view of statistics to introductory courses. Then, I share implications for future research and training involving statistics GTAs.

7.1. DISCIPLINARY COMPARTMENTALIZATION

While studying the content knowledge of statistics GTAs, Noll (2011) explained that many participants compartmentalized the theoretical perspectives with which they were familiar in their graduate courses from the more conceptual perspectives promoted in introductory course content. Consistent with those findings, several of the GTAs in this study likewise compartmentalized their personal disciplinary perspectives from the work of students learning introductory statistics. This compartmentalization did not require the participants to necessarily change their disciplinary perspectives—several still expressed that statistical work can be flexible and contextual, that statistics is distinct from mathematics, and that statistics is a body of concepts rather than isolated procedures. What they lacked was a theory of learning that linked these facets of the discipline to robust pedagogy for introductory statistics.

Situated views of learning argue that learners develop meaningful understanding by participating in the authentic practices of experts in the field, rather than merely learning *about* their work (Bruner, 1960/2009; Lave & Wenger, 1991). While Mindy's "learning by doing" motto of instruction would loosely relate to this perspective, a situated learning perspective can go farther by bringing attention to the tasks themselves. It is not enough to be engaged in tasks; students need *authentic* tasks.

Disciplinary compartmentalization contrasts with a situated view of learning in the belief that how *students* learn should not necessarily be informed by how *practitioners* engage in their work or even how the discipline has developed knowledge. Bruner (1960/2009) countered that argument:

> Mastery of the fundamental ideas of a field involves not only the grasping of general principles, but also the development of an attitude toward learning and inquiry …. Just as a physicist has certain attitudes about the ultimate orderliness of nature and a conviction that order can be discovered, so a young physics student needs some working version of these attitudes if he is to organize this learning in such a way as to make what he learns usable and meaningful in his thinking. (p. 20)

All of the participants eventually adopted the notion that students needed to learn "the basics" before they would be able to engage meaningfully in contextually-based problems. Yet Bruner suggested that learning basic content soundly need not compete with learning and engaging in disciplinary practices.

Jaber and Hammer (2016) add nuance to Bruner's message by highlighting the importance of affective response in disciplinary engagement. In describing the scientific learning of elementary students, the

authors described affective response as part of the "substance" students need when learning science and as a necessary component to motivate and structure learning experiences. Authentic experiences that excite students and acquaint them with the questions that disciplinary experts engage with can provide a platform for rich learning to take place (Engle & Conant, 2002).

Additionally, a constructivist view of learning provides important insights toward creating a meaningful instructional vision. Constructivism brings attention to how students think and develop conceptions of new ideas and processes (NRC, 2000). Tasks that foster opportunity for students to construct their knowledge into meaningful frameworks (rather than as an accumulation of facts for recall) are more open-ended, involve peer discussion, grant students more autonomy, and are comprised of more than finding right answers (Garfield & Ben-Zvi, 2009; Schoenfeld, 1998). Eliciting students' preconceptions, creating space for students to test ideas, and providing opportunity for students to reflect and synthesize on their thought-experiments, represent key features of a constructivist learning environment (National Research Council, 2000).

To exemplify situated and constructed views of learning in the statistics classroom, statistics educators have recommended a number of instructional approaches. Informal inferential reasoning proposes that students use visual aids and informal arguments in the discussion of inference before learning formal methods (Gil & Ben-Zvi, 2011; Pfannkuch, 2011). This approach to learning engages students in the practices of statisticians who often adapt methods or create new methods to make sense of previously unexplored problems. Secondly, exploratory data analysis is an important learning opportunity to demonstrate to students the importance of letting context and curiosity drive decisions and analysis (Cobb & Moore, 1997). Third, the use of computer simulations and other digital or physical tools can be leveraged strategically to allow students to explore their own questions and ideas as they make sense of important statistical concepts and phenomena (Chance & Rossman, 2006).

The discussions above reflect important considerations for GTAs like Mindy, Li, and Sahil. Kathy's story is a little different, as her disciplinary perspective was already well aligned with an instructional vision focused on instrumental understanding (Skemp, 1976). She had no reason to question this curricular and instructional approach. The tasks were seemingly preparing students for the work of statistics, which she viewed as rather methodical, objective, and straightforward. Kathy's story demonstrates that disciplinary perspectives that align with the true nature and the practices of the discipline are likely necessary; Li, Sahil, and Mindy's stories demonstrate that holding such views is probably necessary, but certainly not sufficient to exemplifying the reform-oriented instructional principles outlined in the GAISE Report (GAISE College Report ASA Revision Committee, 2016).

7.2. IMPLICATIONS FOR TRAINING GTAS TO TEACH STATISTICS

Highly effective statistics pedagogy engages students in disciplinary practices (Wild & Pfannkuch, 1999), pushes students to think deeply about concepts like sampling variation (Noll, 2011), prepares students to use statistical tools appropriately (ASA, 2016), and orients students toward contextual meaning and decision-making (Pfannkuch, 2011). While many of these pedagogical sentiments were expressed by the GTAs in this study, they never materialized into concrete plans as they entered their solo teaching semester. This section offers several possible steps to address how department's can support GTAs' productive sentiments toward enacted practice.

As a first step, department training should consider the backgrounds and statistical perspectives of new GTAs. As was apparent with Kathy, some incoming statistics GTAs may not yet have distinct conceptions of statistics. Without this disciplinary foundation, it may be difficult to motivate the need for open-ended tasks and contextual decision-making in the introductory statistics curriculum. GTA preparation programs in statistics should consider whether the GTAs themselves may benefit from statistical activities intended to widen their view of statistics. As an example, Visnovska and Cobb (2019) discuss how secondary teachers were able to make shifts in their views of teaching statistics through statistical activities. According to the authors, activities that truly changed how the teachers thought about statistics offered an accessible yet meaningful context, drove analysis by first provoking motivation, and prompted the teachers to think holistically and critically about the data-generating process.

For Sahil and Li (and especially for Mindy), productive disciplinary perspectives were not enough to support instruction that facilitated authentic experiences for students (much like Zachary's experience as documented by Speer [2008]). Providing GTAs with a conceptually-rich curriculum may help. For

example, statistical activities that use informal inferential reasoning and exploratory data analysis could bridge this gap by linking the work of experts to that of introductory students.

We also know from research that curriculum alone is often insufficient in promoting high-quality instruction for novice teachers (Ball & Cohen, 1999; Kaplan & Roland, 2018). What may also be needed is a philosophy for teaching statistics that can solidify these various pieces into a cohesive pedagogical framework. Past studies document varying success engaging science GTAs in learning theories as part of their instructional training (Hammrich, 2001; Pentecost et al., 2012). Based on the disciplinary compartmentalization that took place among the participants in this study, there is reason to believe that immersion in situated views in particular might motivate a clearer connection between the work of experts and the work of students. Future work is needed to explore how the inclusion of learning theories in statistics GTA preparation may strengthen the effectiveness of buy-in for strong curricular materials.

Additionally, all four GTAs found that students showed resistance to tasks that were not straightforward. As no surprise, this might cement even more the idea that procedural or close-ended questions are all that introductory students can handle. GTAs may then benefit from a module on "productive struggle" to enhance their views about lasting student learning (Warshauer et al., 2019). Future research may consider GTAs' perceptions about the value of open-ended tasks and what instructional environment may best support learning in this context.

ACKNOWLEDGMENTS

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APPENDIX A

Please rate the extent to which you agree with the following statements about instruction in introductory statistics courses for non-majors.

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Most students learn best when they try statistical problems using their own ideas before learning formal methods (like *t*-tests and Chi-Square tests).					
Most students learn more from a good lecture than they do from a good activity.					
Most students learn best when they use simulations (a web page or software application with interactive scales/buttons) to learn difficult concepts.					
Students should occasionally work with *messy* datasets (missing data, outliers, and/or messy formatting).					
Students should get quizzes or tests back with written feedback to improve their learning.					
Student grades should be determined primarily by individually completed homework, quizzes, or exams.					
Students grades should be determined primarily by projects, presentations, or group assignments/activities.					
Questions using made-up data are just as effective as questions using real data, just as long as students aren't misled to believe it's real.					
Most students should learn more topics in less detail instead of fewer topics in more detail.					
Students should learn how to use software beyond calculators (like Excel or R) to do basic statistical analysis.					
Students should develop a deep understanding of sampling distributions.					
The course should spend at least one class period covering rules of probability (like the multiplication rule, conditional probability formula, or adding disjoint events).					
The course should familiarize students with the binomial probability mass function (pmf).					
The course should familiarize students with the normal probability density function (pdf).					
It is important for students to see and learn about statistical formulas (like the formula for standard deviation).					
The course should require students to make calculations using formulas (by hand or with calculator).					
Students do not need to learn the mathematics behind statistical methods as long as they can use the methods properly and interpret results correctly.					
Students should learn how to write statistical questions.					

Students should learn how to outline a statistical study, including a plan for data collection and analysis.					
Students should complete a statistical project in the course.					
Students should learn how to write up a report describing a study from start to finish.					
Students should learn to carefully judge and evaluate data-based arguments and claims they see in the media.					

Consider the total amount of in-class time you have as an instructor for the entire semester. What percentage of class-time would you like to spend for each of these things? Percentages should add up to 100%

    a) Lecture, teacher demonstration, or teacher answering student questions:

    b) Activities completed in small groups, students discussing with students, group quizzes:

    c) Students working on problems independently:

    d) Individually completed exams/quizzes:

    e) Other (like student presentations, showing videos, clicker questions, etc.):

Indicate the method of computing numerical solutions to problems that you believe helps students learn statistics best.

    a) All solutions computed by hand

    b) Most solutions computed by hand

    c) Equal amounts of computing solutions by hand and using technology tools

    d) Most solutions computed using technology tools

    e) All solutions computed using technology tools

APPENDIX B

Interview 1 (September, 35 – 45 min)
- What degree programs were you a part of before entering this program?
- Do you have any teaching experience? Tutoring experience?
    o Did you enjoy teaching/tutoring? What was enjoyable? What was difficult?
- What statistics coursework, if any, have you had up until now?
- Tell me about the previous statistics (or mathematics) teachers you have had.
    o Tell me about how they taught. (how much did they lecture? How much did students ask questions and engage in class discussions? Did you complete any activities in class? What was homework like? Did you do any tests or projects?)
    o What did you like and what did you dislike?
- Tell me about the kind of teacher you will be. How will you be similar or different than the teachers you have had before?
    o How do you describe the role of an instructor in an introductory statistics course? How is a statistics instructor different from a mathematics instructor?
- How would you define statistics?
    o (another way to ask): How would you define the field of statistics to someone who doesn't know much about statistics?
- What do you think it means to do statistics?
    o (another way to ask): What kinds of tasks do you think a statistician or a data scientist does?
    o What about a non-statistician who uses statistics for their job? What kinds of tasks might they do?
- Why should undergraduate students in a non-mathematical/statistical major take an introductory statistics course? What should they learn?
- Read the following statements. How would you rank these potential course goals in order of importance for introductory statistics students?
    1) Students should learn to carefully judge and evaluate data-based arguments and claims they see in the media.
    2) Students should learn applied methods to be able to complete statistical investigations
    3) Students should learn the foundations of statistics and the mathematics behind methods

Interview 2 (December, 45 – 60 min)
- Tell me about your graduate classes.
    o How are they going?
    o What are you learning about?
    o Which class is hardest and why?
- Tell me about your interactions with others in the department
    o Do you ever have informal and unplanned discussions with other graduate students, lecturers, or faculty members to discuss topics related to teaching or assisting courses?
        ▪ With whom? How frequently? What kinds of things do you discuss?
- How do you feel about your recitation duties?
    o How do you facilitate your activities?
    o How familiar is the content to you? Do the questions and tasks look similar to things you've seen in your own classes?
    o Any interesting or unexpected events happen so far in your recitation duties?
    o If you were the instructor, is there anything you would do differently?

Statistics Mind Map Task
    1) When you think about "statistics," what words, terms, or phrases come to mind?
        a. Create a word wall of any term, phrase, or idea you associate with a statistics course and doing statistics

          b.   Try to list at least 20 things
2) Are you able to categorize any of these words/terms/phrases together? (like apples, bananas, and pears would be subsets of fruit)
3) Create a mind map that organizes these ideas in a way that makes sense to you
          c.   Which of these ideas and skills would you consider central to what statistics is? Which are less central?

Interview 3 (March, 80-100 min)
- Tell me about this semester so far
  - How are your classes going? What's been the hardest class? Your favorite class?
  - How have your recitation duties been going?
- Tell me about the workshop
  - What are the activities and assignments you completed that were the most helpful?
  - Review their post-workshop evaluation and discuss their scores to different segments.
    - Let's follow up on your survey results to see if anything changed from the first time you took it
- Do you feel significantly different about this item now than you did before?
  - What caused that change for you?"
- Tell me about the classroom visits you made.
  - What do you remember about X's classroom?
  - What did you like? What did you dislike?
  - How do you imagine your classroom and instruction being similar or different?
    - How would you describe your role as a teacher (solo instructor)?

The Nature of Statistics
- Is there an advantage to statistics being its own department, as opposed to statistics being embedded in mathematics departments?
  - As far as statistical research is concerned, do you think it matters whether statisticians are in their own department, or working out of a mathematics or mathematical science department?
  - What distinguishes a statistical problem from a mathematical problem?
    - If I gave you a list of 10 questions, half being from mathematics department courses and half from statistics department courses, would you be able to sort out which questions came from where? How?
    - Can you draw a Venn Diagram with one circle representing mathematics and one representing statistics? How much should they overlap? What things should be in each sector?

The Nature of Statistical Knowledge
- [I will display the formula for standard deviation] Tell me what you think this formula represents. What is it measuring, and why is it constructed this way? [reassurance that this is not an assessment, that it's ok to be unsure]
  - How would you react to reading a peer-reviewed research paper that used mean absolute deviations instead of mean squared deviations in the formula?
    - Do you think there is a context where that alteration could be ok, or is that wrong?
    - Do you think all statisticians view this formula as the best way to measure variability?
  - Statistics research has traditionally been pushed forward by researchers in the United States and in the West. If another culture (say the Far East like China, Korea, and Japan) instead was the predominate source of new statistical research, would that change any of the conventions we use or the nature of future methods?

The Nature of Knowing Statistics
- Would you say research in statistics is mainly an individual or a collective process?

- o If I prove something in my office or refine a new method, is it statistical knowledge right away, or does it need to be read, evaluated, negotiated, criticized, published, and taken up before we could consider it statistical knowledge?
- o Some claim that statistical knowledge is discoverable truth, yet others argue that such knowledge is invented or constructed by our minds. What is your opinion about this?
- o What role does proof play in the development of statistical knowledge and methodology?
  - ▪ Is there a difference between the nature of mathematical proofs and statistical proofs?
  - ▪ Do statistical proofs require assumptions? When you think about what it means to prove something in statistics, do you think it matters if proofs and methodologies require certain assumptions and conditions?

The Nature of Doing Statistics
- What are the different ways people participate in the discipline of statistics? [Possible ideas to probe: within research for statistics journals, data science, carrying out research methods, student/statistical literacy, teaching]
  - o Some hold that solving problems in statistics is a thinking activity involving personal creativity. Others argue that solving these problems require following predetermined, known procedures. What is your opinion about this?
    - ▪ Do you think that solving statistical problems is an objective or subjective process, or somewhere in between? Can you explain/provide examples?
  - o Do you think that data is objective?
  - o Do you think statistics is related to art? Why or why not?

Pedagogical Questions
- Can someone at the level of your introductory students participate in statistics?
  - o What might you reasonably expect of them after taking an intro course?
  - o How will what they do in your intro course prepare them for these roles?
- What are the characteristics of someone who is knowledgeable in statistics?
  - o Can you think of the different kinds of ways someone can be knowledgeable in statistics? Including outside the traditional statistics degree track?
  - o Can someone at the level of your introductory students be knowledgeable in statistics? If so, how?
  - o How can intro students become knowledgeable in statistics?
    - ▪ After initial thoughts, list ideas: Listening, working problems, discussing and collaborating with others on projects, evaluation of peer work or ideas, questioning conventions or established methods, doing projects independently, writing and reflecting, reading, working under a supervisor on statistical project?
  - o What role do you as the instructor play in helping your students become knowledgeable?
  - o After initial thoughts, list ideas: Lectures, working practice problems, posting important things on course site (what things?), promoting discussion, writing and/or reflection assignments, solo or group projects, examinations, activities, assigning things to read, posing difficult problems, having students explore/analyze messy datasets?

Interview 4 (May, 45 – 60 min)
- Tell me how your course planning went.
  - o What resources or experiences did you consult as you were planning?
    - ▪ Did you consult the course notes? Any other written notes/book?
    - ▪ Did you consult online resources?
    - ▪ Did you consult people (the GTA Coordinator, classmates, professors)?
  - o Do you feel like you learned anything new about statistics or that your understanding of statistics was enriched?

- ▪ From the workshop?
- ▪ From preparing specifically for your course?
  - o Do you see the introductory course you teach and the graduate courses you take as portraying similar perspectives of statistics, or do you see them representing different perspectives?
- Tell me about your plan for teaching.
  - o Tell me about [X] in your syllabus, why did you decide to structure/manage your class this way?
  - o In a typical class period, how do you plan to piece out your time? Lecturing (writing on the whiteboard, using doc cam? etc.), activities, individuals working on problems, other things?
    - ▪ Are these different than the breakdown you had on the previous survey?
    - ▪ Tell me why you feel this breakdown will be best (Student learning? Instructor convenience? Other thoughts?)

Course Objectives Task
  - o For this task, I want to capture GTAs' philosophy regarding the aims of the intro course and how that might connect to their conceptualization of statistics. This task will also connect GTAs' philosophy with their curricular knowledge by laying out their vision for the progression of the course.
  1) Think about what you want students to learn and be able to do by the end of your course. Create a list of potential learning objectives (skills, understandings, kinds of questions they should be able to answer, ways of looking at the world differently, etc.)
  2) Describe the progression of your course in a general timeline. What do you see as the big ideas in your course?
  3) Does the ordering matter? Do you see any of these topics building on one another?
  4) Are there certain key ideas or themes that stream through multiple topics? Are there any foundational ideas that you see your course building from?
  5) Now, consider the following list of objectives (listed on slips of paper):

      - ▪ Students should become critical consumers of statistically-based results reported in popular media, recognizing whether reported results reasonably follow from the study and analysis conducted.
      - ▪ Students should develop a deep understanding and appreciation for the mathematics behind statistical methods.
      - ▪ Students should view statistics as a process of posing questions, collecting data, analyzing data, and drawing inferences about the population.
      - ▪ Students should develop a deeper awareness of variability and the implications on everyday life.
      - ▪ Students should recognize and be able to explain the role of randomness in designing studies and drawing conclusions.
      - ▪ Students should recognize the close link between probability and statistical inference.
      - ▪ Students should learn about basic probability and distribution theory, including foundational rules and probabilistic notation.
      - ▪ Students should gain experience with using and understanding statistical models.
      - ▪ Students should demonstrate an awareness of ethical issues associated with sound statistical practice.

      There are 9 objectives listed here, but let's say you could have only 8 on your syllabus. Which one would you eliminate? And why? [Continue process (you can only have 6, 5, etc.) until GTAs have essentially ranked all course objectives.]

APPENDIX C

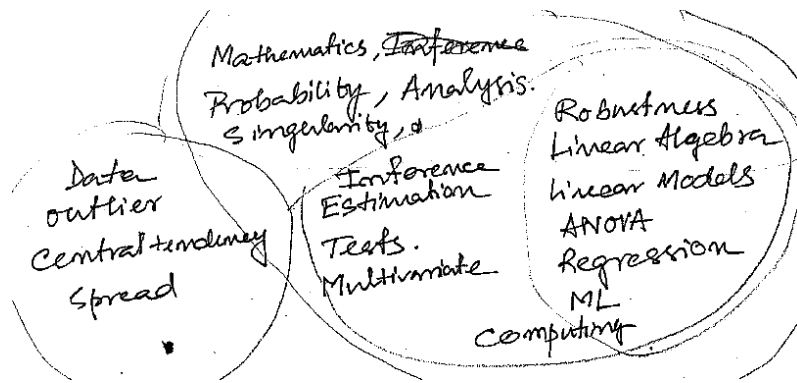*Figure C1. Kathy's Original Mind Map*
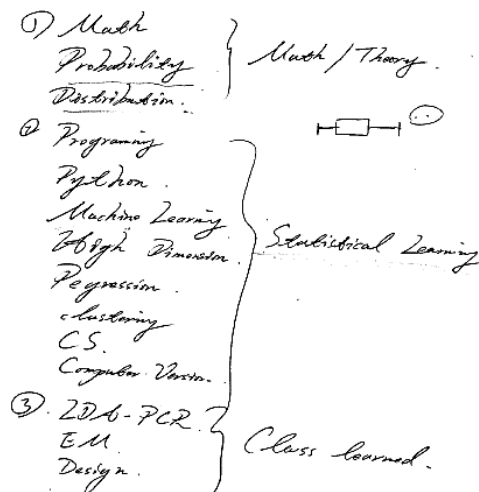

Figure C2. Sahil's Original Mind Map

Figure C3. Li's Original Mind Map

Explaining the field of stats
- Populations - parameters
- Samples - stats
- Descriptive vs inferential
. Probability / Random Variables

Normal Distributions
. Central Limit Theorem
. Shapes
. Skewness
. outliers
. Spread

Testing
° Experimental Design
. Confidence intervals
. Hypothesis testing
. 1 sample - 2 sample
. Z - tests
. T - tests
. test statistic.

Data Science
Data Viz ⋆ . Chi squared
Analytics
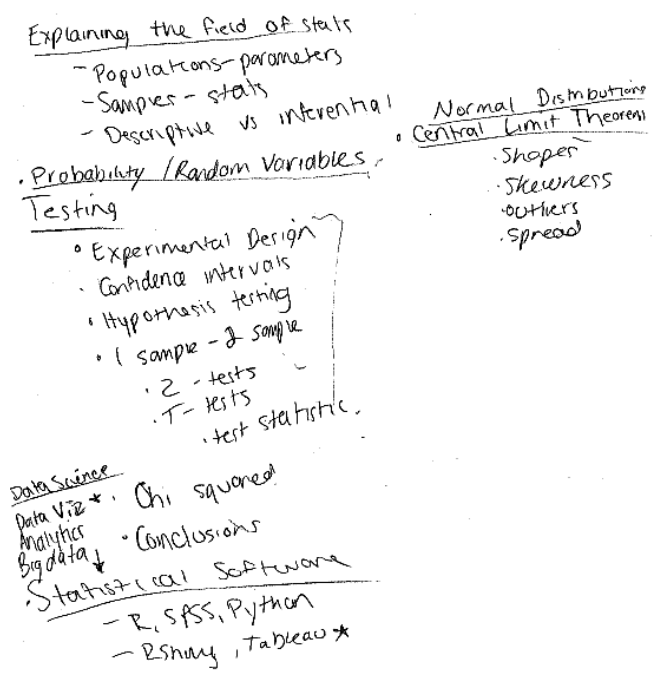Big data . Conclusions
. Statistical Software
- R, SPSS, Python
- Rshiny, Tableau ⋆

Figure C4. Mindy's Original Mind Map