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Publication Date

2014

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UNIVERSITY OF CALIFORNIA, SAN DIEGO

SAN DIEGO STATE UNIVERSITY

Preparing Future College Instructors: The Role of Graduate Student Teaching Assistants
(GTAs) in Successful College Calculus Programs

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor
of Philosophy

in

Mathematics and Science Education

by

Jessica Fabricant Ellis

Committee in charge:

San Diego State University

Professor Chris Rasmussen, Chair
Professor Susan Nickerson

University of California, San Diego

Professor Mark Appelbaum
Professor Beth Simon
Professor Laura Stevens

2014

The Dissertation of Jessica Fabricant Ellis is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California, San Diego

San Diego State University

2014

Dedication

There are many people who have supported me in different ways over the course of preparing this dissertation, and I thank you all.

I thank my **friends** for balancing, entertaining, listening to, and loving me.

I thank my **family**, especially my mama, Dr. Kathleen Hayes, for believing in and supporting me.

I thank my **colleagues** for inspiring and challenging me, reading drafts of my writing and helping me improve, listening to my ideas, and pushing me as a writer, researcher, and academic.

This dissertation is focused on how graduate students are prepared to teach Calculus 1, and further brought into the community of undergraduate faculty. I have been lucky enough to have many mentors support me over the years in becoming part of various communities. I thank my **mentors** for seeing me for me, and for my potential, and for helping me reach my potential. Professor Steven Agronsky brought me into the community of Mathematics, Professor Todd Grundmeier brought me into the community of Mathematics Education, and Professor Chris Rasmussen brought me into the community of Research in Undergraduate Mathematics Education.

I dedicate this work to Professor Steven Agronsky, who passed away this year. Professor Agronsky inspired me to become a math major after taking Calculus 2 with him, believed in me when I was failing his Introduction to Proof course, shared his own dissertation work with me during my Senior Project, helped me decide to pursue graduate school, and is the reason I have thrived throughout all of these experiences. When I was debating graduate school, I asked one professor about his experience, and he said he had never worked so hard in his entire life. When I asked Prof. Agronsky, he said he surfed every day and got to think deeply about what he wanted to think about – and that it was a blast. I've spent the past four years surfing as frequently as possible, and loving the work I do.

I look forward to my future in academia, continuing to love this work and thrive because of my friends, family, colleagues, and mentors.

Thank you all.

Table of Contents

Signature Page	iii
Dedication	iv
Table of Contents	v
List of Figures	xi
List of Tables	xii
Curriculum Vitae	xiv
Abstract of the Dissertation	xx
CHAPTER 1: Study Overview and Significance	1
Call for Change	1
Role of Graduate Students	3
Background	5
Personal Experiences.....	5
Characteristics of Successful Programs in College Calculus (CSPCC).....	6
Motivating results from the survey data	7
Revisiting Research Questions	12
CHAPTER 2: Literature Review	16
Teacher Quality	18
Teacher and Instructor Qualifications.....	21
Teacher Characteristics.....	25
Teacher Practices	30
Student Success	36

Summary of Teacher Quality.....	40
Professional Development.....	42
Types of Professional Development Programs.....	43
GTA Professional Development.....	53
Features of Successful Professional Development Programs	60
CHAPTER 3: Methodology	62
Methodological Overview: How to conceive of teacher learning.....	62
Theoretical Perspective: Situated Learning.....	64
Data Collection	68
Phase One: Determining Successful Institutions.....	68
Phase Two: Case Studies at Successful Institutions.....	70
Data Analysis	74
Overview of Data Collection and Analysis	81
CHAPTER 4: Instructor Quality Comparison Across Instructor Types	84
Instructor Qualifications	85
Instructor Characteristics	87
Instructor Demographics	87
Instructor Beliefs.....	88
Instructional Practices	99
Class Structure.....	100
Frequency of Certain Pedagogical Activities.....	101
Classroom Discourse	104
Nature of Tasks.....	106
Summary of Instructional Practices.....	109

Student Success.....	110
Instructor Quality Summary.....	114
CHAPTER 5: Models of Graduate Student Professional Development Programs	
.....	119
Guiding Questions.....	121
<i>What is the institutional and departmental context that the model is embedded in and supported by?</i>	<i>121</i>
<i>What is the (implicit or explicit) guiding philosophy of the model?</i>	<i>122</i>
<i>What are the structural components of the model?</i>	<i>123</i>
<i>What knowledge and practices are emphasized through this model, and how?</i>	<i>124</i>
Additional Questions for Implementation and Evaluation	127
<i>What aspects are necessary to institute this model?</i>	<i>127</i>
<i>What are the affordances of this model?</i>	<i>128</i>
Three Models of GTA Professional Development.....	129
Apprenticeship Model	134
<i>What is the institutional and departmental context that the model is embedded in and supported by?</i>	<i>134</i>
<i>What is the (implicit or explicit) guiding philosophy of the model?</i>	<i>135</i>
<i>What are the structural components of the model?</i>	<i>138</i>
<i>What knowledge and practices are emphasized through this model, and how?</i>	<i>145</i>
<i>What aspects are necessary to institute this model?</i>	<i>147</i>
<i>What are the affordances of this model?</i>	<i>148</i>
Coordinated innovation Model.....	150

<i>What is the institutional and departmental context that the model is embedded in and supported by?</i>	150
<i>What is the (implicit or explicit) guiding philosophy of the model?</i>	151
<i>What are the structural components of the model?</i>	152
<i>What knowledge and practices are emphasized through this model, and how?</i>	161
<i>What aspects are necessary to institute this model?</i>	163
<i>What are the affordances of this model?</i>	164
Peer-Mentor Model	166
<i>What is the institutional and departmental context that the model is embedded in and supported by?</i>	167
<i>What is the (implicit or explicit) guiding philosophy of the model?</i>	170
<i>What are the structural components of the model?</i>	171
Institution 4	177
<i>What knowledge and practices are emphasized through this model, and how?</i>	183
<i>What aspects are necessary to institute this model?</i>	184
<i>What are the affordances of this model?</i>	185
Summary and Conclusions	186
CHAPTER 6: Instructor Quality Comparison Across GTA-PD Models	191
Overview of Data Sources	191
Instructor Survey.....	192
Case Study Data	194
GTA Follow-up Survey	195
Apprenticeship Model	198
Instructor Survey.....	199

Case Study Data	205
GTA Follow-up Survey	210
Apprenticeship Model Summary	212
Coordinated Innovation Model.....	214
Instructor Survey.....	214
Case Study Data	223
GTA Follow-up Survey	226
Coordinated Innovation Model Summary	229
Peer-Mentor Model.....	231
Case Study Data	232
GTA Follow-up Survey	239
Peer Mentor Model Summary	244
Influence of Programs on GTA Beliefs and Practices	245
CHAPTER 7: Framework for GTA-PD.....	247
Aspects of a GTA-PD Program	248
Relationships Between Aspects of the Framework	249
Three Examples	252
Using the Framework	254
Implementation.....	255
Evaluation.....	255
Qualities of a successful GTA-PD program	258
Sustained over a long period of time.....	259
Focus on subject matter	259
Provide opportunities for “hands on” learning	261

Integrated into daily lives.....	262
Provide feedback and assessment.....	262
Support from other constituents.....	263
Summary of GTA-PD program success.....	264
Connection to Theoretical Perspectives.....	265
Limitations and Future Directions	266
References	269
APPENDECES.....	282
Appendix A: CSPCC Surveys	282
Appendix B: GTA Survey	283
Appendix C: Case Study Protocol	287
TA Trainer Interview Protocol.....	287
TA Interview Protocol.....	291
Description of Observation Protocol for CSPCC.....	297
Appendix D: Survey Response Rate	309

List of Figures

Figure 2.1 Graphic representation of framework for teacher quality from Goe (2007)	19
Figure 2.2 Instructional Triangle describing the interaction patterns of instruction (Cohen, Raudenbush, & Ball, 2003)	31
Figure 2.3 Graphic representation of instructor quality, based on Goe's (2007) framework for teacher quality	41
Figure 3.1 Step-by-step guide for conducting thematic analysis (Braun & Clarke, 2006, p. 87).	77
Figure 3.2 Data collection and analysis diagram	82
Figure 4.1 Beliefs about student capabilities	90
Figure 4.2 Interest in teaching and student learning	91
Figure 4.3 Perceived value of reflection on teaching and learning	93
Figure 4.4 Beliefs about teaching and learning	94
Figure 4.5 Summary of aggregate beliefs variables	95
Figure 6.1 Summary of aggregate beliefs variables	193
Figure 6.2 Beliefs questions from GTA follow-up survey related to Instructor survey questions	197
Figure 6.3 Instructional practices questions from GTA follow-up survey related to Instructor survey questions	198
Figure 7.1 Framework of GTA-PD programs	252
Figure 7.2 Apprenticeship model	253
Figure 7.3 Coordinated Innovation Model	253
Figure 7.4 Peer Mentor model	254

List of Tables

Table 1.1	Distribution of participating institutions by type	8
Table 1.2	The number of instructors and students taught by them, by instructor status	9
Table 1.3	Number of PhD institutions utilizing TAs, both as instructors and recitation leaders....	9
Table 1.4	Frequency and effectiveness of activities to select or prepare GTAs	10
Table 3.1	Overview of data sources used for research question 3	81
Table 3.2	Summary of data sources and anticipated analysis by research question	83
Table 4.1	Comparison of Instructor Qualifications	85
Table 4.2	Comparison of Instructor Characteristics – Demographics	88
Table 4.3	Comparison of Instructor Characteristics – Beliefs	96
Table 4.4	Comparison of Instructional Practices– Classroom Structure	101
Table 4.5	Comparison of Instructional Practices– Frequency of certain pedagogical activities	103
Table 4.6	Comparison of Instructional Practices–Instructor reports of classroom discourse	104
Table 4.7	Comparison of Instructional Practices– Student reports of classroom discourse	105
Table 4.8	Comparison of Instructional Practices– The nature of the tasks: Structure	107
Table 4.9	Comparison of Instructional Practices– The nature of the tasks: Content	108
Table 4.10	Comparison of Student Success – Student preparation coming in	112
Table 4.11	Student success by instructor type	114
Table 5.1	GTA Model Summary	131
Table 6.1	Beliefs about mathematics among GTAs from the Apprenticeship model.....	200
Table 6.2	Comparison of Instructional Practices– Frequency of certain pedagogical activities	201
Table 6.3	Comparison of Instructional Practices–Instructor reports of classroom discourse	202
Table 6.4	Comparison of Instructional Practices– Frequency of certain pedagogical activities	203
Table 6.5	Comparison of Instructional Practices– Nature of Tasks.....	204
Table 6.6	Comparison of Instructional Practices– Content.....	205

Table 6.7 GTA Follow-up survey – Beliefs: Apprenticeship Model	211
Table 6.8 GTA Follow-up survey – Practices: Apprenticeship Model	212
Table 6.9 Beliefs about mathematics among GTAs from the Coordinated Innovation model ...	216
Table 6.10 Comparison of Instructional Practices– Freq. of certain pedagogical activities	217
Table 6.11 Comparison of Instructional Practices–Instructor reports of classroom discourse ...	218
Table 6.12 Comparison of Instructional Practices– Student reports of classroom discourse	219
Table 6.13 Comparison of Instructional Practices– Nature of Tasks	220
Table 6.14 Comparison of Instructional Practices– Content.....	222
Table 6.15 GTA Follow-up survey – Beliefs: Coordinated Innovation Model	227
Table 6.16 GTA Follow-up survey – Instructional Practices: Coordinated Innovation Model ..	229
Table 6.17 GTA Follow-up survey – Beliefs: Peer-Mentor Model	241
Table 6.18 GTA Follow-up survey – Instructional Practices: Peer-Mentor Model	242

Curriculum Vitae

EDUCATION

September 2014 Ph.D. in Mathematics and Science Education, joint doctoral program
University of California San Diego & San Diego State University, San Diego, CA

June 2010 M.S. in Pure Mathematics
California Polytechnic University, San Luis Obispo, CA

June 2007 B.S. in Pure Mathematics
California Polytechnic University, San Luis Obispo, CA

EMPLOYMENT

2014 - Present Assistant Professor of Mathematics Education, Department of Mathematics, Colorado State University, Fort Collins, CO

RESEARCH EXPERIENCE

Project personnel: National Science Foundation Research and Evaluation in Education in Science and Engineering award, Characteristics of Successful Programs in College Calculus, (CSPCC). David Bressoud (PI), Chris Rasmussen, Marilyn Carlson, Vilma Mesa, Michael Pearson (co-PIs), \$1,999,701, 2010-2014.

Responsibilities include: Assisting in creating and piloting surveys that were administered at over 300 universities; Conducting quantitative analyses of survey data; Cleaning and organizing data; Creating, piloting, and refining case study interview protocols; Conducting interviews for case studies; Conducting qualitative analyses of case study interviews.

Research Assistant: National Science Foundation Research and Evaluation in Education in Science and Engineering award, Collaborative Research: Investigating Issues of the Individual and Collective along a Continuum between Informal and Formal Reasoning, C. Rasmussen (PI) and M. Zandieh (PI). \$525,076, 2007-2010.

Conducted two analyses of interview data with Dr. Michelle Zandieh and Dr. Chris Rasmussen, which investigated (a) students' conceptions of function and linear transformation and (b) students' conceptions of matrix representations of linear transformations. Conducted preliminary analysis of interview data with project personnel Dr. Jeff Rabin, UCSD, which investigated students' connections between the geometric, abstract, and computational aspects of linear algebra. Conducted qualitative analysis of individual student interviews that were conducted as part of an inquiry based approach to linear algebra.

Research Rotation: Designed and constructed an interactive model for students to explore properties of the derivative, specifically inflection points, and conducted and analyzed

semi-structured interviews with students while interacting with the model, 30-hour research apprenticeship with Dr. Ricardo Nemirovsky, SDSU, Fall 2010.

PUBLICATIONS

Papers in Progress

- Zandieh, M., Ellis, J., & Rasmussen, C. Student Concept Images of Function and Linear Transformation. Manuscript under review. *Educational Studies in Mathematics*.
- Wawro, M., Ellis, J., & Soto-Johnson, H. MPWR: Mentoring and Partnerships for Women in RUME. Manuscript under review. *American Women in Mathematics (AWM) Newsletter*.
- Rasmussen, C., Ellis, J., & Bressoud, D., Who is switching out of STEM and why? Manuscript under review.

Papers

- Ellis, J., Kelton, M., & Rasmussen, C. (2014). Student perception of pedagogy and persistence in calculus. *ZDM*.

Refereed Conference Proceedings

- Rasmussen, C., & Ellis, J. (2013). Who is switching out of calculus and why? In Lindmeier, A. M. & Heinze, A. (Eds.). *Proceedings of the 37th Conference of the International Group for the Psychology of Mathematics Education*, Vol. 4 (pp. 73-80). Kiel, Germany: PME.
- Uysal, F., Ellis, J., & Rasmussen, C. (2013). What do college calculus students believe about mathematics? *Proceedings of the 37th Conference of the International Group for the Psychology of Mathematics Education*, Kiel, Germany.
- Ellis J, Rasmussen, C, Duncan, K. (2013). Students' differing experiences in Calculus I. *Proceedings of the 16th Annual Conference on Research in Undergraduate Mathematics Education*; Denver, CO.
- Ellis, J., Henderson, F., Rasmussen, C., & Zandieh, M. (2012). Student reasoning about linear transformations. In (Eds.) S. Brown, S. Larsen, K. Marrongelle, and M. Oehrtman, *Proceedings of the 15th Annual Conference on Research in Undergraduate Mathematics Education*, (pp. 413-421). Portland, OR.
- Zandieh, M., Ellis, J., & Rasmussen, C. (2012). Student concept images of function and linear transformation. In (Eds.) S. Brown, S. Larsen, K. Marrongelle, and M. Oehrtman, *Proceedings of the 15th Conference on Research in Undergraduate Mathematics Education*, (pp. 320-329). Portland, OR.
- Carlson, M., Rasmussen, C., Bressoud, D., Pearson M., Jacobs, S., Ellis, J., & Weber, E. (2011). Surveying mathematics departments to identify characteristics of successful programs in college Calculus. In (Eds.) S. Brown, S. Larsen, K. Marrongelle, and M. Oehrtman, *Proceedings of the 14th Annual Conference on Research in Undergraduate Mathematics Education* (pp. 33-39). Portland, OR.

GRANTS

National Science Foundation Innovations in Undergraduate STEM Education, *Pathways Through Calculus*, D. Bressoud (PI), L. Braddy (Co-PI), J. Ellis (Co-PI), S. Larsen (Co-PI), C. Rasmussen (Co-PI). \$2,225,000

National Science Foundation Transforming Undergraduate Education in STEM, *Mentoring and Partnerships for Women in RUME (MPWR)*, M. Wawro (PI), J. Ellis and H. Soto-Johnson (Senior Personnel), \$44,148, DUE-1352990

RESEARCH PRESENTATIONS AND POSTERS (Presenter underlined)

Invited Presentations

Ellis, J., (2014, January). Preparing Future College Instructors: The Role of Graduate Student Teaching Assistants (GTAs) in Successful College Calculus Programs. Invited colloquium for the Department of Mathematics, Portland State University, Portland, OR.

Ellis, J., (2014, January). Preparing Future College Instructors: The Role of Graduate Student Teaching Assistants (GTAs) in Successful College Calculus Programs. Invited colloquium for the Department of Mathematics, Colorado State University, Fort Collins, CO.

Ellis, J., (2013, December). Preparing Future College Instructors: The Role of Graduate Student Teaching Assistants (GTAs) in Successful College Calculus Programs. Invited colloquium for the Department of Mathematics, Montclair State University, Montclair, NJ.

Ellis, J. (2013, October). Students who switch out of calculus and their perceptions of pedagogy. Invited colloquium for the Department of Mathematics and Statistics, California State Polytechnic University, Pomona, CA.

Zandieh, M., Ellis, J., & Rasmussen, C. (2013, January). Student concept images of function and linear transformation. Invited presentation at the 2013 Joint Mathematics Meeting, San Diego, CA.

Conference Presentations (refereed proposals)

Wawro, M., Ellis, J., Soto-Johnson, H. (2014, August). MPWR: Mentoring and Partnerships for Women in RUME. Paper presented at the Mathematical Association of America's (MAA) MathFest, Portland, OR.

Ellis, J. (2014, July). Preparing Future Professors: Highlighting The Importance Of Graduate Student Professional Development Programs In Calculus Instruction. Paper presented at the 38th Conference of the International Group for the Psychology of Mathematics Education, Vancouver, British Columbia.

Rasmussen, C., Ellis, J., Zazkis, D., & Bressoud., D. (2014, July). Features Of Successful Calculus Programs At Five Doctoral Degree Granting Institutions. Paper presented at the 38th Conference of the International Group for the Psychology of Mathematics Education, Vancouver, British Columbia.

Johnson, E., Ellis, J., & Rasmussen, C. (2014, July). It's About Time: How Instructors And Students Experience Time Constraints In Calculus I. Paper presented at the

- 38th Conference of the International Group for the Psychology of Mathematics Education, Vancouver, British Columbia.
- Ellis, J. (2014, February). Graduate students Teaching Assistants' (GTAs') beliefs, instructional practices, and student success. Paper presented at the 17th Annual Conference on Research in Undergraduate Mathematics Education, Denver, CO.
- Rasmussen, C., Ellis, J., Zazkis, D. (2014, February). Lessons Learned from Case Studies of Successful Calculus Programs at Five Doctoral Degree Granting Institutions. Paper presented at the 17th Annual Conference on Research in Undergraduate Mathematics Education, Denver, CO.
- Hanson, K., Nunez, G., Ellis, J. (2014, February). Beyond Plug and Chug: The nature of calculus homework at doctoral institutions. Poster presented at the 17th Annual Conference on Research in Undergraduate Mathematics Education, Denver, CO.
- Ellis, J. (2013, November). Highlighting the Importance of Graduate Student Professional Development Programs in STEM Education. Poster presented at the Association of American Colleges and Universities (AAC&U) Conference for Transforming STEM Education: Inquiry, Innovation, Inclusion, and Evidence, San Diego, CA.
- Rasmussen, C. & Ellis, J. (2013, November). Who is switching out of calculus and why? Paper presented at the 35th Annual Conference of the North American Chapter of the International Group for the Psychology of Mathematics Education, Chicago, IL.
- Rasmussen, C. & Ellis, J. (2013, July). Who is switching out of calculus and why? Paper presented at the 37rd Conference of the International Group for the Psychology of Mathematics Education, Kiel, Germany.
- Uysal, F., Ellis, J., & Rasmussen, C. (2013, July). What do college calculus students believe about mathematics? Paper presented at the 37rd Conference of the International Group for the Psychology of Mathematics Education, Kiel, Germany.
- Ellis, J. (2013, June). Highlighting the Importance of Graduate Student Professional Development Programs in STEM Education. Poster presented at the 1st Annual Working Conference on Preparing Graduate Students to Teach Undergraduate Mathematics, Cambridge, MA.
- Rasmussen, C., Ellis, J., Duncan, K., Bressoud, D., & Carlson, M. (2013, May). Who are the students that switch out of Calculus, and why? Presentation at the 2013 Annual meeting of the American Education Research Association, San Francisco, CA.
- Zandieh, M., Ellis, J., & Rasmussen, C. (2013, February). Students Reconciling Notions of One-to-One Across Two Contexts. Paper presented at the 16th Annual Conference on Research in Undergraduate Mathematics Education, Denver, CO.
- Ellis, J., & Rasmussen, C. (2013, February). Switcher and Persister Experiences in Calculus I. Paper presented at the 16th Annual Conference on Research in Undergraduate Mathematics Education, Denver, CO.
- Ellis, J., Rasmussen, C., Duncan, K. (2013, February). Students' differing experiences in Calculus I. Paper presented at the 16th Annual Conference on Research in Undergraduate Mathematics Education, Denver, CO.

- Ellis, J., & Rasmussen, C. (2013, January). Students' Differing Experiences in Calculus I. Presentation at the 2013 Joint Mathematics Meeting, San Diego, CA.
- Ellis, J. (2012, June). Students' perceptions of pedagogy and the relation to persistence. Poster presented at the Second Conference on Transforming Research in Undergraduate STEM Education, St. Paul, MN.
- Ellis, J. (2012, March). A Report on a National Study of College Calculus: Who is Switching out of STEM and Why? Presentation at the Student Research Symposium at San Diego State University, San Diego, CA.
- Ellis, J., Henderson, F., Rasmussen, C., & Zandieh, M. (2012, February). Student reasoning about linear transformations. Paper and poster presented at the 15th Annual Conference on Research in Undergraduate Mathematics Education, Portland, OR.
- Zandieh, M., Ellis, J., & Rasmussen, C. (2012, February). Student concept images of function and linear transformation. Paper presented at the 15th Annual Conference on Research in Undergraduate Mathematics Education, Portland, OR.
- Ellis, J. (2012, February). Students' perceptions of pedagogy and the relation to persistence. Poster presented at the 15th Annual Conference on Research in Undergraduate Mathematics Education, Portland, OR.
- Ellis, J. (2012, January). Student reasoning about linear transformations. Poster presented at the Judy Sowder Tribute, San Diego, CA.
- Carlson, M., Rasmussen, C., Bressoud, D., Pearson M., Jacobs, S., Ellis, J., & Weber, E. (2011, February). Surveying mathematics departments to identify characteristics of successful programs in college Calculus. Paper presented at the 14th Annual Conference on Research in Undergraduate Mathematics Education, Portland, OR.

TEACHING EXPERIENCE

- | | |
|----------------|--|
| Spring
2013 | <p>Co-Course Coordinator, SDSU Department of Mathematics and Statistics</p> <ul style="list-style-type: none"> • Math 210 Number Systems in Elementary Mathematics • Math 211 Geometry in Elementary Mathematics • Math 311 Statistics in Elementary Mathematics • Math 313 Selected Topics in Elementary Mathematics |
| Spring
2012 | <p>Co-Instructor, SDSU Department of Mathematics and Statistics</p> <ul style="list-style-type: none"> • Math 302 Transition to Higher Mathematics • Course taught using an Inquiry Based Learning approach • Attended all classes and assisted for 15 weeks • Taught course for 6 weeks |
| Summer
2011 | <p>Instructor, Grauer School in Encinitas, CA</p> <ul style="list-style-type: none"> • Courses: Algebra 1 and 2 • The school is a small private high school that utilizes both teaching for mastery and discovery based learning. I was responsible for curriculum development and implementation based on individual student needs. |
| Fall 2008 – | <p>Teaching Associate, California Polytechnic University, Department of</p> |

- Spring
2010
- Mathematics
- Math 221 Business Calculus: Taught seven sections over the course of four quarters
 - Math 118 Precalculus: Taught two sections over the course of two quarters

SERVICE

Reviewer for the Journal for Research in Mathematics Education (JRME).

Reviewer for the Seventeenth Conference on Research in Undergraduate Mathematics Education, Denver, CO.

Reviewer for ZDM: The International Journal of Mathematics Education.

Reviewer for the Sixteenth Conference on Research in Undergraduate Mathematics Education, Denver, CO.

Reviewer for the 37th Conference of the North American Group for the Psychology of Mathematics Education, Chicago, IL.

Volunteer at the Las Chicas de Matemáticas summer camp held at the University of Northern Colorado, Greeley, CO, 2012.

AWARDS AND HONORS

Awarded student travel grant for the 1st Annual Working Conference on Preparing Graduate Students to Teach Undergraduate Mathematics, a working conference promoting research into the preparation of graduate students; \$350 airfare plus room and board.

Awarded student travel grant for the 2012 Transforming Research in Undergraduate STEM Education (TRUSE), a cross-disciplinary conference promoting integration of math, physics and chemistry education, \$400 airfare plus room and board.

Awarded Teaching Associate of the Year at California Polytechnic University, San Luis Obispo, 2010, \$250.

Awarded student travel grant for the Twelfth Annual Nebraska Conference for Undergraduate Women in Mathematics, 2008, airfare plus room and board.

Abstract of the Dissertation

Preparing Future College Instructors: The Role of Graduate Student Teaching Assistants (GTAs) in Successful College Calculus Programs

by

Jessica Fabricant Ellis

Doctor of Philosophy in Mathematics and Science Education

University of California, San Diego, 2014
San Diego State University, 2014

Professor Chris Rasmussen, Chair

Graduate student Teaching Assistants (GTAs) contribute to calculus instruction in two ways: as the primary teacher and as recitation leaders. GTAs can also be viewed as the next generation of mathematics instructors. Thus, in addition to their immediate contribution to the landscape of Calculus 1 instruction, GTAs will contribute significantly to the long-term state of calculus in their future occupations. However, their preparation for these roles varies widely and is often minimal. In this study, I first compare the mathematical beliefs, instructional practices, and student success of GTAs to other

Calculus 1 instructors. I then provide rich descriptions for three GTA professional development (PD) programs that prepare graduate students as course instructors, as recitation leaders, and as future faculty. I then investigate the instructional practices and mathematical beliefs of graduate students coming from these three PD programs. I conclude this work with a description of a framework for GTA-PD programs.

To accomplish this work, I conducted a mixed-method analysis on national survey data and case study data from four doctoral granting institutions. These four institutions were chosen because of their higher-than-expected student success in Calculus 1. The results of these analyses indicate that graduate students teach in more innovative ways than other instructors, though their students were less successful. Among the four case study institutions, I identified three models of GTA-PD, each of which appeared successful in accomplishing their goals. These goals included transitioning graduate students into the role of instructor, preparing graduate students to implement an innovative approach to Calculus 1, and supporting graduate students as recitation leaders. These analyses also led to the development of a framework to be used to characterize, evaluate, and consider the implementation of graduate student professional development programs. This GTA-PD framework is thus one of the major contributions put forth by this dissertation.

CHAPTER 1: Study Overview and Significance

Call for Change

In this study I investigate the roles of Graduate Student Teaching Assistants (GTAs) in Calculus 1 instruction and their preparation to do so. Calculus 1 is not only an integral part of all Science, Technology, Engineering, and Mathematics (STEM) fields, but student experiences in Calculus 1 has also been shown to be a main contributing factor to students' decisions to leave the STEM disciplines (Seymour & Hewitt, 1997). Recent studies show that although the demand for STEM majors has been increasing from 1971 to 2009, the number of students declaring their intention to pursue STEM majors remains constant (at around 30% nationwide) (Carnevale, Smith, & Melton, 2011; Hurtado, Eagan, & Chang, 2010). In addition to a decreasing percentage of students pursuing STEM degrees, a low percentage of STEM-intending students persist in obtaining a STEM degree. As reported in the recent report from the President's Council of Advisors on Science and Technology (PCAST, 2012) an increase in STEM students, both pursuing STEM degrees and those persisting in those degrees, will be the determining factor in the United State's continued status as a world leader. This report predicts that, over the next decade, approximately 1 million more STEM graduates above and beyond the current level of STEM graduate production will be needed in order to meet the demands of the workplace.

Student persistence in the STEM disciplines continues to be a national problem, and this ongoing need has driven a large body of research that has sought to identify the nature and underlying reasons for student disengagement and dissatisfaction with their

STEM courses (Carnevale et al., 2011; Griffith, 2010; Hurtado et al., 2010, PCAST, 2012; Pascarella & Terenzini, 1991; 2005, Rasmussen, & Ellis, 2013; Seymour & Hewitt, 1997; Thompson et al., 2007). The Higher Education Research Institute (HERI) has determined that between 40% to 60% of STEM-intending students obtain a STEM degree within 6 years (Hurtado et al., 2010). Thompson and his colleagues (2007) found that only 50% of STEM-intending students enrolled in first semester calculus at a large research I university went on to complete second semester calculus, and only 30% of these students completed Calculus 3. Rasmussen, and Ellis (2013) recently found that nationwide 87.5% of STEM-intending Calculus 1 students intended to take Calculus 2 after completing Calculus 1. Students report leaving STEM majors primarily because of poor instruction in their mathematics and science courses, with Calculus often cited as a primary reason (Rasmussen et al., 2013; Thompson et al., 2007). These reports indicate the critical need to improve calculus instruction at the national level. It is important for students to have positive experiences in calculus, and other introductory STEM courses, not only because these courses provide them with the knowledge they need to succeed in their intended careers but also because these courses have the potential to preserve (or increase) students' interest in STEM and in one-day entering the STEM workforce. Thus, if we are to meet the increasing demand of the STEM workforce we must better understand the experiences students have along the way to get there. For many students, Calculus 1 plays a pivotal role in this trajectory, and graduate students often play a pivotal role in Calculus 1, especially at research universities that are responsible for a large percentage on the nations competitive STEM graduates.

Role of Graduate Students

Graduate student Teaching Assistants contribute to calculus instruction in two ways: as the primary teacher and as recitation leaders. As teachers, GTAs are completely in charge of the course just as a lecturer or tenured track/ tenured faculty would be, although they lack the experience, education, or time commitment of their faculty counterparts. In the College Board of Mathematical Sciences (CBMS) report, GTAs were determined to have taught eight percent of the 201,000 students enrolled in mainstream Calculus 1, and 22% of all mainstream Calculus 1 sections at PhD granting institutions, hereafter referred to as “doctoral institutions” (Lutzer, Kirkman, & Maxwell, 2007). Graduate students are also frequently utilized as recitation leaders, tutors, or graders. Belnap and Allred (2009) found that of the 23 doctoral institutions involved in their study, 35.4% of the GTAs were the sole instructor for one or two classes, while 39.1% of the GTAs were discussion/ recitation leaders, and 24.5% had other responsibilities such as grading or tutoring.

GTAs can also be viewed as the next generation of mathematics instructors. Thus, in addition to their immediate contribution to the landscape of Calculus 1 instruction, GTAs will contribute significantly to the long-term state of calculus in their future occupations. The preparation GTAs receive to prepare them for teaching Calculus therefore has the potential to influence both their long-term pedagogy as well as their immediate teaching practices. There has been much discussion about what knowledge and experiences are needed to foster excellent (or even adequate) teachers in mathematics at the K-12 level (Ball, Thames, & Phelps, 2008; Hill, Ball, & Schilling, 2008; Shulman, 1986) and instructors at the undergraduate level (Johnson & Larsen, 2012; Speer &

Wagner, 2009). The clear consensus is that developing expertise in mathematics alone is not sufficient in the preparation of teachers.

Learning how to be a teacher also involves learning how to be part of the community of teachers. This learning occurs as newcomers develop the practices, knowledge, and dispositions of more central members of the community (Ball et al., 2008; Grossman et al., 2009; Hill et al., 2008; Lave & Wenger, 1991; Shulman, 1986). Accordingly, professional development efforts to improve teaching are often aimed at developing teachers' knowledge, beliefs, and instructional practices in order to support new teachers as they become members of the teaching community (Grossman et al., 2009; Kazemi & Stipek, 2001; Putnam & Borko, 2000; Sowder, 2007). If student success in Calculus 1 is related to quality of instruction they receive, and graduate students are responsible for a significant amount of this instruction, then it is important to investigate the ways graduate students are prepared for their roles in Calculus 1 instruction. While there is extensive research on the professional development of K-12 teachers, little is known about GTA professional development on a national level. Consequently, I have identified the following research questions:

Research Question 1: *How do GTAs compare to tenure track/tenured faculty and other full/part time faculty on their (a) mathematical beliefs¹; (b) instructional practices; and (c) students' success in Calculus 1?*

Research Question 2: *What are the characteristics of GTA programs being implemented by institutions with successful calculus programs?*

Research Question 3: *What are the (a) mathematical beliefs and (b) instructional practices of GTAs coming from these programs, and in what ways are the beliefs and practices related to GTAs' experiences in the professional development programs?*

¹ I use the term *mathematical beliefs* to include beliefs related to doing, teaching, and learning mathematics.

Background

In this section, I describe two motivations for these research questions: first, my own experience as a GTA; and second, my experiences as part of a large, national project looking at characteristics of successful Calculus 1 programs. My initial interest in the professional development of GTAs grew out of my experiences as a GTA and has been shaped and deepened by my involvement in current research focused on student success in Calculus.

Personal Experiences

As a GTA during my studies for a Masters in pure mathematics, I had full teaching responsibilities of both precalculus courses and business calculus courses. I received this position as a means of financial support (as was the case for my peers in the program) and received no training or formal support before stepping into the classroom, for which I was fully responsible. During the first quarter teaching precalculus to 35 college students, I was enrolled in a weekly hour-long course with the other GTAs, where the focus was on issues such as how to deal with students who cheated on an exam. After this first quarter, we received no further professional development, but were encouraged to discuss questions or issues with multiple professors in the department.

While my fellow GTAs and I survived and even received strong student evaluations, I felt that we (and our students) would have had better experiences if we had received training prior to teaching and continued support while teaching. As a result, I developed a brief mentoring program where the second year GTAs were assigned as the mentors to first year GTAs. Anecdotally we saw improvements in two ways: the new

GTAs appeared more confident in their teaching than our class had been and they were less surprised by their students' experiences in their class than we were. A positive feature of this mentoring program was that it was developed by a GTA and inspired by a need identified by GTAs. A weakness of the program is that it was essentially developed without knowledge or connection to research and thus lacked a theoretical grounding in teaching and learning. However, this program continues to this day and is supported each year by the GTAs who received the mentoring in the previous year.

Characteristics of Successful Programs in College Calculus (CSPCC)

My interests in the professional development of GTAs were reinvigorated during my current work on a nationwide research project entitled, *Characteristics of Successful Programs in College Calculus (CSPCC)*. This project consists of two main phases, a large-scale national survey followed by case studies at institutions with calculus programs whose students are more successful than students at other institutions. Student success was defined in terms of passing Calculus 1 with a C or better; positive attitudinal changes (including confidence about mathematics ability, increased enjoyment of mathematics, and the development of expert-like beliefs about the nature of mathematics); and maintaining (or increasing) STEM intentions (as measured by the intention to take Calculus 2). One main component of this measure of student success in Calculus that is missing is some measure of students' knowledge of the content; it was decided that it was outside the scope of this project to assess students' content knowledge on such a large scale in any meaningful way (Bressoud, Carlson, Mesa, & Rasmussen, 2013).

The large-scale national survey of mainstream Calculus 1 (defined as the Calculus for mathematics and science majors) included three surveys given to students (one at the beginning of Calculus 1, one at the end of Calculus 1, and one a year later to students who volunteered their email address), two surveys given to instructors (one at the beginning of Calculus 1 and one at the end of Calculus 1), and one survey given to the Calculus course coordinator. In addition, instructors reported on the distribution of final grades and submitted a copy of the final exam. All surveys were completed online, and no incentives were given for completing the surveys.

In the following paragraphs, I briefly describe this project and provide some initial findings that serve as a background for the study of GTAs in the teaching of college Calculus. The findings address the distribution of institution types that participated in the survey, the distribution of instructor types and the percentage of students taught by them, the utilization of GTAs, and the preparation of GTAs as reported by the Course Coordinators at institutions that utilize GTAs.

Motivating results from the survey data

The survey was sent to a stratified random sample of mathematics departments following the selection criteria used by Conference Board of the Mathematical Sciences (CBMS) in their 2005 Study (Lutzer et al., 2007). For the purposes of surveying post-secondary mathematics programs in the United States, the CBMS separates colleges and universities into four types, characterized by the highest mathematics degree that is offered: community colleges, Bachelor's granting, Master's granting, and PhD granting. Within each type of institution, we further divided the strata by the number of enrolled

full-time equivalent undergraduate students, creating from four to eight substrata. We sampled most heavily at the institutions with the largest enrollments. In all, we selected 521 colleges and universities: 18% of the community colleges, 13% of the Bachelor's colleges, 33% of the Master's universities, and 61% of the PhD universities. Table 1 shows the distribution of the 159 institutions that participated: 36 community colleges, 40 Bachelor's colleges, 18 Master's universities, 40 small PhD (with enrollment less than 20,000), and 25 large PhD.

Table 1.1 Distribution of participating institutions by type

Institution type	Frequency	Percent
CC	36	22.6
Bach	40	25.2
Masters	18	11.3
Small PhD	40	25.2
Large PhD	25	15.7
Total	159	100.0

There are 14,247 students and 1,149 instructors for whom we have either start of term survey data, end of term survey data, or both. Of these, 12,383 students were matched with 648 instructors with (mostly) complete data. The number of students per institution ranges from 1 to 1,045 and the number of students per instructor ranges from 1 to 596. As shown in Table 2, 15.6% of the instructors were GTAs, and 12.4% of students were taught by a GTA. The largest number of instructors was tenured faculty (33%) or other full-time faculty (26%), though other full-time faculty taught the largest percentage of students (43%).

Table 1.2 The number of instructors and students taught by them, by instructor status

Instructor Status	# of Instructors	Percent	# of Students	Percent
Tenure track faculty	93	14.4	1373	11.1
Tenured faculty	215	33.2	3397	27.4
Other full-time faculty	170	26.2	5323	43.0
Part-time faculty	57	8.8	503	4.1
Graduate teaching assistant	101	15.6	1540	12.4
Visiting/ Post Doc	12	1.9	247	2.0
Total	648	100.0	12,383	100.0

Table 3 shows the utilization of TAs at doctoral institutions. Instructors were asked to report if TAs (undergraduate students and graduate students) taught a recitation section attached to their Calculus 1 course. TAs were reported to lead recitation sections at 2 Community Colleges, 2 Bachelors granting institutions, 2 Masters granting institutions, and 50 doctoral institutions. Instructors who filled out the surveys were also asked to report their position. There were 29 doctoral institutions for which at least one graduate student filled out the instructor survey, indicating that at these institutions GTAs serve as course instructors. There were no GTAs who served as course instructors from other institutions types that were part of this study. For the purposes of this study, I restrict further analyses to doctoral granting institutions because of the more widespread use of TAs, both as recitation leaders and course instructors, and availability of graduate TAs. Notably, 62 of the 65 doctoral institutions utilized TAs in the teaching of calculus in some way.

Table 1.3 Number of PhD institutions utilizing TAs, both as instructors and recitation leaders

Utilization of TAs	Frequency	Percent
TAs lead recitation only	33	53.2
GTAs teach only	12	19.4
TAs do both	17	27.4
Total	62	100.0

At these 62 institutions that utilize GTAs in some capacity, various activities geared to select or prepare GTAs were implemented to varying degrees of effectiveness. Table 4 conveys the implementation of GTA professional development and selection activities as well as the rated effectiveness as assessed by the Course Coordinator from the 62 doctoral granting institutions that employ TAs in the teaching of Calculus 1. As shown in Table 4, about half of the institutions have a program that pairs new GTAs with a faculty member, but only about 60% of these programs were said to be very effective or effective (by the Course Coordinator). Table 4 also shows that the most common programs for selecting or preparing GTAs are a seminar or class for the purpose of GTA professional development, some sort of screening of GTAs before assigning them to a recitation section, and faculty observation of GTAs for the purpose of evaluating their teaching. It appears relatively uncommon to interview GTAs in order to select them, with only about a third of the institutions employing this method of selection.

Table 1.4 Frequency and effectiveness of activities to select or prepare GTAs

GTA selection or preparation activity	Number with this activity	Percent of institutions utilizing activity (62)	Very effective or effective	Minimally or not effective
Pairs new GTAs with faculty members	33	53.2%	20 (60.6%)	13 (39.4%)
Seminar or class for the purpose of GTAs professional development	47	75.8%	39 (83.0%)	8 (17.0%)
Other program for GTA mentoring or professional development	27	43.5%	19 (70.4%)	8 (29.6%)
Faculty observation of GTAs for the purpose of evaluating their teaching	47	75.8%	33 (70.2%)	14 (29.8%)

In summary, GTAs taught a large proportion of students involved in the CSPCC survey, and received a wide variety of preparation in their teaching. It is well documented that there is a significant link between students' in-class experiences and their performance in undergraduate STEM courses, especially for women and under-

represented minorities (Cohen, Garcia, Purdie-Vaughns, Apfel, & Brzustoski, 2009; Miyake et al., 2010). Thus it is necessary to understand how GTAs' instruction compare to other instructors and how this instruction is related to their preparation.

It is important for students to have positive experiences in Calculus, and other introductory STEM courses, not only because these courses provide them with the knowledge they need to succeed in their intended careers but also because these courses have the potential to preserve (or increase) students' interest in STEM and in one day entering the STEM workforce. Graduate students play a primary role in many STEM students' experiences in introductory STEM courses, either as the main instructor or as the recitation leader. Thus, GTAs hold an important role in both teaching students the content in the introductory STEM courses and inspiring (or maintaining) an interest in STEM fields. Analyses from data coming from the CSPCC project point to a variety of experiences students had when interacting with GTAs in Calculus 1. Unfortunately, a number of students explicitly referenced their GTA's teaching as a contributing factor to their negative experiences in the course when asked to report on their experiences in Calculus 1 one-year after they completed the course:

I could not understand my GSI [Graduate Student Instructor] very well and started to fall behind. I was frustrated, because I could not understand the assignments. I started to see a tutor and I improved in understanding, but I still needed more help to fully comprehend the material. I would like to try to class again, but I need more time to focus on the class if and when I do.

-White, female, Social scientist (e.g. psychologist, sociologist), not intending to take Calculus 2

The grad student teaching the class was inexperienced and lazy. The electronic quizzes/homework he made us do were ridiculous; the system was not smart enough to realize that there was more than one way to

denote a correct answer. I spent over \$1,000 of my own money on tutoring and tens of hours each week doing homework and barely passed the course. It has made me too scared to take physics or Calc 2, so I need to rethink my career plans as a doctor.

-White, female, Life scientist (e.g. biologist, medical researcher), not intending to take Calculus 2

My TA was very confusing and did not quiz or assess our understanding. The class was poorly structured and the tutoring services in the Math Strategies Center weren't of much help. I just wish I had felt more supported in this class, especially since it was fall of my freshman year.

- Hispanic, female, Life scientist (e.g. biologist, medical researcher), not intending to take Calculus 2

While these student responses highlight the experiences many students had in introductory STEM courses across the country, more students offered positive comments regarding their GTA's instruction, highlighting the impact that GTAs can have on students' disposition towards further STEM studies. In this study I delineate the attributes of GTA professional development programs that are most likely to foster similar positive experiences for students:

My teaching assistant had the greatest impact on my experience in Calculus 1. He would have a 'warm-up' question that covered the topics from lecture the previous day. If the class was unable to correctly find the answer in a minute or two he would go over the concepts again. This was extremely helpful in identifying whether or not we understood the lecture concepts. Sometimes during the lecture it all seemed to logically flow together but when asked to do the same without guidance it didn't go as smoothly. The extra exposure to the material really helped.

- White, female, Engineer, Taking Calculus 2

Revisiting Research Questions

It is clear that GTAs are contributing to the current landscape of college Calculus, and while they do so we want to encourage them to be contributing to this landscape in a

positive way. On a national level we need to understand the nature of their current contribution, and aspects of their professional development that shape their contribution. The research questions stand to address each of these issues in turn, and are reproduced here:

Research Question 1: *How do GTAs compare to tenure track/tenured faculty and other full/part time faculty on their (a) mathematical beliefs; (b) instructional practices; and (c) students' success in Calculus I?*

Research Question 2: *What are the characteristics of GTA programs being implemented by institutions with successful calculus programs?*

Research Question 3: *What are the (a) mathematical beliefs and (b) instructional practices of GTAs coming from these programs, and in what ways are the beliefs and practices related to GTAs' experiences in the professional development programs?*

In answering these questions, I develop a model of GTA professional development (PD) programs, and begin to identify what constitutes a successful GTA-PD program. This model articulates critical dimensions of these programs and communities, including the goals and structure of the program, what types of knowledge are targeted, and the context the program is situated within. A driving goal of this study is to begin to articulate how to characterize such programs as successful. How to determine a GTA-PD program's success is necessarily related to one's conception of increasing instructor quality. There are many different ways to operationalize instructor quality, and thus there are many ways to assess a GTA program's success. Goe (2007) provides a framework for K-12 teacher quality that comprises teacher characteristics (including beliefs, knowledge, and demographics), teacher practices, and their students' success. It is not a coincidence then that the main indicators of a successful K-12 professional development program are a change in teacher beliefs, and increase in teacher knowledge, a change in instructional

practices, and increased student success (Sowder, 2007). For this study, I adapt Goe's (2007) framework for teacher quality to characterize instructor quality, and with this framework can reframe the research questions as (1) comparing the instructor quality of GTAs to non-GTAs, (2) describing GTA professional development programs, and (3) relating these programs to instructor quality among GTAs as an initial attempt to discuss the success of these programs.

As previously mentioned, there are many ways to conceive of instructor quality. For this study, I draw on Goe's (2007) framework of teacher quality to operationalize instructor quality and to situate my work within the broader community of work surrounding teacher quality. Theoretically, I draw on the situated learning perspective. From the perspective of situated learning, the locus of learning is not the individual but rather the community. Learning is thus viewed as the process of coming to participate in a community as a central community member rather than as an outside (or peripheral) member, or transitioning from being a newcomer to the community to an experienced member (Lave & Wenger, 1991). Learners are viewed as *legitimate peripheral participants* (LPPs) in the community, and from this stance learning occurs as the novices participate in the community by developing the practices and dispositions of the community. In regards to learning how to teach, this means learning to "think, talk, and act like a teacher" (Putnam & Borko, 2000, p. 10). From this lens, instructor quality would be inseparable from the instructor's participation in the community, which is related to the dimensions of instructor quality articulated above but not entirely captured by this framework. Throughout this study, I consider the alignment and misalignment of

these perspectives of instructor quality, and specifically what it means in relation to characterizing the success of a GTA-PD program.

In this chapter, I provided an overview of the focus and significance of this project. *Chapter 2* contains a more elaborated review of the literature I have alluded in the present chapter. *Chapter 3* expands on the theoretical perspective I draw on in order to motivate and further clarify the framing of the research questions, and details the methods I use to answer these questions. *Chapters 4, 5, and 6* present the findings related to each of the three research questions, and *Chapter 7* synthesizes these findings and provides a discussion of limitations and future directions of this work.

CHAPTER 2: Literature Review

*“The view of knowledge as socially constructed makes it clear that an important part of learning to teach is becoming enculturated into the teaching community - **learning to think, talk, and act like a teacher**” (Putnam and Borko, 2000, p. 10).*

What it takes to be a good mathematics teacher and how best to prepare mathematics teachers are two open and related questions. These questions have been most highly researched with regards to mathematics teachers at the K-12 level, and in exploring answers to these questions at the post-secondary level I draw significantly on research at the K-12 level. However, what constitutes good teaching at the K-12 level may or may not be the same as what constitutes good teaching at the post-secondary level. In the following chapter, I first review literature surrounding teacher quality at both the K-12 and the undergraduate levels. In doing so I attend to the potential differences in needs at various levels. I then review literature related to professional development and teacher training. This literature is much more extensive at the K-12 level than at the undergraduate level, and so I draw on this literature and consider ways that research on professional development at the K-12 level may inform the preparation of graduate students to teach Calculus 1.

Before beginning this review, it is useful, for the purpose of situating this study, to briefly address various perspectives on teacher quality and teacher learning. The most pervasive perspective is called the *process-product* paradigm, which correlates measures of teacher classroom behaviors (the processes) to measures of student learning outcomes (the products). This perspective has been repeatedly identified as problematic for a multitude of reasons, including practical concerns and theoretical concerns (Darling-

Hammond, 2007; Doyle, 1977; Goe, 2007; Hill et al., 2008; Putnam & Borko, 2000).

However, it is still a predominant perspective on teacher efficacy, dominating the literature surrounding teacher quality and preparation to teach. A deeper understanding of this dominant paradigm may prove useful in offering some insights relevant to this study (although I understand and agree with the concerns entailed in it) and better enable me to share my work with a broader set of constituents.

An alternative perspective on teacher quality and teacher learning comes from a social and situated perspective on learning (Lave & Wenger, 1991; Putnam & Borko, 2000; Kazemi & Hubbard, 2008; Wenger, 1998). From this perspective, learning occurs as an individual participates in a community and engages in the authentic practices of the community with increasing agency. As opposed to the process product paradigm, teacher quality cannot be directly correlated with student learning due to the social and situated nature of learning. Student learning (of mathematics) does not simply depend on the teacher's classroom practices, but also on the student's own history, their perception of the teacher's practices, the student's engagement with the practices, their engagement with other students, among other variables. Similarly, teacher learning (of how to teach mathematics) cannot be simply linked to the inputs of a professional development program.

The process-product perspective looks at a static snapshot of a teacher's practice by linking student's performance to teacher quality. Conversely, the situated perspective attends more emphatically to the process of a teacher's practice, which necessarily entails the context they are teaching in, their own social and cultural history, and the students' social and cultural histories. I find the process-product paradigm to be a useful way to

gain a snapshot of teacher practice. I complement this snapshot with in depth, qualitative analyses that attend to the processes of instructors' practices, and their preparation for these practices. Thus, I acknowledge the fundamental differences in these two perspectives, but find them both useful in describing the practices involved in Calculus 1 instruction and how one comes to learn these practices. In *Chapter 3*, I further expound on the role these perspectives have played into the design and analysis of this study.

Teacher Quality

There is an extensive body of literature surrounding teacher quality (and the related but not identical *teaching* quality) at the K-12 level. Goe (2007) provides a comprehensive literature review and synthesis of this body of literature, and developed a summative framework for the components most often identified as related to teacher quality. Teacher quality is comprised of a number of *inputs*, including (a) teacher qualifications and (b) teacher characteristics, the *process* of (c) teacher practices, and the *output* of (d) student success. Figure 2.1 shows the interrelationships for each component.

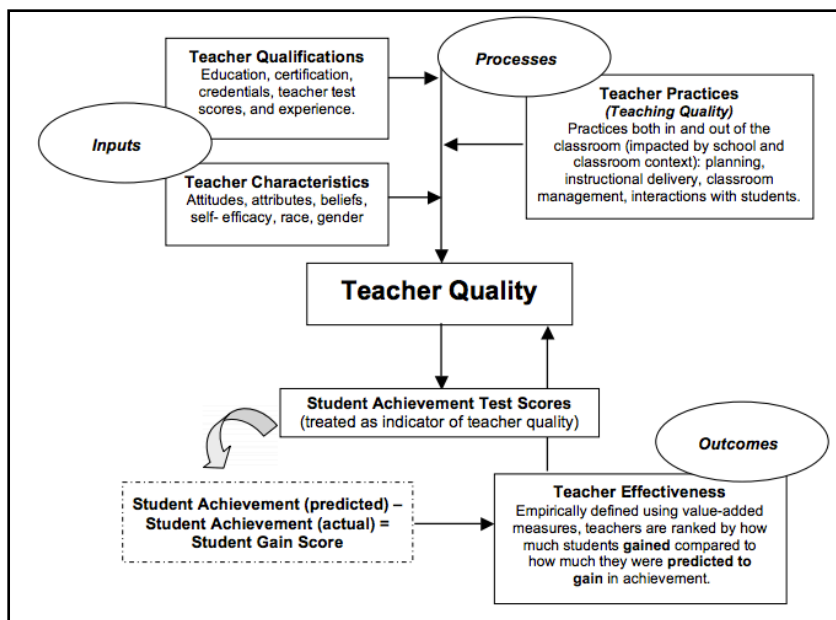


Figure 2.1 Graphic representation of framework for teacher quality from Goe (2007)

Teacher qualifications include experience, education, credentials, participation in professional development, and teacher test scores. With respect to this study, the relevant qualifications of post-secondary Calculus 1 instructors include experience (both teaching-related and non-teaching-related), degree type, field of degree, and professional development participation and type of GTA training. *Teacher characteristics* include demographics, such as gender, age, race, ethnicity, and affective characteristics, such as beliefs, dispositions, and attitudes. Note that the inputs of this system contextualize the teacher (based on demographics and attitudes/beliefs) in relation to their practices and their students' success. For the purposes of this study, I attend to both instructor demographics as well as affective characteristics to see how these aspects of instructor's are related to their position (GTA or non-GTA), their preparation to teach, and their students' success. *Teacher practices* include practices both in and out of the classroom,

such as planning, instructional delivery, and interactions with students. This strand of the framework for defining teacher quality attends to the actual classroom practices and correlates these practices with student outcomes. One example of this would be attending to teacher questioning strategies and connecting these to students' test performance. For this study, I attend to a number of aspects of teacher practices, such as frequency of specific pedagogical activities (such as lecture, whole-class discussion, or group work) and classroom discourse patterns, and when possible connect these to students' persistence in the calculus sequence. The final strand of the framework for defining teacher quality is *teacher effectiveness*. In Goe's (2007) research synthesis, teacher effectiveness was exclusively measured by student performance of standardized achievement tests. For this study, rather than attending to student achievement as indicative of teacher effectiveness I attend to student persistence in the calculus sequence. This decision is motivated by the drastic national need for more STEM graduates and the continued connection between students' negative experiences in introductory STEM courses, especially the calculus sequence, and students' decisions to leave their STEM pursuits (PCAST, 2012; Seymour & Hewitt, 1997; Thompson et al., 1997). Additionally, due to the large number of students involved in the quantitative components of this study it is logistically impossible to assess students' content understanding in a meaningful way. Grade data is be taken into consideration, though with a grain of salt as grades are subjective across instructors and institutions.

Goe's (2007) framework identifies four main components of teacher quality: (a) qualifications, (b) characteristics, (c) practices, and (d) effectiveness. Accordingly, professional development programs often target improvement along the same strands

(Sowder, 2007). In the following sections, I discuss relevant literature regarding each of these components at both the K-12 and the post-secondary levels, highlighting literature that articulates successful components of K-12 professional development programs, with an eye towards how this literature may inform the answer to the question: what makes a graduate student training professional development program successful?

Teacher and Instructor Qualifications

Teacher qualifications include things that can be put on paper, such as degrees and certifications, as well as experience. At the K-12 level, research connecting teacher qualifications to student success is robust, and indicates that:

- Both teaching experience and teacher certification matter, though both are of greater importance at the high school level rather than earlier grades (Rice, 2003);
- The specific coursework within the certification programs, both content specific and pedagogically oriented, has a positive impact on student learning at all grades, especially among mathematics coursework (Rice, 2003);
- The impact of teachers' level of education and degree type on student achievement are inconsistent (Goe, 2007).

At the undergraduate level, there is much less research connecting instructor characteristics to student success. A small number of studies exist that seek to relate the increased instruction by adjunct faculty, who often have different levels of education than tenure-track faculty, to some measure of student success, with the limited results indicating a negative relationship between adjunct use and student success. In a large-scale, 15-year longitudinal study drawing on Department of Education data, Ehrenberg

and Zhang (2004) found a negative relationship between adjunct faculty and GTA usage and undergraduate students' 5- and 6-year graduation rates. This relationship was larger at public colleges and universities than at public universities, and held among low achieving and high achieving students alike (as determined by SAT mathematics scores). Similarly, Bettinger and Long (2004) focused on the value-added impact of graduate students and young adjunct faculty on full-time, traditional, first-time freshman at public, four year colleges in Ohio. The authors estimated that adjuncts and graduate student instructors had a negative affect on students in humanities and in the sciences (including mathematics), and young adjunct faculty (under 40-years old) accounted for the majority of this effect. Interestingly, adjuncts had a positive effect on pass rate in subsequent courses in technical or professional fields (i.e. computer science, business, and architecture). Conversely, Hoffman and Oreopoulos (2007) found that a number of indicators of instructor qualifications (including whether an instructor teaches full-time or part-time, does research, has tenure, or is highly paid) had no influence on a college student's grade, likelihood of dropping a course or taking more subsequent courses in the same subject. In this study I investigate the relationship between a number of indicators of instructor qualifications to student success in Calculus 1.

The value placed on teaching experience, coursework, level of education, degree type, and (at the post-secondary level) instructor type, speaks to the underlying implied level of knowledge gained through these experiences. However, not only is it problematic to assume a certain level of knowledge based on specific coursework, for instance, but what type of knowledge is needed for teaching is a controversial and well-researched

topic. In the following section, I review the literature on teacher knowledge, both at the K-12 level and the undergraduate level.

Teacher Knowledge. There is extensive research into the knowledge and understanding needed to teach mathematics effectively (Ball et al., 2008; Shulman, 1986). Shulman (1986) classically differentiated between various knowledge needed for teaching, introducing pedagogical content knowledge (PCK) into the mathematics education research lexicon. Pedagogical content knowledge is distinct from a blend of basic pedagogical knowledge and basic content knowledge and was introduced by Shulman in response to the wide-held belief that content knowledge alone was sufficient to teach. PCK is the particular form of content knowledge related to the aspects of content knowledge “most germane to its teachability”, including ways of representing content so that it is understandable to others (Schulman, 1986, p. 9). Ball, Thames, and Phelps (2008) extended this construct by further elaborating *Mathematical Knowledge for Teaching (MKT)* and have aimed professional development efforts at developing the various components of this knowledge.

MKT is thought to be comprised of two main categories of knowledge: knowledge of the subject matter and its organizing components, referred to as content knowledge (CK); and the knowledge of how to teach this content so that it is comprehensible to others, referred to as Pedagogical Content Knowledge (PCK) (Shulman, 1986). Two especially critical components of PCK are knowledge of how students understand and think about specific content, referred to as Knowledge of Content and Students (KCS), and the knowledge of how to teach specific content so that students understand it, referred to as Knowledge of Content and Teaching (KCT) (Ball et

al., 2008). Many, including myself, find these distinctions useful in categorizing the types of knowledge targeted by various professional development programs. Research into teachers' knowledge is most robust at the K-12 level, but these distinctions are being used within the post-secondary literature base as well.

MKT at the undergraduate level. At the undergraduate level, there is a growing body of literature surrounding instructors' mathematical knowledge for teaching (i.e. Johnson & Larsen, 2012; Wagner, Speer, & Rossa, 2007; Speer, King, & Howell, 2014), with Speer and her colleagues predominantly leading research into GTA knowledge. In 2005, Speer and Kung drew attention to the lack of research surrounding GTA's teaching practices, their preparation to teach, and the knowledge they need to teach. Almost ten years later, this body of research has expanded. In this study, I investigate the current state of GTA instruction and their preparation to teach, with the goal of identifying the components of successful GTA-PD programs to promote more widespread propagation of these programs. One component of GTA-PD programs that I attend to is the type of knowledge focused on during the training: content knowledge, pedagogical knowledge, or pedagogical content knowledge. GTAs often come into their roles as instructors with strong content knowledge and little teaching experience, resulting in little mathematical knowledge for teaching (Speer & Hald, 2008). Speer, Strickland, and Johnson (2005) found that even experienced graduate students often lack knowledge of student learning of key ideas and have not developed strategies to support student learning of these topics. However, Kung (2005) found that it is possible for GTAs to develop rich knowledge of their students' mathematical understandings through professional development programs that emphasize student thinking. Recently, Speer, King, and Howell (2014) have

suggested that the MKT framework itself is problematic in application at the undergraduate level due to the level of mathematical exposure of instructors teaching at the post-secondary level compared to elementary mathematics teachers. I keep these suggestions in mind in this study, and add to this ongoing conversation by considering the ways this framing does (or does not) add insight to the professional development of post-secondary instructors. In this study, I do not measure instructor knowledge as a component of instructor quality. Instead I attend to the types of knowledge that may be developed through various PD activities. For instance, an institution may ask GTAs to consider hypothetical reasons for various incorrect student solutions to an exam. This task has the potential to develop an understanding of student thinking, and thus PCK.

Teacher Characteristics

Teacher characteristics include characteristics that cannot be changed, such as demographics, characteristics that are difficult to change, such as attitudes and beliefs, and characteristics that are easier to change, such as knowing a second language. For the purposes of this study, I am interested in the relationships between student persistence and instructor demographics and student persistence and instructor beliefs.

Teacher Demographics. Research into the relationship between teacher demographics, such as sex, race, ethnicity, and language spoken, and student success, such as persistence, are sparse and mixed. There are no identifiable links between teacher race, gender, and ethnicity in terms of student achievement in general, though in mathematics, one study found that students taught by a teacher of the same race outperform students taught by a teacher of a different race (Dee, 2004; Ehrenberg,

Goldhaber, & Brewer, 1995). Research at the undergraduate level shows mixed findings. A number of studies have found that science and mathematics instruction by a female instructor decreases female grade performance, the number of same subject courses taken in later years (Hoffman & Oreopoulos, 2007) and has a negative impact on student persistence in STEM studies (Price, 2010). However, another study using four-year longitudinal data from first-time freshman enrolled in a college or university in Ohio found that these results held in physics and biology, but in mathematics and geology courses females taught by females took more additional STEM courses (Bettinger & Long, 2005). Additionally, females taught by a female instructor are less likely to persist in their STEM studies than those taught by a male instructor (Price, 2010). However, Seymour and Hewitt (1997) found that a leading reason females choose not to pursue degrees in STEM fields is the lack of other women in these fields, making it difficult to envision oneself succeeding in these fields. For the purposes of this study, I attend to instructors' race/ ethnicity, gender, and country where their highest degree was obtained.

Teacher Beliefs. Research into teachers' mathematical beliefs is not quite as developed as research into teachers' mathematical knowledge though still plays a large role in teacher professional development. Within this research, the construct of *mathematical beliefs* is not as clearly defined as *mathematical knowledge*. Philipp (2007) distilled the various conceptions of beliefs into one precise definition, that I use: "Psychologically held understandings, premises, or propositions about the world that are thought to be true...beliefs might be thought of as lenses that affect one's view of some aspect of the world or as dispositions toward action" (p. 259). From this perspective, mathematical beliefs can be conceptualized as the lenses that affect teachers' views of the

teaching and learning of mathematics. Mathematical beliefs include, but are not limited to, beliefs about doing mathematics, beliefs about teaching mathematics, beliefs about learning mathematics, and beliefs about technology. The following is an example of differing beliefs about doing mathematics that may lead to differing actions: Teacher A may believe that mathematics is about getting the exact answer to specific problems, and Teacher B may believe that mathematics is about making connections and forming logical arguments. These differing views have the potential to greatly affect many aspects of their students' calculus experience, including classroom instruction, what content is emphasized on homework and assessments, and how the instructor interacts with students outside of class. However, the relationship between beliefs and aspects of instruction are not as clear as one may imagine, especially due to difficulties in measuring or describing beliefs. Specifically there are often discrepancies between one's stated or espoused beliefs and the observed beliefs.

In a review of the literature surrounding teacher beliefs Philipp (2007) concluded that the relationship between how teachers' beliefs change with respect to their instructional practices is mixed: for some teachers beliefs change before practices, and for others changes in instructional practices occur before a change in their beliefs. He hypothesized that meaningful changes take place when teachers' beliefs and practices change together, and that this dual change occurs when teachers have opportunities to "reflect upon innovative reform-oriented curricula they are using, upon their own students' mathematical thinking, or upon other aspects of their practices" (p. 309), especially when these opportunities are afforded in practice-based environments.

Leatham (2006) addresses the oft pointed to discrepancies between espoused teacher beliefs and their actions through a reconceptualization of the notion of a belief-system. This reconceptualization calls into question the assumption that individuals are able to articulate their beliefs, and instead favors Pajares' (1992) perspective: "beliefs cannot be directly observed or measured but must be inferred from what people say, intend, and do – fundamental prerequisites that educational researchers have seldom followed" (p. 207). In order to infer an individual's beliefs, Leatham insists on relying on numerous resources instead of asking someone to articulate their beliefs. From this perspective, Leatham argued that there are no longer discrepancies between teachers' beliefs and their actions; rather that their beliefs need to be understood as a system comprised of both their evoked beliefs and their inferred beliefs based on their actions.

In order to measure teachers' beliefs, researchers often utilize one of two approaches: Likert surveys or case study approaches. Likert surveys are comprised of both positively stated and negatively stated prompts, and ask the responder to indicate how much they agree with statements. For instance, on a survey assessing change in teachers' beliefs about teaching and learning mathematics, Hart (2002) asked teachers to respond to the following related positive and negative statements: "Good mathematics teachers show students lots of different ways to look at the same question"; "Good math teachers show you the exact way to answer the math question you will be tested on." Likert surveys are optimal for assessing the *evoked* beliefs of a large quantity of individuals, but are believed to be inferior to the case-study approach in the level of richness, and accuracy of the beliefs (Philipp, 2007).

Case study approaches, comprised of a combination of interviews, classroom observations, surveys, responses to vignettes or videotapes, and linguistic analysis are the favored method for assessing teachers' beliefs for a manageable number of teachers (Philipp, 2007). By collecting this extensive data, one is able to rely on case study methodologies to ensure reliable data, such as triangulation and posing alternate hypotheses, as well as draw on both evoked and inferred beliefs as encouraged by Leatham (2006). For the purposes of this study, I draw on both methods to discuss GTAs' beliefs: I rely on survey data for the large scale comparison of beliefs held by GTAs to beliefs held by other groups of Calculus 1 instructors; and I rely on observations, interviews, and survey data to discuss the beliefs held by GTAs at the selected institutions.

The survey items are adapted from the Views About Math Survey (VAMS) which has been used to assess both teachers' and students' views about doing, teaching and learning mathematics, including graduate students, in-service teacher, and precalculus students' (Carlson, 1997; Oerhtman, Carlson, & Vasquez, 2009), which itself was based on the Views About Science Survey (Halloun, 1997). The VAMS taxonomy is grouped into two broad dimensions: epistemological beliefs, pertaining to the structure of mathematical knowledge, the validity of mathematical knowledge, and the structure of math; and pedagogical beliefs, pertaining to the learnability of mathematics, the role of critical thinking, and personal relevance of mathematics. This survey aims to distinguish between the *expert view* of mathematics, or the one typically held by mathematicians, and the *folk view* of mathematics, the view often attributed to the lay community. An expert view of mathematics is characterized by views that mathematics is about solving

problems, the role of the teacher is to help students make sense of mathematics, all students are capable of learning mathematics, there are multiple ways to solve problems, etc. Conversely, a folk view of mathematics is characterized by views that mathematics is about memorizing algorithms, there is only one way to solve problems, mathematics is a field that only select people can understand, etc. (Carlson, 1997).

In a study targeting GTAs' beliefs about the nature of mathematics and who can learn it, Gutmann (2009) interviewed seven new mathematics teaching assistants about their biographies, why and how they came to be graduate students, and their beliefs about mathematics. Specifically, GTAs were asked to respond to two questions regarding their mathematical beliefs: "What would you identify as the reasons that student's don't learn mathematics as well as their teacher would like?" and "Can everyone learn mathematics?" (p. 65). Gutmann found that a prevalent view held by GTAs is that only some students are capable of learning mathematics past precalculus, which would be characterized as a folk view of mathematics by VAMS (Carlson, 1997). He recommends that professional development programs explicitly assist GTAs in developing more expert like beliefs towards the teaching and learning of mathematics, and that the relationship between GTAs' beliefs about mathematics and their classroom practices needs to be investigated.

Teacher Practices

In addition to what teachers know and believe about the teaching and learning of mathematics, teacher quality is often assessed based on what teachers do in the classroom. Teaching is a multidimensional practice, and thus there are multiple aspects of the class to attend to. One way to structure the types of aspects one attends to is by

focusing on the specific interaction patterns within the classroom. Cohen, Raudenbush, and Ball (2003) introduce the Instructional Triangle as a tool for describing the various patterns of interaction within the classroom (Fig. 2.2). Researchers have used this model to argue that student success does not depend on the resources available to students but rather on the way students interact with these resources (Cohen et al., 2003). Teachers interact with students, students interact with content, and teachers interact with the content, all situated within external environments such as the school, parents, and the department. In this section I articulate three specific interaction patterns: (a) discourse patterns, taken as a form of interaction between teachers and students; (b) use of certain instructional practices (e.g. lecture, whole-class discussion, or group work), taken as a form of interaction between teacher, students, and content; and (c) the nature of the tasks; taken as a form of interaction between the teacher and the content and the students and the content.

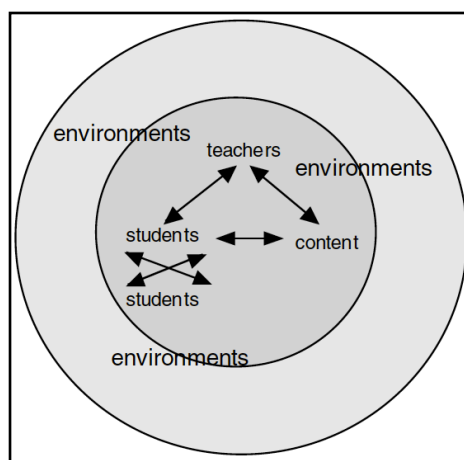


Figure 2.2 Instructional Triangle describing the interaction patterns of instruction (Cohen, Raudenbush, & Ball, 2003)

Discourse. A primary component of classroom interaction is through discourse. However, narrowing ones focus to classroom discourse still leaves many options surrounding whose discourse to attend to and what aspects of the discourse to attend to. Researchers have studied both students' and instructors' utterances to understand how their discourse affects the co-creation of the classroom environment (Bowers & Nickerson, 2001; Mesa & Chang, 2010; Kazemi & Stipek, 2001; Webb et al., 2009; Wells, 1996). The foci of discourse analysis are expressed interactions, including verbal, written, and gestural expressions. There exists a variety of analytic methods used within discourse analysis, which allows the researchers to use the most appropriate analytical methods for their questions. Typically, in order to conduct an in-depth discourse analysis one must have recorded video or audio in order to document all verbal (or written or gesticular) interactions. However one may also use classroom discourse patterns more informally as one of multiple classroom components used to holistically describe the instructional practice of a specific classroom.

In this study I view discourse patterns as one important component of understanding and characterizing GTAs' classroom interactions. The way that students interact with one another and the way that teachers interact with students provide a rich indication for the learning opportunities (Bowers & Nickerson, 2001; Mehan, 1979; Mesa & Chang, 2010; Kazemi & Stipek, 2001). For instance, if the only questions that teachers ask students are rhetorical or can be answered with one word answers (such as "What is the derivative of x^2 ?") then this indicates that students are not expected to explain their thinking during class, and may be indicative of a more procedural emphasis in the course. If, instead, students frequently ask one another questions and argue with each others'

answers, this may be indicative of an environment that engages student in authentic mathematical activity and provides more learning opportunities for students. In this study I use responses to a post observation survey intended to characterize the nature of the discourse patterns, as a way to characterize potential learning opportunities for students. See *Appendices* for full observation protocol. On this survey, an observer responded to questions such as:

1. Describe students' interaction with the instructor. What were the main forms of interaction?
2. Describe uniformity or non-uniformity of student-instructor interaction.
3. Describe observed student-to-student interaction, if any.
4. Describe what you can remember about instructor questioning behaviors.
5. Describe what you can remember about student questioning behaviors.

Frequency of certain pedagogical activities. There is an abundance of research in mathematics education pointing to the benefits on student achievement of specific pedagogical activities, including aspects of Inquiry-Oriented instruction (characterized by whole-class discussion, increased student-to-student interaction, student presentations of their groups' work, and expected explanation of student thinking) (Boaler, 1998; Kung, 2011; Rasmussen, 2001), and other innovative classroom practices, such as Peer-Instruction, where students formally share ideas with one another (Mazur, 1997), and using clickers in class to elicit student feedback (Liu & Stengel, 2011). For instance, Boaler (1998) compared student learning at two high schools, one in which students worked on problems together in groups and presented their findings to each other in an inquiry-oriented instructional environment and the other that fostered a very traditional

instructional environment. Boaler found that the Inquiry-Oriented environment helped students develop superior conceptual understanding and problem solving skills compared to students taught in a more traditional setting.

While the benefit of these instructional practices does not lie solely in their use but in *the nature* of their use, one coarse way to characterize classroom activities is by the frequency of such activities: How frequently do students work in groups? How frequently do students present their work at the board? In this study I rely most heavily on frequency reports, during interviews and on surveys. I also record the frequency of specific pedagogical activities, such as group work and lecture, during classroom observations. Taken together the frequency reports allow me to characterize a classroom environment as traditional, inquiry-oriented, or somewhere in between. While looking at the frequency of such activities rather than the way in which they are implemented tells a limited story, this limited story provides a basic understanding of the structural components of various classrooms and one that can most easily be assessed on a large scale (Huffman, Thomas, & Lawrenz, 2003).

Nature of problems. A third critical aspect of instructional practice is the nature of the problems or tasks that students are asked to solve in class, on homework, and on exams, and the problems the instructor demonstrates in class (Silver, 1996; Stein & Lane, 1996). Silver and his colleagues have connected tasks with high cognitive demand (or those tasks that encourage students to engage in high-level reasoning) to student learning gains, though they caution that setting up high-level tasks does not guarantee students' high-level engagement. Instead, it is of great importance to attend to the combination of the nature of the tasks and the ways in which students engage with the tasks. Similarly,

Newmann, Bryk, and Nagaoka (2001) studied over 2,000 assignments from 3rd, 6th, and 8th grade classes in Chicago and found that in classes with assignments that had low levels of intellectual demand, learning gains among students were 20-25% lower in mathematics than in classes with high intellectual-demand tasks. Additionally, these authors found that low-achieving students benefited more from high-demand assignments in mathematics than high-achieving students. These authors found that student achievement is connected to the nature of the tasks students are asked to engage with, either on their own, with other students, or watching the instructor solve them. Because of this, one way to assess instructional practices is to assess the nature of the tasks. In this study, I record the tasks that students or instructors work on in class, as well as on exams and homework. Specifically, I rely on student and instructor reports of the types of questions asked on assignments and assessments (e.g. routine short answer problems, proofs or justifications, non-routine word problems, etc.) and the relationship between problems on assignments and on assessments. I do not directly assess the cognitive demand of the tasks as this is outside the scope of this study.

Thus, in this study I characterize the classroom environment using a combination of:

- descriptions of observed discourse on a post-observation survey,
- reported frequency of various instructional practices from surveys and interviews,
and
- a characterization of tasks from assignment and assessments based on student and instructor reports.

Student Success

There are many aspects of student success that may be used in connection to teacher quality, including student achievement on assessment tools (such as class exams or the Calculus Concept Inventory [CCI]), academic success in subsequent courses, change in student beliefs and affect, and persistence (Kuh, Kinzie, Buckley, Bridges, & Hayek, 2011). Goe (2007) relies on a conception of student success based on student achievement test scores and a related conception of teacher effectiveness based on a value added measure of student achievement. There are a number of critiques against using student achievement on standardized tests as a measure of teacher quality, including the difficulties in isolating the effect of the teacher from the effect of the school and district (Goe, 2007), the difficulties in connecting teacher knowledge to student achievement (Hill et al., 2008), and the amass of student level factors to account for, including home support and classroom social interactions (Darling-Hammond, 2007).

From the perspective of situated learning, learning is marked by participation in a community (Lave & Wegner, 1991), and thus measuring student learning by performance on a test is especially problematic. Instead, student success is marked by increased participation in a community, such as the community of STEM practitioners. One measure that an individual is participating in a community is by the intention to continue being a member of that community. Another measure is expressing similar beliefs as the community is known to hold (Putnam & Borko, 2000). With respect to participating in the STEM community, this includes expressing a positive disposition towards mathematics and more expert like beliefs regarding mathematics (Carlson, 1997).

Driven by the current state of undergraduate STEM education and a situated perspective on learning, I conceive of student success as maintained positive disposition towards mathematics, continuing on in calculus and the ability to do so, as marked by passing the course. Specifically, in this study I define *student success* as composed of three interrelated components: (a) a positive change in students' interest in, and enjoyment of mathematics, and confidence in their mathematical ability, (b) student persistence onto Calculus 2 (as a proxy for STEM persistence), and (c) pass rate in Calculus 1.

Student Beliefs. There is extensive research into the role that students' mathematical beliefs play on their mathematical success (McLeod & McLeod, 2002; Leder, Pehkoren, & Toerner, 2002). However, there is little consensus in mathematics education as to what mathematical beliefs entail. In an effort to clarify this, Op 't Eynde, De Corte and Verschaffel (2002) defined students' mathematics-related beliefs as the implicitly or explicitly held subjective conceptions students hold to be true about (a) mathematics education (i.e. the teaching and learning of mathematics), (b) about themselves as mathematicians, and (c) about the nature of mathematics. These various mathematic-related beliefs have been shown to have substantial impact on students' interest in mathematics, their enjoyment of mathematics, and their motivation in mathematics classes (McLeod & McLeod, 2002; Kloosterman, 2002; Liu, 2010). In a study investigating Taiwanese college students' epistemological beliefs about mathematics, Liu (2010) found that students who were more enthusiastic about doing mathematics performed better on standard problems than students who espoused less sophisticated beliefs about mathematical knowledge and their interest in doing

mathematics. However, Liu did not find a clear relationship between students' epistemological beliefs about mathematics and their performance on open-ended and non-routine problems, such as the Tower of Hanoi. Other studies have more clearly linked students positive epistemological beliefs about mathematics (including what they think it means to be good at mathematics and how they view themselves as doers of mathematics) with their performance on non-routine problems (Bendixen & Hartley, 2003; Leder et al., 2002; Lerch, 2004; Schoenfeld, 1983). In this study I attend directly to students' stated interest in mathematics, enjoyment of mathematics, and confidence in their own mathematical abilities. Similar to teacher beliefs, student beliefs are often assessed either using case-study approaches or a survey approach. In this study, I employ a survey approach to identify students' espoused beliefs due to the large number of participants in the study.

STEM Persistence. Researchers in Higher Education have extensively studied factors related to student retention at the post-secondary level (not STEM specific), often focusing on the effects of student engagement and integration on persistence (Kuh et al., 2008; Tinto, 1975, 2004). According to Tinto's integration framework (1975), persistence throughout college studies occurs when students are socially and academically integrated in the institution. This integration occurs through a negotiation between the students' incoming social and academic norms and the norms of the department and broader institution. From this perspective, student persistence through their college studies is viewed as a function of the dynamic relationship between the student and other actors within the institutional environment, including the classroom environment. Research into the reasons students switch out of *STEM majors* (rather than disengaging from college in

general) points to the classroom environment as the underlying commonality (Rasmussen, & Ellis, 2013; Seymour & Hewitt, 1997; Thompson et al., 2007).

In *Talking about Leaving: Why Undergraduates Leave the Sciences* (Seymour & Hewitt, 1997) discussed their findings from a study of persistence among well-qualified students (i.e., those with SAT mathematics scores of 650 or above) who entered STEM majors in seven institutions. Through extensive longitudinal interviews, Seymour and Hewitt found that reports of poor learning experiences were by far the most common complaint both of those who switched out of science, mathematics, and engineering majors and those who persisted in those majors. “Poor teaching” was ranked as the number one problem with their major cited by undergraduates at six of the seven institutions. Further, unsatisfactory learning experiences in introductory science and mathematics courses were the primary cause of switchers losing their initial interest in a STEM field, causing them to move into disciplines where they reported better educational experiences.

Seymour and Hewitt’s study highlights the influence that students experiences in introductory mathematics courses, such as Calculus 1, have on students’ decisions to pursue a STEM degree. Thompson and his colleagues (2007) found that of the STEM-intending students who enrolled in first semester calculus at one large research I university over 50% did not go on to complete second semester calculus and only 30% of these students completed Calculus 3. Rasmussen and his colleagues (2013) found that of STEM-intending students enrolled in first semester calculus at over 200 institutions across the country, the number of students who initially intended to but did not go on to complete Calculus 2 was closer to 15%. This research indicates that while Calculus 1 is

not the only mathematics course affecting students' persistence in STEM fields, it is one of the most influential. Individual instructors play an integral role in the students' experiences in first semester calculus, and thus their preparation to teach is of great importance.

Summary of Teacher Quality

In an extensive review of the literature connecting teacher quality to student success, Goe (2007) articulated four primary components of teacher quality: teacher qualification, teacher characteristics, teaching practices, and student success. In this study, I first compare instructor quality of GTAs to tenure/ tenure-track faculty and to other full and part time faculty along each of the components articulated by Goe (2007). In Figure 2.3 I summarize my reinterpretation of these components, necessitated by both differences between K-12 teachers and post-secondary instructors as well as my perspective on learning.

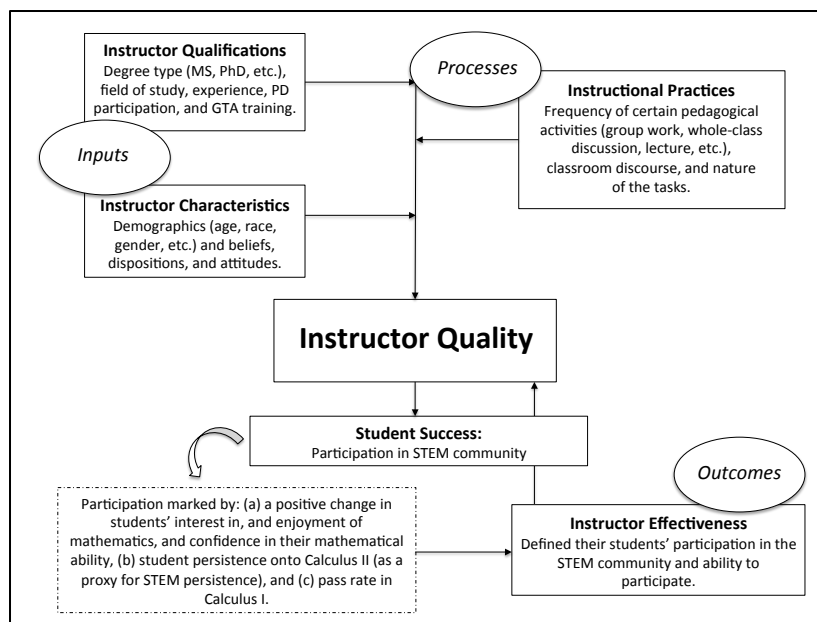


Figure 2.3 Graphic representation of instructor quality, based on Goe's (2007) framework for teacher quality

In the comparison on instructor quality (in *Chapter 4*), I attend to:

- instructor qualifications, including highest degree completed and field of study of degree completed (i.e. Mathematics, Statistics, Mathematics Education, Other);
- instructor characteristics, including demographics as well as beliefs about the teaching and learning of mathematics;
- instructional practices, specifically attending to discourse, frequency of certain pedagogical activities, and the nature of the tasks;
- instructor effectiveness as measured by their students' participation in the STEM community, marked by students' interest, enjoyment, and confidence in mathematics, their students' persistence onto Calculus 2, and their students' pass rate in Calculus 1.

After this comparison, I develop a rich characterization of professional development programs for GTAs (in *Chapter 5*) and consider aspects of instructor quality among GTAs coming from different programs (in *Chapter 6*). In the following sections, I review literature surrounding professional development programs at both the K-12 level and the post-secondary level. After developing this characterization, I then connect components of GTA-PD programs to the components of graduate student instructor quality.

Professional Development

The National Science Board (NSB) uses the term *professional development* to refer both to teacher preparations (i.e. the teaching of preservice and prospective teachers) and to the development of practicing teachers (i.e. in-service teachers) (National Science Board, 2012). Graduate student Teaching Assistants (GTAs) have commonalities with both categories of teachers: the training they receive as GTAs is typically the first training to teach they will have received, however often they receive this training while they are teaching. Because of these commonalities I draw from the literature on professional development programs designed both for preservice and in-service teachers at the K-12 level with attention to how it relates to GTA-PD, as well as research specifically focused on professional development of post-secondary instructors. There is extensive research into the professional development of teachers at the K-12 level (i.e., Ball & Cohen, 1999; Stigler & Hiebert, 1999; Loucks-Horsley, Stiles, Mundry, Love, & Hewson, 2010; Putnam & Borko, 1997; Sowder, 2007). Consistent with the above-discussed criteria for which teacher quality is assessed, professional growth – and thus

the success of professional development programs – is marked by changes in aspects of teacher quality that can be changed, namely teacher knowledge, beliefs about teaching and learning of mathematics, instructional practices, and student achievement (Sowder, 2007). In this section, I first discuss various categories of professional development and then discuss common features of successful professional development programs.

Types of Professional Development Programs

In a seminal book on the design of professional development programs, Loucks-Horsley and her colleagues (2010) articulate a framework for the design of K-12 professional development programs and articulate six types of programs. The authors stress that these programs are not to be thought of as distinct models; instead they can be combined and adapted in ways that best suit the institution developing the program. The six categories of PD programs determined by Loucks-Horsley and her colleagues (2010) are those that:

1. align and implement specific curriculum (such as curriculum supportive of Inquiry-Based Learning);
2. develop professional communities;
3. rely on understanding student thinking;
4. immerse participants into the mathematics;
5. provide participants with practice in teaching; and
6. involve the participants in workshops, seminars, and classes.

Among in-service teachers, a class or seminar is not viewed as a necessary nor sufficient structure for professional development. However, almost all GTA-PD programs involve a workshop, seminar, or class that attends to (at least) one of the other five aspects of PD, and often this is the only component of PD that is required before entering the classroom. For this reason, it is not the involvement in a workshop, seminar, or class that may vary in interesting ways across GTA-PD programs. Instead, the content discussed and activities involved in the workshop, class, or seminar are of much greater importance, and are discussed in this chapter.

Because graduate students come into their roles as GTAs with strong content knowledge and often little (or no) teaching experience, GTA-PD programs do not need to emphasize participants in the mathematics in the same ways that a PD programs for elementary teachers specializing in mathematics may. Thus, I do not explicitly draw on research on K-12 PD programs that immerse participants into the mathematics. Similarly, it is much less common for GTAs to need PD surrounding a specific curriculum than it is at the K-12 level, as the curricular standards are more specific and change more frequently at the K-12 level than they do at the post-secondary level. In this section, I review the research surrounding K-12 PD programs that (a) develop professional communities; (b) rely on understanding student thinking; or (c) provide participants with practice in teaching.

Professional communities. Professional development programs that emphasize the development of professional communities are strongly aligned with the perspective that learning is a social endeavor (Kazami & Hubbard, 2008; Putnam & Borko, 1997). This entails predominately either a socio-cultural perspective or a situated learning

perspective. From the socio-cultural perspective, teacher learning occurs as individual teachers progress from assisted teaching (as in practice teaching) to unassisted teaching, referred to as transitioning along the Zone of Proximal Development (ZPD) (Stein & Brown, 1997; Vygotsky, 1987). From the situated learning perspective, teacher learning occurs as a novice teacher becomes enculturated into the community of teachers by developing the knowledge and practices necessary for teaching (Brown, Collins, & Duguid, 1989; Putnam & Borko, 1997). These perspectives toward teacher learning deemphasize the cognitive attributes and instructional practices of individual teachers in favor of collaborative interactions that occur as professional communities of teachers, teacher educators, and administrators work together to improve their school's mathematics instructional programs (Putnam & Borko, 1997; Sowder, 2007). The goals of these professional communities are to (a) provide teachers with meaningful experiences situated within the classroom; (b) allow novice teachers to experience the classroom alongside expert teachers; (c) enculturate novices into the teaching community; and (d) to provide professional development to experienced teachers (Sowder, 2007).

With an eye towards preparing graduate students as future faculty, the goals of professional communities are especially relevant. There has been a national effort focused on preparing graduate students as future faculty: Preparing Future Faculty (PFF) (<http://www.preparing-faculty.org/>). This program addresses the teaching, research, and service preparation of graduate students in multiple disciplines, including mathematics. PFF programs exist at a number of institutions, and provide graduate students with multiple mentors who provide reflective feedback to graduate students on their research,

teaching, and service activities. These programs have been shown to ease the transition from graduate student to faculty (DeNeef, 2002). However, these programs do not focus in depth on creating professional communities surrounding teaching mathematics, but rather more broad communities around being university faculty. In the following section, I examine one professional development category that focuses clearly on developing professional communities surrounding teaching mathematics that has been implemented widely at the K-12 level and has also been successfully adapted for GTA professional development. This is the Japanese practice of lesson study.

Lesson Study. While the notion of creating professional communities focused on teacher learning is a natural consequence of viewing teacher learning from either a socio-cultural or situated perspective, this idea become concretized through lesson study. Results from the 1999 *Trends in International Mathematics and Science Study (TIMSS)* indicated that 8th graders from the United States were the worst performing students of the seven participating countries while Japan's students were among the best (along with Hong Kong) (Hiebert et al., 2003). These results prompted researchers to look in depth into differences between the U.S. and Japan's educational systems. One of the largest differences the researchers found was the professional development of teachers in each country: in the U.S. teachers were trained as individuals and held individually accountable for their teaching; in Japan teachers continuously engaged in the practice of lesson study, which is community driven at its core (Stigler & Hiebert, 1999). Japanese lesson study consists of three cyclic parts (Shimizu, 2002). First a group of teachers (drawn from communities as small as from one school or as large as from entire cities) together choose a particular topic and in small groups collaboratively create a lesson

around that topic. Next, many of the participating teacher delivers the lesson to their students while other participating teachers observe. When lesson study is implemented city-wide, it is often impossible *for every* participating teacher to deliver the lesson, but when the scale is smaller (as in one school) all participating teacher is encouraged to enact the lesson. Lastly, the group discusses the lesson, taking into consideration the teachers' experiences teaching it and observing others teach. Sometimes the process is repeated. Lesson study has been implemented in many U.S. K-12 PD programs with success (i.e., Lewis, 2004; Rearden, Taylor, Hopkins, 2005), although there have also been challenges (Lewis, Perry, Hurd, & O'Connell, 2006; Takahashi & Yoshida, 2004). Successful implementation of lesson study comes from the careful and thoughtful *adaptation* of the practice as opposed to *borrowing* all tenants of lesson study (Lewis & Takahashi, 2013). Lesson study is an especially promising form of professional development for GTAs, due to frequent on-the-job training and the need for GTAs to be enculturated into the community of undergraduate mathematics instructors (Dotger, 2011; Alvine, Judson, Schein, & Yoshida, 2007).

There are a number of studies that detail the experiences of GTAs participating in PD programs informed by the Japanese practice of lesson study (Alvine et al., 2007; Barry & Dotger, 2011; Nickerson & Whitacre, 2008). Alvine and her colleagues (2007) describe a GTA-PD program at Harvard based on Lesson study. All mathematics graduate students at Harvard participate in a one term apprenticeship program before teaching their own class, during which they attend their mentor's class, run office hours for this course, and prepare and teach a number of lessons in their mentor's class – one of which is videotaped and analyzed in depth by the GTA and the mentor. Based on the

GTA's performance, the mentor recommends either additional training or approves the GTA to be appointed as an instructor the following term. Once GTAs are approved to teach their own class, they participate in lesson study as an ongoing form of PD where GTAs worked with an experienced instructor in small groups to develop a lesson together, individually implement the lesson, and immediately debrief and discuss each teacher's delivery of the lesson. The addition of lesson study as a way to continue GTA-PD at Harvard was determined to be "relatively easy to set up at the undergraduate level (p.111)," provide a non-evaluative environment to improve teaching, vicariously increased all participants teaching experiences by observing one-another, and had the added benefit of ensuring that the graduate students would have at least one faculty member familiar with their teaching who could provide a letter of reference when they seek employment in the future. Barry and Dotger (2011) similarly articulate the benefits of a lesson study-inspired PD for GTAs teaching introductory Biology at Syracuse University. Similar to the Harvard model, several GTAs and a more experienced instructor together developed a lesson, each implemented it, observed one another's classes, and debriefed after each lesson to discuss student thinking and alter the lesson as needed. The researchers found that lesson study allowed GTAs to explore aspects of the content they were required to teach in a non-evaluative environment, provided models for how to deliver instruction, and provided a space for GTAs to discuss their students' thinking.

Understanding student thinking. As discussed above, much attention has been placed on the types of knowledge that teachers need to teach. This includes content knowledge, pedagogical knowledge, and pedagogical content knowledge. One of the

main components of pedagogical content knowledge is Knowledge of Content and Students (KCS) (Ball et al., 2008; Wagner et al., 2007). This element of knowledge comprises knowing how students may understand specific content, various solutions they may arrive at, struggles they have with the material, what examples students will find interesting and understandable, and generally understanding student thinking. Teachers may gain this knowledge from reflecting on their teaching experiences, reading mathematics education research into student thinking, or from professional development programs that focus on student thinking (Ball et al., 2008). Because GTAs often come into their roles as instructors with little experience to reflect on and little (or no) knowledge of mathematics education literature. Thus, professional development programs that focus on student thinking are especially relevant to graduate students. In the following section, I describe one especially successful K-12 professional development program that emphasizes student thinking, which can develop knowledge of content and students (KCS).

Cognitively Guided Instruction (CGI). Cognitively Guided Instruction (CGI) is based on the hypothesis that if teachers listen to children and understand their reasoning, and teach to this understanding, this will provide students a better math education (Carpenter, Fennema, Peterson, & Carey, 1988). There exists an extensive body of literature pointing to the benefits CGI has had on primary teachers' instructional practices and subsequently their students' achievement (e.g. Carpenter & Fennema, 1992; Carpenter & Moser, 1983; Carpenter et al., 1988; Carpenter, Fennema, Peterson, Chiang, & Loef, 1989; Franke, Carpenter, Levi, & Fennema, 2001). The professional development connected with CGI consists of a summer workshop in which teachers

investigated various solution strategies students use for addition and subtraction, and interviewed students to understand first hand student thinking and to explore reasons for common student misconceptions. Participation in CGI professional development programs has been repeatedly and clearly linked to an increase in teacher MKT, specifically PCK and KCS.

Use of case studies. An alternate strategy employed in professional development to foster an understanding of student thinking is the use of case studies, either written or video based. Case studies preserve the complexity of teaching while providing opportunities to examine it, and are classically used in law and medicine but are becoming more popular in education (Barnett-Clarke, 2001; Sowder, 2007). One way to utilize case studies is through written case studies. Richert (1991) outlined three important components of written case studies: they should be descriptive, describe teaching practices, and situate the reader in the particular setting. This combination allows teachers to examine how other teachers think and act, and compare these findings to how they think about the situation and what they would do.

A more commonly utilized form of case studies are video case studies or multimedia case studies (Boaler & Humphreys, 2005; Bowers & Doer, 2003; Putnam & Borko, 1997; Richardson, & Anders, 1994; Seago & Mumme, 2002; Sykes & Bird, 1992). Seago and Mumme (2002) utilized video cases in the Videocases for Mathematics Professional Development project (VCMPD) and highlight the benefit of videos: “video provides an opportunity to study an instance of teaching that is emotionally distant enough to create a safe place to scrutinize practice carefully” (p. 5). Videocases can create meaningful settings for teacher learning without putting teachers in particular

classroom settings; instead they can provide teachers with “vicarious encounters” with those settings (Putnam & Borko, 1997, p. 8). For instance, Bowers and Dooer (2003) found that teachers especially valued and benefitted from watching other teachers reflect on their teaching practices. In addition to allowing teachers to explore the richness and complexity of a classroom setting without being in one, video cases also allow for reflection and critical analysis that is not possible when acting in the setting. Videocases additionally are able to benefit both preservice and in-service, though these groups of teachers benefit in different ways (Sowder, 2007). While in-service teachers can watch the videos and compare the teachers’ moves to their own and how they may react, preservice teachers do not yet have the experiences that allow them to ask the same questions that in-service teachers would ask or notice what they would notice. Instead, video cases allow preservice teachers to vicariously experience the classroom before being in one. Case studies, both written and video, provide preservice teachers with vicarious teaching experiences to reflect on and develop some understanding of student thinking. This form of professional development has begun to be utilized in GTA-PD, led by Hauk and her colleagues (Hauk, Kung, Segalla, Speer & Tsay, 2006).

Practice in teaching. Preservice teachers are typically given the experience of practice teaching before they enter the classroom through student teaching. This experience allows the preservice teachers to be apprenticed into teaching without taking on all responsibilities of teaching all at once (Sowder, 2007). Thus, the quality of the practice teaching experience is dependent on the apprenticeship and mentoring that accompany it. Feiman-Nemser and Beasley (1997) found that while mentoring in general was beneficial to the preservice teacher, the scaffolding that the mentor provided played a

critical role in guiding the preservice teachers' pedagogical thinking. Grossman and her colleagues (2009) call these experiences in scaffolded practice *approximations of practice* and note that these approximations allow novice teachers to engage in the practices of teaching within narrow boundaries, which "limit the difficulty of the task, helping novices hone in on dimensions of the practice that otherwise might get lost in the fray" (p. 2090). The authors contrast approximations of practice, in which novices engage in the practice, with *representations of practices*, in which a facet of a practice is illustrated to the novice. They highlight the importance of both in teaching novices the practice of a profession, such as teaching or becoming clergy. They also point to the important role that the mentor plays in these approximations of practice, noting that who is guiding the approximation and the nature of the feedback they provide to the novice are highly important to the experience. Though this is a form of professional development typically reserved for preservice teachers, it can be combined with other forms of professional development for in-service teachers, such as with lesson study or video cases.

In summary, there are a number of existing K-12 professional development programs that seem especially relevant to GTA-PD. Because GTAs often come into their roles as instructors with little teaching experience, programs designed for preservice K-12 teachers can be very informative for GTA-PD. Professional development programs for GTAs can also productively leverage K-12 PD for preservice teachers by including apprentice teaching, and opportunities for investigating student thinking. Professional development programs for graduate students can also be informed by aspects of in-service teacher professional development, as GTAs are often practicing instructors while

they participate in their training. Thus, programs such as lesson study have been informative for graduate student professional development. In the following section, I elaborate on existing GTA-PD programs, many of which implement variations of professional development programs designed for preservice and in-service K-12 teachers.

GTA Professional Development

The literature surrounding GTA professional development is growing as national reports point to the significance of undergraduate education, especially in preparing STEM students (PCAST 2012), as well as to the increasing role GTAs are playing in the teaching of STEM courses (CBMS, 2005, 2010). Preliminary results from the most recent College Board of Mathematical Sciences (CBMS) survey show that, while there is a steady increase in the number of students enrolled in introductory mathematics courses nationwide, there is a 5% decrease in the number of tenured and tenure-track mathematics faculty from 2005 to 2010 (Lutzer et al., 2007). The heightened instructional need is being met by an increase in the number of “other faculty,” a category including graduate student teaching associates and postdoctoral appointments.

Increased attention to GTA training is necessitated by the growing employment of GTAs in the teaching of undergraduate level mathematics coupled with a number of studies pointing to GTAs’ lacking Mathematical Knowledge of Teaching (MKT) (Kung, 2010; Kung & Speer, 2009; Speer et al., 2005) and an abundance of novice beliefs regarding the teaching and learning of mathematics (DeFranco & McGivney-Burelle, 2001; Gutmann, 2009; Hauk et al., 2009; Raychaudhuri & Hsu, 2012). Teacher knowledge and beliefs are primary components of instructor quality, and thus these

studies point to a potential deficiency in graduate students' instruction and preparation for this instruction.

These studies together highlight a fact that is coming to be more widely accepted since first put forth by Shulman (1986): strong content knowledge alone is not sufficient for teaching mathematics. Instead, knowledge and beliefs about the teaching and learning of mathematics are developed through experience and professional development. Because GTAs often lack teaching experience, these instructional qualities are fostered in GTAs primarily through professional development. In the following sections, I review research that addresses the professional development of graduate students in the teaching of mathematics as well as other sciences. Although there are an increasing number of studies looking into the preparative needs and existing programs preparing GTAs (Hauk et al., 2009; Kung & Speer, 2009; Speer, Gutmann, & Murphy, 2005), this research body is still substantially dwarfed by mathematics K-12 professional development literature. I find research into the professional development needs of other STEM GTAs, such as in Biology, Chemistry, and Physics, to be both germane and complementary to that of mathematics GTAs.

Discipline specific GTA-PD programs. A number of studies of GTA preparation to teach indicate that science and math GTAs do not greatly benefit from campus wide GTA preparation programs. These programs are reported as providing superficial information about the roles and responsibilities of GTAs, and do not address content specific issues or pedagogical training specific to teaching science or math classes (Dotger, 2011; Kung & Speer, 2009). Instead, successful programs are found to stress content specific pedagogical knowledge and specific pedagogical training targeting

content specific instructional practices (Hauk et al., 2006; Kung & Speer, 2009; Luft, Kurdziel, Roehrig & Turner, 2004).

Luft and colleagues (2004) illustrate this clearly in their study of science GTAs in physics, chemistry, and biology at one research university. These researchers found that GTAs in the various science departments gained much more from their discipline based professional development than the university wide training that was offered. Specifically, many of the GTAs were asked to implement an inquiry-oriented instructional method (including students solving novel problems in groups, whole class discussions, and student presentation of their work) in their lab and recitations sections and found that the university-wide training did not prepare them at all for this unique setting. When GTAs were *not* provided training specific to this setting, GTAs relied on their experiences as students –often experiences steeped in traditional models of instruction such as lecture and students solving problems on their own. However, even among the GTAs that received both the university-wide training and discipline specific training connected to innovative practices, they still reported that they did not receive enough preparation for the specific instruction they were expected to implement, and relied on their own views about teaching and learning. Seymour and colleagues (2005) drew attention to the specific pedagogical needs GTAs have in implementing innovative instructional practices, such as those encouraged in inquiry-oriented instruction. In a review of the literature surrounding GTA-PD for instruction in innovative science classes, the authors found that effective programs secure GTA buy-in to the approach of teaching, emphasize the theory and methods of the innovative practices, have faculty observe their teaching and provide feedback, and encourage GTAs to reflect on their teaching practices.

Kung and Speer (2009) explicate this issue from a theoretical approach, drawing on literature surrounding K-12 professional development. The authors argue that GTAs involved in the teaching of mathematics may develop much needed pedagogical content knowledge through specific “on the job” training. Specific activities the authors identify include (a) required responsibilities, such as grading student work and conducting office hours, and (b) extra responsibilities, such as predicting student thinking while planning lessons, reading research articles on student thinking, and interviewing students about their thinking. The authors encourage professional development programs to expose GTAs to such as contextually integrated experiences, as much as possible, before they enter the classroom.

Today there exist a number of resources that help to provide these types of experiences to GTAs through the use of case studies. For instance, Meel (2009) and the MAA “Handbook for Mathematics Teaching Assistants” (Rishel, 2013) both offer a number of hypothetical cases for GTAs to consider in order to build their MKT:

This week in teaching I struggled with fractional exponents. It was very difficult for me to explain to the students how to solve the expressions having fractional exponents. They also had a problem in solving $(9 \text{ to the power } 3/2)/(27 \text{ to power } 2/3)$ – Rujul (Meel, 2009, p. 126).

After posing such hypothetical scenarios, Richel and Meel encourage GTAs to consider how they would respond to the situations, allowing GTAs to mentally engage in teaching scenarios. Hauk and her colleagues offer contextually rich video cases in order to allow GTAs to experience elements of teaching without yet being in the class (Hauk et al., 2006).

Resources such as these are valuable artifacts of what GTA-PD programs may glean from the abundance of research on K-12 PD. In the following sections I examine a number of studies surrounding existing professional development programs, some of which explicitly draw on research on K-12 PD.

One-site case studies. Among the studies surrounding discipline specific GTA-PD programs, there exists a relative abundance of one-site case studies that demonstrate the strengths or weaknesses of programs preparing GTAs at a single institution (Alvine et al., 2007; Barry & Dotger, 2011; Belnap, 2005; DeFranco & McGivney-Burelle, 2001; Harris, Forman & Surlles, 2009). While these articles provide in depth contextualization of the professional development programs, they are limited in their scope. DeFranco and McGivney-Burelle (2001) conducted an in depth analysis of the effect a mathematics pedagogy course had on 22 GTAs had on their beliefs and instructional practices. The pedagogy course consisted of 5 seminar classes and focused on pedagogical, epistemological, curricular, and assessment issues and encouraged GTAs to implement instructional changes based on these seminars. The researchers collected GTAs' journal reflections on these changes, observed their teaching, and interviewed them. Analyses of these data indicated that the GTAs adopted a new set of beliefs regarding the teaching and learning of mathematics but failed to alter their instructional practices based on these beliefs. The authors hypothesize connections between the preparation course and these results and offer recommendation for other GTA professional development. One such recommendation is the inclusion of practice teaching during the seminars so that GTAs can actualize altered instructional practices in a supportive and low-stakes environment.

Belnap (2005) conducted a yearlong study of 8 graduate mathematics teaching assistants (GMTAs) at one institution in which he focused on GTAs' instructional development and influences on this development, including both formal and informal influences. GTAs at this institution participated in three formal preparative activities: (1) a three day seminar through the mathematics department addressing pedagogical, epistemological, curricular, and assessment issues; (2) a one-day university-wide GTA training that addressed general pedagogical techniques, the GTA union, sexual harassment, and similar Human Resource information; and (3) a one semester course, concurrent to their first teaching assignment, addressing pedagogical issues, microteaching opportunities, and student thinking. Through longitudinal observations and interviews, Belnap determined that these preparations influenced GTA's teaching but not exclusively: the impact of these experiences is affected greatly by a number of other factors, such as the knowledge, preparation, and attitudes GTAs brought with them into these experiences. Based on these findings Belnap concluded that GTA preparation programs need to provide extended instructional knowledge and allow for opportunities of guided instructional practices.

In the second multi-institution study on GTA-PD, Belnap and Allred (2009) conducted a mixed methods study that investigated the role that undergraduate and graduate mathematics teaching assistants are playing in the teaching of mathematics and the preparation these TAs receive for these roles. This study involved over 200 institutions that employ either graduate students or undergraduate students in the teaching of mathematics, including Baccalaureate Institutions (BIs), Masters Institutions (MIs) and Doctoral Institutions (DIs). TAs were determined to be most heavily involved in the

teaching of mathematics at DIs, where over 90% of institutions reported hiring TAs to teach. At MIs this number decreased to just over 30%, and no BIs reported hiring TAs to teach. The authors found that the nature of TAs' teaching assignments was related to the institution type: while DIs were more likely to employ TAs in some form, MIs were more likely to employ TAs as the sole teacher of a class.

Of the departments that reported hiring TAs to teach, over 90% provided some form of professional development. Descriptions of these programs were open-ended responses that the researchers coded across six dimensions: (a) timing of training, (b) frequency of training, (c) duration of training, (d) goals and objectives, (e) topics covered, and (f) overall design utilized by the program. Variances across these dimensions resulted in a classification of programs into four categories. *Orientation programs* are short programs that take place prior to the start of classes. These programs ranged from a few hours to five days and covered a range of topics, including the roles and responsibilities of the TAs, teaching resources and strategies, and preparing for class. *Transitional programs* extend into the school term, ranging from a half to a full term and had similar objectives to the orientation programs. Transitional programs were found to employ case studies and observation of other instructors teaching. These activities were not found to occur during any orientation program. *Refresher programs* generally took place during or just prior to a school term and lasted between a few hours and five days in total duration. TAs participated in these programs either every year or each time they taught a new course. These programs often focused on lecture skills, preparing for class, and teaching resources. The fourth type of programs are *Establishment programs*. TAs participate in Establishment programs every term they teach a course and the programs

themselves last for the entire term. Establish programs focused on student behavioral problems, lecture and presentation skills, class preparations, teaching resources, and assessment. The content was delivered through lectures, microteaching where TAs give miniature lessons to one another and are provided feedback from other TAs as well as the program facilitator, and case discussions.

Departments often employed a combination of these programs, with the most common program type a being combination of either an Initial or Refresher Program with an Establishment program. The study provides a foundational characterization of GTA-PD programs. I draw on this existing characterization in the development of a model of GTA-PD programs. Additionally, I extend this work by (a) providing in depth case studies of four PD programs specifically related to the teaching of calculus (*Chapter 5*), and (b) relating these programs to components of GTAs' instructor quality (*Chapter 6*).

Features of Successful Professional Development Programs

A professional development program is marked as successful based on a positive change in teachers' knowledge, beliefs, instructional practice, or their students' success (Sowder, 1997). A number of researchers have separately assessed multiple K-12 professional development programs and determined common characteristics of the successful programs (Clarke, 1994; Elmore, 2002; Garet, Porter, Desimone, Birman, & Yoon, 2001; Hawley & Valli, 1999; Kilpatrick, Swafford, & Findell, 2001). These separate reviews pointed to common six characteristics.

Successful K-12 professional development programs:

1. Are sustained over a long period of time;

2. Focus on subject matter, both helping teachers understand the mathematics of specific content domains and students' mathematical thinking in those domains;
3. Provide opportunities for "hands on" learning by modeling the type of instruction expected;
4. Are integrated into daily lives of teachers;
5. Provides teachers with feedback and assessment that they need to grow as teachers; and
6. Have support from other constituents, such as administrators and the school district.

As of today, there is no such list of characteristics of successful GTA-PD programs. After providing an in depth review of GTAs' roles in undergraduate mathematics education, Belnap and Allred (2009) state: "We need research that builds a knowledge base for not just telling us whether a [professional development for graduate students] program had a specific impact, but *why* and *how*" (p. 36, emphasis added). This study will begin answer this call by (1) comparing GTAs to other instructors along various measures of instructor quality, and (2) connecting preparation to teach among graduate students to student success in Calculus 1. An overarching goal of this work is to begin to answer the questions: how do you determine that a graduate student teaching assistant professional development program is successful, and why and how is it successful? While these questions drive the entire body of this dissertation, they are explicitly addressed in *Chapter 7*.

CHAPTER 3: Methodology

Methodological Overview: How to conceive of teacher learning

In order to teach Calculus at the secondary level in California (a state with some of the most stringent requirements), one must at a minimum (1) obtain a Bachelor's Degree from an accredited university, (2) complete a teacher preparation program involving student teaching, and (3) demonstrate subject matter knowledge by completing a waiver program (which includes specific mathematics and capstone courses) or passing all three subtests the California Subject Examinations for Teachers (CSET) or completing specified mathematics content courses. In order to teach Calculus at the post-secondary level, one must at minimum obtain a Bachelor's Degree and be enrolled in a graduate program at the institution, or obtain a Master's Degree or a Doctorate and teach as a professor. In a recent scan of job postings for Assistant Professor positions in Mathematics Departments, the specific requirements of the positions depended on the institution type, but often involved a PhD in mathematics, some demonstration of research experience/ promise (via a resume, publication list, research statement, examples of manuscripts, and/or letters of recommendation), and some demonstration of teaching interest/ concern/ experience (via a teaching statement, letter of recommendation that speaks to teaching, and/or teaching evaluations). The primary difference between the requirements needed to teach at the secondary level versus the post-secondary level is in formal pedagogical training. This difference demonstrates differing assumptions of what experiences are needed in order to teach at the varying levels.

Due to this implicit assumption, often the only form of training an instructor receives is as a Graduate student Teaching Assistant (GTA). (I use the term *instructor* to refer to those teaching at the post-secondary level and the term *teacher* to refer to those teaching at the K-12 level). As such, the training of GTAs is one of few ways to influence the way post-secondary mathematics is taught, and thus the nature and emphases of these training programs are of high significance to the future landscape of post-secondary mathematics. Today there are a number of initiatives focused on improving college mathematics instruction at the national level, such as Project NeXT and the Academy of Inquiry Based Learning. These programs target new faculty with support and professional development aimed at more progressive pedagogy and attention to student thinking. GTA professional development programs have the opportunity to add to these efforts by providing pedagogical training to the next generation of instructors as they work to obtain their degrees.

As part of developing as an instructor and becoming a part of a broader community of college mathematics instructors, one develops specific knowledge, dispositions, and practices shared by that community. Sfard (1998) distinguishes between two metaphors for learning: *acquisition* and *participation*. Those who ascribe to the acquisition metaphor view knowledge as something one possesses and consequently, learning as the attainment of knowledge. Alternatively, those who ascribe to the participation metaphor view knowledge as participating in a community and learning as the act of becoming a more central participant in the community. While these two metaphors may seem in opposition, they are in fact complementary and each metaphor is at play as individuals develop and hone their pedagogical skills and knowledge. For

instance, as GTAs become members of their local communities of calculus instructors, they *acquire* specific skills, knowledge, and beliefs that allow them to *participate* in the practices of their communities, and vice versa. I find the theoretical perspective of situated learning (Lave & Wenger, 1991; Wenger, 1998) especially useful in describing the ways GTA professional development programs are preparing the next generation of university faculty.

Theoretical Perspective: Situated Learning

The theoretical perspective of situated learning accounts for development at both the individual level and the community level. For individuals, learning occurs as one engages in and develops the practices of a community; for communities, progress occurs as practices are developed and refined and new members are enculturated into the community (Wenger, 1998). This shift alters the locus of learning from the individual to the *community of practice*. Lave and Wenger (1991) introduced the term community of practice (CoP) to describe communities with a specific structure and a sustained pursuit of a shared enterprise in which newcomers are increasingly enculturated into the activities that surround the community. As novices become more full participants they are able to engage in the practices of experts in that community. The interactive process in which the novices (also referred to as peripheral participants) develop the practices of experts (or more central participants) is *legitimate peripheral participation*.

The term “legitimate” indicates that the practices novices are involved in must be authentic activities of the community, and be similar to what people in the community actually do. Many have used this perspective to compare the mathematics that students

engage in during school to the practices of real mathematicians, and have identified activities such as conjecturing, arguing, defining, proving, and others as the actual activities of mathematicians that students should be engaging in (Richards, 1991; Rasmussen, Zandieh, King, & Teppo, 2005). The term “peripheral” indicates that the practices novices are involved in are less central versions of the authentic practices, or are central practices with limited responsibility. As one clinical psychology Professor involved in Grossman et al.’s study (2009) said when describing how clinical-psychologists are prepared, ‘If you’re learning to paddle, you wouldn’t practice kayaking down the rapids. You would paddle on a smooth lake to learn your strokes’ (p. 2026).

Individuals tasked with preparing novices to become part of a community of practice must consider the questions: “What are the practices of the community” and “How does one engage novices peripherally in legitimate practices of their community?” Grossman and her colleagues (2009) identified three concepts for understanding the pedagogies of practice in professional education: representations of practice, decompositions of practice, and approximations of practice. *Representations of practice* comprise different ways practice can be represented for novices. In teacher education, one may represent the practices of teaching through written case studies, Videocases, photographs of the classroom, narratives, lesson plans, technological reproductions, among many others. The authors note that “the nature of the representation determines to a large extent the visibility of certain facets of practice” (p. 2066) and thus different representations of the same practices have different affordances for the learner. *Decompositions of practice* break down a complex practice into its multiple parts, which has affordances as well as limitations. By decomposing a practice, it may remove the

practice from the actual context within which it is situated (for an elaboration on this point see Putnam & Borko, 2004) however it also enables the novice to focus on specific aspects of a practice without the complications of the actual context. *Approximations of practice* are activities that allow novices to engage in legitimate practices of a community in a peripheral way, meaning that they are “more or less proximal to the practices of a profession.” These approximations may take the learner directly to the practice, as is done during student-teaching, or bring the practice to the learner through various representations, such as video or role-playing.

Professional development programs provide many examples of representations, decompositions, and approximations of the practices of teaching with varying levels of authenticity. For instance, by watching Videocases, novice teachers are able to “enter” the classroom, observe student behavior and imagine how they would react as the teacher, without the actual responsibility of being in the classroom. This approximation of teaching has a low level of authenticity because real teachers do not have the opportunity to pause or rewind classroom activity in order to decide how to react or how to interpret the situation. Practice teaching is an example of an approximation of teaching with much higher authenticity. During practice teaching, novice teachers have limited responsibility in the classroom, but are able to experience it in real time and in a much more authentic way than by watching a video. Grossman and her colleagues (2009) highlight the benefits of representations, decompositions, and approximations of practice with varying levels of authenticity, which “quiet the background noise so that they can tune in to one facet of practice at a time” (p. 2083). They encourage professional educators to begin with representations, decompositions, and approximations with less

authenticity and move to more authentic practices as novices gain confidence and experience.

As novices participate in the practices of a community (through approximations of practice, representations of practice, and/or decompositions of practice) they do not just develop the skills of the community, but also develop (to varying degrees) a shared knowledge base and shared dispositions. In this dissertation, I view graduate students as novice instructors, and examine the ways they are prepared for their role as instructors.

In *Chapter 4* (in answer to Research Question 1), I provide a snapshot of how graduate student instructors compare to other types of calculus instructors. In this comparison, I attend to their espoused beliefs related to doing, teaching, and learning mathematics in order to understand the degree to which different instructor types have a shared disposition surrounding mathematics education, and to their reported instructional practices to understand the degree to which they participate in similar practices. These analyses explicate the practices of Calculus 1 instructors and compare novice instructors to more expert instructors in their reports of these practices. In *Chapter 4* I also draw on more traditional dimensions of teaching to compare across instructor types, including student success. There has been much discussion of the problems associated with using student success as a measure for comparing instructors, but this a component of instruction that cannot be ignored and that many stake holders are interested in. In *Chapter 5* (in answer to Research Question 2), I develop a characterization of professional development programs, and provide three examples of existing models of programs. In this characterization, I attend to the specific ways the professional development programs facilitate legitimate peripheral participation through

representations, decompositions, and approximations of the practices identified in *Chapter 4*. In *Chapter 6* (in answer to Research Question 3), I investigate the beliefs and practices of graduate students coming from each of the three programs described in *Chapter 5*. In doing so, I explore the relationships between the professional development programs themselves and the graduate students' beliefs and practices, and thus explore the ways in which these programs facilitate their enculturation into the community of Calculus 1 instructors. To achieve these goals, I conduct a mixed method project, including quantitative and qualitative data collection and quantitative and qualitative data analysis. In the following sections I articulate the data collection and analyses associated with answering each of my research questions.

Data Collection

Informed by this theoretical perspective and the literature on professional development, I collected data that allowed me to assess Calculus 1 instructors' beliefs, instructional practices, and student success as well as data that will allow me to identify the ways professional development programs prepare graduate students as calculus instructors or recitation leaders. I draw upon three data sources each coming from a large, multiphase, nationwide study focused on successful calculus programs: Characteristics of Successful Programs in College Calculus (CSPCC).

Phase One: Determining Successful Institutions

The first source of data is the survey data, and is a result of the first phase of the CSPCC study. The first phase was comprised of six surveys: three surveys given to

students (one at the beginning of Calculus 1, one at the end of Calculus 1, and one a year later), two surveys given to instructors (one at the beginning of Calculus 1 and one at the end of Calculus 1), and one survey given to the Calculus course coordinator (see Appendix for surveys). The survey was sent to a stratified random sample of mathematics departments following the selection criteria used by Conference Board of the Mathematical Sciences (CBMS) in their 2005 Study (Lutzer et al., 2007). Recall that, for the purposes of surveying post-secondary mathematics programs in the United States, the CBMS separates colleges and universities into four types, characterized by the highest mathematics degree that is offered: Associate's degree (hereafter referred to as two-year colleges), Bachelor's degree (referred to as undergraduate colleges), Master's degree (referred to as regional universities), and Doctorate (referred to as national universities). Within each type of institution, we further divided the strata by the number of enrolled full-time equivalent undergraduate students, creating from four to eight substrata. We sampled most heavily at the institutions with the largest enrollments. In all, we selected 521 colleges and universities: 18% of the two-year colleges, 13% of the undergraduate colleges, 33% of the regional universities, and 61% of the national universities. Of these, 222 participated: 64 two-year colleges (31% of those asked to participate), 59 undergraduate colleges (44%), 26 regional universities (43%), and 73 national universities (61%). There were 660 instructors and over 14,000 students who responded to at least one of the surveys. I draw exclusively on data coming from the doctoral granting institutions, as it is at these institutions that graduate students play the most significant role in the teaching of Calculus.

The goals of these surveys were to gain an overview of the various calculus programs nationwide, and to determine which institutions had successful Calculus 1 programs. We defined *success* by a combination of student variables: persistence in calculus as marked by stated intention to take Calculus 2; affective changes, including enjoyment of math, confidence in mathematical ability, interest to continue studying math; and passing rates in Calculus 1. These variables are used to discuss student success. I restrict my analyses to students who initially indicate that they intend to take Calculus 2, and use this as an indication that they are STEM intending. The instructor surveys address various components of instructors' demographics, espoused beliefs and instructional practices. I draw on the beginning of term and end of term surveys from students and their instructors, coming from 59 doctoral granting institutions. From these 59 institutions, there are 242 instructors who filled out the beginning-of-term survey, 199 instructors who filled out the end-of-term survey, 1,834 students who filled out the beginning-of-term survey, and 2,826 who filled out the end-of-term survey. See Appendix for these numbers broken down by institution and instructor type.

Phase Two: Case Studies at Successful Institutions

For the second phase of this study, we wanted to learn more about institutions with successful programs, and conducted explanatory case studies to achieve this goal (Yin, 2003). We identified 17 institutions with Calculus 1 programs that were a balance between being unique (in their success) and being ordinary (in their similarity to other institutions), as recommended by Stake (1995). For instance, we excluded a service academy from our site visit selection because of the very specific nature of this institution

although it was exceptionally successful by many of our measures. For my second data source, I draw upon the only four successful sites that employ GTAs in the teaching of calculus, referred to as Institution 1, Institution 2, Institution 3, and Institution 4. We chose these institutions because each rose to the top of our statistical analysis of outcomes variables (change in confidence, enjoyment, and interest; and pass rate), had a large number of students intending to take Calculus 2 at the onset of Calculus 1 (and thus are STEM-intending) and continued to intend to at the end of Calculus 1. In addition, each of the four sites that were chosen at the PhD level are relatable to a large number of other institutions across the country in terms of size, types of students attending, and selectivity.

Reasons for selecting the sites

- Institution 1 was chosen because they had exceptionally positive gains in each variable reported, and have a large number of STEM-intending students and a large number of those students who persisted in their STEM intentions after completing Calculus 1 as well as high response rates from students and instructors.
- Institution 2 was chosen for less straightforward reasons. Institution 2 had lower than average change in confidence, interest in math, and enjoyment in math, but also higher than average number of students enrolled in Calculus 1 that did not intend to take Calculus 2. It therefore is understandable that many of the (non-STEM) students had less positive affect towards Calculus 1. Institution 2 had very high response rate from both students and instructors, is recognized as

implementing innovative practices in the teaching of Calculus as well in their preparation of GTAs. Lastly, students at Institution 2 scored exceptionally high on the Calculus Course Inventory

(http://generated.unlv.edu/cctl/terry_rhodes_unlv.pdf), a measure of conceptual understanding (Epstein, 2006).

- Institution 3 was chosen because the students had a relatively high increased confidence in their mathematical abilities, a high number of students intending to take Calculus 2, a lower than average percent of switchers, high pass rate in Calculus, and high response rate from both students and instructors.
- Institution 4 was chosen because the students had relatively high increased confidence, increased enjoyment in mathematics, high increased interest in mathematics, and high response rates from students and instructors.

At each of these institutions, I collected the following four sources of data:

- *Documentation data* includes handouts to GTAs regarding training, screen captures of websites with information for GTAs, GTA student evaluations, and other records related to the GTAs role in teaching Calculus.
- *Archival records* include past Calculus enrollment history, GTA enrollment history, number of sections offered and taught by GTAs, passing rates and statistical reports from organizations like Analytic studies that details enrollment and student performance in all freshman courses throughout the California State University system (see <http://www.calstate.edu/as/>).
- *Interviews* include semi-structured individual interviews with key personnel (GTAs both teaching Calculus 1 and leading recitation, course coordinator, GTA

trainer, department chairs, learning center staff, tutoring staff, and university administrators) and semi-structured focus group interviews (Cohen, Manion, & Morrison, 2000) with current and past Calculus 1 students taught by GTAs.

- *Direct observation* of Calculus 1 classrooms taught by GTAs and recitations lead by GTAs. I used a protocol developed for the CSPCC project that records instructor and student activities at 5-minute intervals, as well as open ended questions used to describe the nature of the classroom interactions and environment. When possible, multiple observers recorded the same class to provide a minimal level of reliability.

The goals of collecting the above data were to understand (a) how the GTA programs work at these four institutions, including the training (both before the term and ongoing), the roles and responsibilities of the GTAs, and the history of the program, and (b) how these programs may be related to GTAs' instructional practices and mathematical beliefs.

The third data source comes from a survey sent to all first-time GTAs at the four case study sites. This survey addressed their training, their preparation to teach, and their espoused beliefs about doing, learning, and teaching (see Appendix for this survey). This survey builds on questions asked in the instructor surveys that were modeled after Carlson's (1997) Views About Math Survey (VAMS). Additional data was collected when possible. This data includes additional focus group interviews with GTAs during their training, and observation of the training classes, workshops, and lectures. Table 3.2 summarizes how these three data sources were used to answer the research questions.

Data Analysis

The three research questions for this study were designed to support a mixed-method research design, including (as articulated above) the collection of both quantitative and qualitative data, and a combination of quantitative and qualitative analytic methods. In this section I describe the analytic methods employed, broken down by research question.

***Research Question 1:** How do GTAs compare to tenure track/tenured faculty and other full/part time faculty on their (a) mathematical beliefs; (b) instructional practices; and (c) students' success in Calculus 1?*

I answered my first research question by conducting descriptive analyses to provide a snapshot of instruction along three dimensions: (a) mathematical beliefs; (b) instructional practices; and (c) students' success in Calculus 1. Additionally, I compared instructors along a number of dimensions in order to contextualize the other comparisons. These included comparing instructor demographics (age, gender, race/ethnicity), their qualifications (highest degree completed, field of study, and years of teaching experience), information about their class (class size, primary means of instruction, if the text is common or not, and if there is a recitation section or not), and information about their students (incoming SAT scores and high school preparation). For each of these comparisons, I provide the reports from each instructor type: graduate students, tenure track/tenured faculty, and other full/part time faculty. When conducting tests of significance, I compared graduate students to non-graduate students (grouping tenure track/tenured faculty and other full/part time faculty together). I did this because I am

interested in how graduate students compare to other faculty types, but not how the other faculty types compare to one another.

For quantitative variables, I conducted one-way analyses of variance (ANOVA) to determine differences between instructor types (tenure track/tenured faculty, visiting/post docs, and lecturers). Between-groups ANOVA are used when comparing mean scores from continuous variables across two or more groups (Lentner & Bishop, 1993). Many of the variables involved in this study were not presented as continuous but could be treated as though they were. For example, instructors were often asked to what degree they agreed with a statement, where 1 represented 'strongly disagree,' 2 represented 'disagree', 3 represented 'slightly disagree', 4 represented 'slightly agree', 5 represented 'agree', and 6 represented 'strongly agree'. Although a response of 1.5 was not an option, a median score of 1.5 would indicate a response between strongly disagree and disagree.

ANOVA assumes independence between variables, a normally distributed data set, and homogeneity of variance. The large number of student and instructors responses involved in this study allows for the assumption of normally distributed data, by the Central Limit Theorem. Before doing these analyses, I tested for homogeneity of variance across groups and determined that various types of instructors teach the same types of students. This was necessary in order to account for differences between the outcomes of their students – if the various instructors did not start with statistically similar students than it would not make sense to compare the outcomes of their students.

For categorical variables, I conducted Pearson's chi-square tests. Pearson's chi-square test is used to perform hypothesis tests about the distribution of a qualitative (or

categorical) variable, and evaluates how likely it is that any observed differences between groups arose by chance. There are four assumptions for chi-squared tests. First, the sample data must be a random sample from a population where every collection of members has an equal probability of selection. I restrict the comparison of instructor quality to instructors coming from PhD granting institutions. Among this population, institutions were randomly selected to be asked to participate in the study. The second assumption is related to the sample size, which is clearly met in this study. The third assumption is that observations are independent from one another, which is the case in all comparisons. Finally, the expected cell count must be adequate, which some take to mean that “no more than 20% of the expected counts are less than 5 and all individual expected counts are 1 or greater” (Yates, Moore & McCabe, 1999, p. 734). Thus, I only conducted chi-square tests when all cells of a table are non-zero and where at least 80% of the cells have an expected count greater than 5. When this assumption was not met, I provided the values without conducting tests of significance.

Research Question 2: What are the characteristics of GTA programs being implemented by institutions with successful calculus programs?

I answered my second research question by relying on case study data, including interviews, observations, and collected documents. I drew on well-respected qualitative research strategies (e.g, Braun & Clarke, 2006; Miles & Huberman, 1994; Stake, 1995, 2005; Yin, 2003) and employed three specific techniques for analyzing case study data: pattern matching, explanation building, and cross-case syntheses. Pattern matching is one of the most desirable analytic techniques for analyzing case studies (Yin, 2003). Through

pattern matching I develop systematic groupings of data using *inductive thematic analysis*. Thematic analysis is a prevalent form of qualitative analysis that involves “identifying, analyzing and reporting patterns (themes) within data. It minimally organizes and describes your data set in (rich) detail. However, frequently it goes further than this, and interprets various aspects of the research topic” (Braun & Clarke, 2006, p.79). Inductive thematic analysis is a bottom-up approach, where the themes are data-driven, though are not developed in an “epistemological vacuum” (p. 84). Braun and Clarke provide a step-by-step guide for conducting such analysis (Fig. 3.1), that they say should be used flexibly in order to fit the research questions and data.

Phase	Description of the process
1. Familiarizing yourself with your data:	Transcribing data (if necessary), reading and re-reading the data, noting down initial ideas.
2. Generating initial codes:	Coding interesting features of the data in a systematic fashion across the entire data set, collating data relevant to each code.
3. Searching for themes:	Collating codes into potential themes, gathering all data relevant to each potential theme.
4. Reviewing themes:	Checking if the themes work in relation to the coded extracts (Level 1) and the entire data set (Level 2), generating a thematic ‘map’ of the analysis.
5. Defining and naming themes:	Ongoing analysis to refine the specifics of each theme, and the overall story the analysis tells, generating clear definitions and names for each theme.
6. Producing the report:	The final opportunity for analysis. Selection of vivid, compelling extract examples, final analysis of selected extracts, relating back of the analysis to the research question and literature, producing a scholarly report of the analysis.

Figure 3.1 Step-by-step guide for conducting thematic analysis (Braun & Clarke, 2006, p. 87)

This process involves first familiarizing yourself with the data, then generating initial codes (similar to *open coding* from grounded theory), searching for themes (similar to *axial coding* from grounded theory), reviewing these themes, defining and naming these themes, and lastly producing the report. In answering my second research question,

I closely followed this process with one notable exception. I did not exhaustively code my entire data set, which included interviews, observations, and collected data from the four case study institutions. Instead, I grouped relevant chunks of data into themes, which I later named with a guiding question. These themes (or guiding questions) emerged from the data set and were also influenced by the literature. For instance, I attended to the structure of the programs, specifically addressing the dimensions of GTA-PD programs identified previously by Belnap and Allred (2009). Similarly, influenced by literature on Mathematical Knowledge for Teaching, I attended to the types of knowledge that was emphasized through the graduate student professional development programs. For each theme, I used multiple components from each data set to complement and triangulate the information obtained through the interviews, specifically to fact check information and to add details when needed.

In conducting this thematic analysis, I also employed two analytic techniques used when multiple cases are involved in the analysis, referred to as explanation building and cross-case synthesis. The goal of explanation building within multiple case studies is to “build a general explanation that fits each individual case, even though the individual cases will vary in their details” (Yin, 2003, p. 142). In general, explanation building results from a series of iterations of making an initial theoretical statement, comparing the findings of an initial case against the statement, revising the statement, comparing other details of the case against the revision, comparing the revision to more cases, and repeating this process as many times as needed (Yin, 2003). In relation to the process of thematic analysis identified by Braun and Clarke, explanation building occurs during step 4 as a specific way to check if the themes work in relation to individual cases and the

entire data set. In my characterization of graduate student professional development programs, I discuss how each case varied in their answers to the guiding questions. I also discuss other potential variations across each guiding question, and in doing so synthesize the findings from each individual case. This process is what Yin (2003) refers to as *cross-case synthesis*, and occurs during steps 4 and 5 of the inductive thematic analysis.

The final stage of thematic analysis entails the “selection of vivid, compelling extract examples, final analysis of selected extracts, relating back of the analysis to the research question and literature, producing a scholarly report of the analysis” (Braun & Clarke, 2006, p. 87). To accomplish these goals, I developed thick descriptions (Ponterotto, 2006) of each of the four cases. Thick descriptions are used in qualitative research to describe events or interactions in context, and “accurately describe observed social actions and assign purpose and intentionality to these actions, by way of the researcher’s understanding and clear description of the context under which the social actions took place” (Ponterotto, 2006, p. 540). Thus, the results of this research question entail thick descriptions of each case, as well as the overarching characterization of GTA professional development programs, itself comprised of four guiding questions.

In order to establish construct validity and reliability of case study analysis, I (1) used multiple sources of evidence, (2) created a case study database, and (3) maintained a chain of evidence (Yin, 2003). By drawing on *multiple sources of evidence*, I allowed for the development of what Yin terms *converging lines of inquiry*, in which any of my findings are based on the convergence of information from numerous data sources, both qualitative and quantitative. Thus, these findings are likely to be more convincing and accurate because these findings are derived from documents, archival records, open-

ended interviews, focus group interviews with students, surveys, and observations. I also collected multiple sources of data into one database, along with case study notes and narratives. The case study notes were the result of interviews, observations, or document analysis and were collected immediately following the case study and/or during the review process. The narratives were composed of answers to the open-ended questions that I asked myself as I reviewed the data, and were a step in the direction of analysis. Finally, by maintaining a chain of evidence I allow an external observer the ability to follow the derivation of any evidence from initial research questions to the case study analysis and resulting conclusions.

Research Questions 3: *What are the (a) mathematical beliefs and (b) instructional practices of GTAs coming from these programs, and in what ways are the beliefs and practices related to GTAs' experiences in the professional development programs?*

To answer my third research question, I employed mixed method analytic techniques (Creswell & Plano Clark, 2010). Specifically, to answer this research question I simultaneously analyzed the quantitative data from the CSPCC instructor and student surveys, the quantitative data from the GTA follow-up surveys, and the case-study data from each of the four selected institutions. Table 3.1 provides an overview of what data source was available from each of the four selected institutions. Graduate students from Institution 3 and Institution 4 were most often employed as recitation leaders, rather than course instructors, and during the CSPCC surveys there were no graduate students who filled out the instructor survey.

Table 3.1 Overview of data sources used for research question 3

	CSPCC surveys		Follow up GTA survey	Case study data
	Start-of-term	End-of-term		
Institution 1	3	1 (22 students)	2	2
Institution 2	23	18 (145 students)	21	10
Institution 3	0	0	33	2
Institution 4	0	0	9	6

I specifically employ a *convergent parallel design* (Creswell & Plano Clark, 2010), which entails the concurrent analyses of quantitative and qualitative data, prioritizes the methods equally, keeps the quantitative and qualitative strands separate during analyses and then mixes the results together during the interpretation of the separate analyses. For the individual analyses, I employed the quantitative or qualitative methods used in answering research questions one and two, respectively.

Overview of Data Collection and Analysis

In this study, I employed a multiphase mixed-method design that involved multiple stages of both quantitative and qualitative data collection and analysis. In Figure 3.2, I provide a diagram that shows how the quantitative and qualitative data collection and analyses are related to each other, and to the research questions. In Table 3.2, I provide a comprehensive overview of the specific data collected for each research question and the analyses conducted to answer each question.

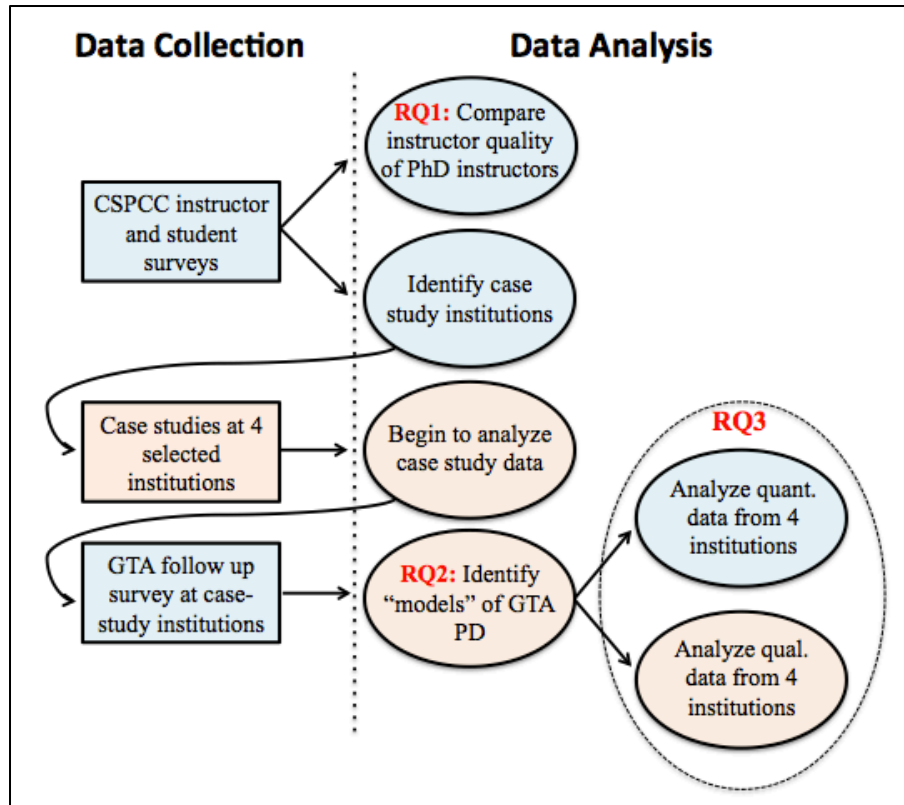


Figure 3.2 Data collection and analysis diagram

Table 3.2 Summary of data sources and anticipated analysis by research question

Research Questions		Data Sources	Data Analysis
1. How do GTAs compare to tenure track/tenured faculty, and other full/part time faculty on their:	(a) mathematical beliefs?	Survey data from instructor surveys	<i>Quantitative analyses:</i> ANOVA for numerical data chi-squared for categorical data
	(b) instructional practices?	Survey data from instructor and student surveys	
	(c) students' success in Calculus 1?	Survey data from student surveys	
2. What are the characteristics of GTA programs being implemented by institutions with successful calculus programs?		Interviews with GTAs, and GTA trainer Observations of teaching Student focus group interviews Observations of GTA training GTA focus group interviews Documents, and archival records from institutions	<i>Qualitative analyses:</i> Case study analysis and thematic analyses
3. What are the (a) mathematical beliefs and (b) instructional practices of GTAs coming from these programs, and in what ways are the beliefs and practices related to GTAs' experiences in the professional development programs?	(a) mathematical beliefs?	Survey data from instructor surveys Interviews with GTAs GTA focus group interviews GTA survey on beliefs and training	<i>Mixed-method analyses:</i> convergent, parallel analysis
	(b) instructional practices?	Survey data from instructor surveys Interviews with GTAs and supervisors Observations of teaching GTA focus group interviews GTA survey on beliefs and training	

CHAPTER 4: Instructor Quality Comparison Across Instructor Types

In this chapter, I compare graduate students to other Calculus 1 instructor types across a number of aspects of instruction, drawing from the instructor quality framework articulated in *Chapter 2*. Instructor quality involves *inputs* of instructor qualifications and instructor characteristics, *processes* of instructional practices, and the *outcome* of student success. In this comparison, I take a static look at how graduate students relate to other members of the community of Calculus 1 instructors, and in doing so identify the practices of novice and more expert Calculus 1 instructors. I attend to instructors' espoused beliefs related to doing, teaching, and learning mathematics in order to understand the degree to which different instructor types have a shared disposition surrounding mathematics education, and to understand what this disposition is. Similarly, I attend to instructors' reported instructional practices to understand the degree to which they participate in similar practices as other members of this community, and to understand what these practices are. In this comparison I also compare the success of students coming from each instructor type. Although this has been identified as a problematic measure for comparing teachers to one another, this is a component of instruction that cannot be ignored and is one that many stake holders are interested in. It thus serves as one important, though potentially controversial, way to compare various members of the community of Calculus 1 instructors.

Instructor Qualifications

To compare instructor qualifications across instructor types, I first conducted chi-square analyses on highest degree completed and field of study of highest degree completed. I then conducted an ANOVA on the number of times each instructor previously taught Calculus 1 by instructor type as a measure of teaching experience. Table 4.1 reveals differences in the highest degree completed among the three instructor types, in the field of study of the highest degree completed, and in the number of times each instructor type taught Calculus 1.

Table 4.1 Comparison of Instructor Qualifications

		Tenured/ Tenure-track	Other full/ part- time	GTAs
Highest degree completed				
	<i>Bachelors</i>	0	4 (3.9%)	32 (43.8%)
	<i>Masters</i>	1 (1.5%)	34 (33.0%)	39 (53.4%)
	<i>EdD</i>	0	1 (1.0%)	0
	<i>PhD</i>	67 (98.5%)	64 (62.1%)	2 (2.7%)
Field of study of degree completed				
	<i>Mathematics</i>	59 (86.8%)	76 (73.1%)	62 (84.9%)
	<i>Applied Mathematics</i>	4 (5.9%)	10 (9.6%)	6 (8.2%)
	<i>Statistics</i>	0	3 (2.9%)	2 (2.7%)
	<i>Mathematics Education</i>	1 (1.5%)	8 (7.7%)	0
	<i>Other</i>	4 (5.9%)	7 (6.7%)	3 (4.1%)
Terms taught Calculus 1				
	<i>Mean</i>	4.29	4.47	2.22
	<i>Std. Deviation</i>	2.80	3.37	1.40
	<i>n</i>	68	107	74

These results agreed with expectations because most tenured and tenure-track faculty hold PhDs, other full and part-time faculty are split between holding Masters and holding PhDs, and that GTAs are split between holding Bachelors and Masters. Mathematics was the most common field of study for the highest degree completed across all instructor types. For tenured and tenure-track faculty and other full and part-

time faculty, this is likely their final degree. In contrast, GTAs are in the process of obtaining an additional degree. On the beginning-of-term instructor survey we did not ask GTAs to identify their current field of study on the main instructor survey. This question was part of the follow up GTA survey administered only to GTAs from the five selected PhD granting institutions. Among the 76 GTAs who filled out the follow up GTA survey, 59.2 percent were working on obtaining a PhD in mathematics, 23.7% were working on obtaining a Masters in mathematics, 3.9% were working on obtaining a Masters in mathematics education, and the remaining were working on a degree outside of these options (with no students working on a PhD in mathematics education). Tenured and tenure-track faculty had taught Calculus 1 an average of 4.29 times, other full and part-time faculty taught Calculus 1 an average of 4.47 times, and GTAs –unsurprisingly- had the least experience, having taught Calculus 1 an average of 2.22 times. There was a high amount of variation among instructors within each instructor type category, with standard deviations of 2.80, 3.37, and 1.40 respectively for the three instructor types.

These results indicate that graduate students have different qualifications to teach than other instructor types, at least along the dimensions considered here. These results also support the distinction that graduate students are “novice” Calculus 1 instructors, compared to tenured/tenure-track and other full/part time faculty as more “expert” members of this community. In the remaining comparisons, I consider the ways the novices relate to the more expert members of this community, with respect to their demographics, beliefs, instructional practices, and student success.

Instructor Characteristics

In this section I compare two components of instructor characteristics, instructor demographics as well as mathematical beliefs. These are characteristics of instructors that are difficult to change, whereas obtaining an additional degree or gaining more Calculus 1 experience are easier to change.

Instructor Demographics

Table 4.2 shows that, as would be expected when comparing demographics among various instructor types, there were differences in age but not in gender. Across all instructor types, the majority of instructors were male: 80% of tenure-track and tenured faculty, 63.5% of other full and part-time faculty, and 73% of GTAs were male. Research has indicated an interesting –though not straightforward– relationship between instructor gender and student success. Some research indicates that females taught by a female instructor are less likely to persist in their STEM studies than those taught by a male instructor (Hoffman & Oreopoulos, 2007; Price, 2010). However, Seymour and Hewitt (1997) found that a leading reason females choose not to pursue degrees in STEM fields is the lack of other women in these fields, making it difficult to envision oneself succeeding in these fields. Since there are a similar percentage of female instructors across all instructor types, the relationship between instructor type and student success (investigated at the end of this chapter) cannot be attributed to a difference in instructor gender. There is, however, a significant difference in age among instructor types: the average age of GTAs was 27, while the average age of other full and part-time faculty was around 40 and of tenure-tenure track faculty around 50. Finally, there were slight

differences in instructor race/ ethnicity, though overwhelmingly instructors across all types are white/ Caucasian: 86.4% of tenure-track and tenured faculty, 76% of other full and part-time faculty, and 73% of GTAs identified as white/Caucasian, while around 70% of GTAs did so. This comparison indicates that the demographics of the more novice members of this community (graduate students) are similar to the more expert members (non-graduate students).

Table 4.2 Comparison of Instructor Characteristics – Demographics

		Tenured/ Tenure-track	Other full/part-time	GTAs
Gender	<i>Male</i>	55(80.9%)	66 (63.5%)	54 (73.0%)
	<i>Female</i>	13 (19.1%)	38 (36.5%)	20 (27.0%)
Age	<i>Mean</i>	49.98	40.95	26.88
	<i>Std. Deviation</i>	13.91	13.05	3.87
	<i>n</i>	66	103	73
Race/Ethnicity	<i>American Indian or Alaskan Native</i>	2 (3.0%)	1 (1.0%)	0
	<i>Asian</i>	6 (9.1%)	18 (17.3%)	14 (18.9%)
	<i>Black or African American</i>	0	1 (1.0%)	5 (6.8%)
	<i>Native Hawaiian or Pacific Islander</i>	0	0	0
	<i>White/Caucasian</i>	57 (86.4%)	79 (76.0%)	54 (73%)
	<i>Hispanic or Latino/a</i>	2 (3.1%)	4 (3.9%)	2 (2.7%)
	<i>Other</i>	1 (1.5%)	4 (4.85)	1 (1.4%)

Instructor Beliefs

A major component of Instructor Characteristics are instructors' beliefs, dispositions, and attitudes. In this section, I do not differentiate between what constitutes a disposition, attitude, or belief, and instead consider these together in examining instructors' mathematical beliefs. There are 14 questions on the beginning-of-term survey and 6 questions on the Instructor end-of-term survey that address mathematical beliefs, including beliefs related to teaching, learning, and doing mathematics (see Appendix for

a list of the questions). In order to understand different types of instructors' beliefs about mathematics, I grouped items into four content similar categories. Before I was able to aggregate the variables together in the groups, I put all variables on a 0 to 1 scale. I converted using the function $(n-1)/3$ for the items on the 4 point scale, and the function $(n-1)/5$ for the items on the 6 point scale. Additionally, questions were reverse coded if they were worded in a way to indicate this would make more sense. By reverse coded, I mean responses closer to 0 align more strongly with "folk" views of mathematics (i.e. "only some people are capable of doing mathematics", "there is only one correct solution for mathematics problems", etc.), while responses closer to 1 align more strongly with an "expert" view of mathematics (Carlson, 1997).

After putting the grouped variables onto the same scales and ordering them, I aggregated the variables within each of the four groups by taking the average of responses to the individual variables. When a group had both beginning and end-of-term variables, separate aggregate variables were created. This was the case for three of the four groups, resulting in a total of seven new aggregate variables. The new aggregate variables remained on a 0 to 1 scale, which preserves interpretability.

The four groups are labeled as: (1) beliefs about student capabilities, which has beginning and end-of-term variables; (2) interest in teaching and student learning, which has beginning and end-of-term variables; (3) perceived value of reflection on teaching and learning; and (4) beliefs about teaching and learning; which has beginning and end-of-term variables.

In the following sections, I identify the variables that comprise each new aggregate variable and note what a 0 and 1 represent. I then provide a summary table of

the new aggregate variables and note what 0 and 1 represent when taken together. The first aggregate variable identified is “Beliefs about student capabilities” and has a beginning and end-of-term component and is comprised of six variables. These six variables point to the respondents’ perception of the preparation of their students, either at the beginning and at the end of the Calculus 1 term, as shown in Figure 4.1. A value closer to 1 on the aggregate variable indicates that the instructor thinks their students are capable and prepared, while a value closer to 0 indicates the perception that the students are not capable or prepared.

Beginning-of-term: Beliefs about student capabilities.
Estimate the percentage of students currently enrolled in your Calculus 1 course that will pass with a C or above. <i>(0=no students; 1=all students)</i>
Estimate the percentage of students currently enrolled in your Calculus 1 course that will get a D or F. <i>(0=no students; 1=all students)</i>
Estimate the percentage of students currently enrolled in your Calculus 1 course that will withdraw. <i>(0=no students; 1=all students)</i>
Approximately what percentage of students currently enrolled in your Calculus 1 course do you expect are academically prepared for the course? <i>(0=no students; 1=all students)</i>
End-of-term: Beliefs about student capabilities.
Approximately what percentage of your students were prepared for the course? <i>(0=no students; 1=all students)</i>
Indicate the extent to which you agree or disagree with the following statement: All students in beginning calculus are capable of understanding the ideas of calculus. <i>(0=strongly disagree; 1=strongly agree)</i>

Figure 4.1 Beliefs about student capabilities

The next set of questions (Figure 4.2) target an instructors’ disposition toward improving their own teaching and interest in student thinking. Are they interested in improving their teaching? How does familiarity with student thinking relate to improving ones’ teaching? A value near 1 on the aggregate variable indicates that the instructor is interested in improving his/her own teaching and that student thinking is helpful for this,

while a value near 0 indicates the instructor is not interested in improving his/her teaching.

Beginning-of-term: Interest in teaching and student learning.
How strong is your interest in: participating in activities that raise your awareness of how students learn key ideas in calculus? (<i>0=not at all; 1=very strong</i>)
How strong is your interest in: teaching Calculus 1? (<i>0=not at all; 1=very strong</i>)
How strong is your interest in: participating in activities that improving your own teaching? (<i>0=not at all; 1=very strong</i>)
End-of-term: Interest in teaching and student learning.
Indicate the extent to which you agree or disagree with the following statement: If I had a choice, I would continue to teach calculus. (<i>0=strongly disagree; 1=strongly agree</i>)
Indicate the extent to which you agree or disagree with the following statement: Familiarity with the research literature on how students think about ideas in calculus would be useful for teaching. (<i>0=strongly disagree; 1=strongly agree</i>)

Figure 4.2 Interest in teaching and student learning

Figure 4.3 shows the three variables that make up the “Perceived value of reflection on teaching and learning” component ask the instructor to indicate how strongly the scholarship of teaching and learning is valued by their department, their institution, and their colleagues. The Scholarship of Teaching and Learning (SoTL) is a multi-disciplinary movement in post-secondary education that promotes academic inquiry into teaching and learning. This movement has increased research into improving post-secondary teaching, developing reflective practitioners, and student thinking at the tertiary level (Hutchings, 2000; Shulman, 1999). Together, these three components clearly point to the perceived value of the scholarship of teaching and learning, and more broadly the practice of reflecting on one’s teaching. A higher value on the aggregate variable indicates that the instructor thinks their institution, department, or colleagues value the scholarship of teaching and learning, while a lower value indicates the

perception that is not valued. There exist a number of SoTL centers on campuses with similar goals, targeting all instructor types:

- “to support the development of a scholarship of teaching and learning that: fosters significant, long-lasting learning for all students; enhances the practice and profession of teaching, and; brings to faculty members' work as teachers the recognition and reward afforded to other forms of scholarly work.”
(<http://www.carnegiefoundation.org/scholarship-teaching-learning>)
- “to help graduate students cultivate a scholarly, evidence-based approach to their students' learning and their own teaching. The scholarship of teaching and learning (SoTL) is a way of treating teaching as a scholarly activity by posing questions about student learning and its relationship to the ways in which they are taught.” (<http://cft.vanderbilt.edu/programs/sotl-scholars-program/>)
- “advances scholarly and innovative approaches to teaching, learning, curriculum and educational technology practices within and across UBC's diverse disciplinary and cultural contexts.” (<http://ctl.ubc.ca/about/vision-mission-and-values/>)

The existence of such centers increased the likelihood that instructors would respond that their institution, department, or colleagues value the scholarship of teaching and learning. Similarly, it is possible for institutions (or departments or individuals) without such centers to support SoTL or the systematic reflection on teaching and learning.

End-of-term: Perceived value of reflection on teaching and learning.
From your perspective, how strongly does your Department encourage and support the scholarship of teaching and learning? (<i>0=not at all; 1=very strong</i>)
From your perspective, how strongly does your Institution encourage and support the scholarship of teaching and learning (defined as systematic reflection on teaching and learning)? (<i>0=not at all; 1=very strong</i>)
From your perspective, how valued by your colleagues is the scholarship of teaching and learning? (<i>0=not valued; 1=very valued</i>)

Figure 4.3 Perceived value of reflection on teaching and learning

Together, the six items on the “Beliefs about teaching and learning” component indicate an instructor’s beliefs about what it means to know mathematics and how students learn mathematics, as shown in Figure 4.4. A higher value on the aggregate variable indicates that the instructor held a more traditional view of learning mathematics, or what Carlson (1997) called a folk view of mathematics, while a lower value indicates the perception that instructor holds a more progressive view, or what Carlson (1997) called an expert view of mathematics.

Beginning-of-term: Beliefs about teaching and learning.
*From your perspective, in solving Calculus 1 problems, graphing calculators or computers help students: (<i>1=understand underlying mathematical ideas; 0=find answers to problems</i>)
From your perspective, student's success in Calculus 1 PRIMARILY relies on their ability to: (<i>0=solve specific kinds of problems; 1=make connections and form logical arguments</i>)
*From your perspective, when students make unsuccessful attempts when solving a Calculus 1 problem, it is: (<i>1=a natural part of solving the problem; 0=an indication of their weaknesses in mathematics</i>)
My primary role as a calculus instructor is to: (<i>0=work problems so students know how to do them; 1= help students learn to reason through problems on their own.</i>)
End-of-term: Beliefs about teaching and learning.
*Indicate the extent to which you agree or disagree with the following statement: Calculus students learn best from lectures, provided they are clear and well-organized. (<i>0=strongly agree; 1=strongly disagree</i>)
*Indicate the extent to which you agree or disagree with the following statement: Understanding ideas in calculus typically comes after achieving procedural fluency. (<i>0=strongly agree; 1=strongly disagree</i>)
Note. * = These items have been reverse coded.

Figure 4.4 Beliefs about teaching and learning

Figure 4.5 summarizes these aggregate variables that target important components of instructors' beliefs about doing, teaching, and learning mathematics. In this section, I compare instructors' beliefs on the aggregate beliefs variables across instructor types. In following sections, I connect these beliefs to instructor practices and student success.

Variable	Survey	0	1
Beliefs about student capabilities	Beginning-of-term	students are not capable or prepared	students are capable and prepared
	End-of-term	students were not capable or prepared	students were capable and prepared
Interest in teaching and student learning	Beginning-of-term	not interested in improving his/her teaching or in student thinking and that knowledge of student thinking is not helpful for improving teaching.	interested in improving his/her teaching or in student thinking and that knowledge of student thinking is helpful for improving teaching.
	End-of-term	not interested in improving his/her teaching or in student thinking and that knowledge of student thinking is not helpful for improving teaching.	interested in improving his/her teaching or in student thinking and that knowledge of student thinking is helpful for improving teaching.
Perceived value of reflection on teaching and learning	Beginning-of-term	instructor thinking their institution, department, or colleagues does not value the scholarship of teaching and learning	instructor thinking their institution, department, or colleagues value the scholarship of teaching and learning
Beliefs about teaching and learning	Beginning-of-term	Traditional/ folk views of teaching and learning	Progressive/ expert views of teaching and learning
	End-of-term	Traditional/ folk views of teaching and learning	Progressive/ expert views of teaching and learning

Figure 4.5 Summary of aggregate beliefs variables

Table 4.3 shows the differences in scores for these aggregate variables between the different types of faculty overall. In order to discuss the strength of these differences, I compare GTAs to “non-GTAs”, which includes both tenure/ tenure-track faculty and other full and part-time faculty. This data shows results comparing not just GTAs to non-GTAs, but also how other full and part-time faculty compare to tenured and tenure-track faculty. While these comparisons are interesting, they are not the focus of this study. I focus only on the differences between GTA’s and non-GTAs. There were statistically significant differences between GTA reports and non-GTAs on only “beliefs about student capabilities”, both beginning and end-of-term, though the differences were

smaller for the end-of-term means. For all other beliefs variables there were no statistically significant differences between GTAs' mean responses and non-GTAs'.

Table 4.3 Comparison of Instructor Characteristics – Beliefs

		Tenured/ Tenure-track	Other full/ part-time	GTA s
<i>Beginning-of-term</i> : Beliefs about student capabilities**	Mean	.793	.802	.833
	Std. Dev.	.084	.099	.071
<i>End-of-term</i> : Beliefs about student capabilities*	Mean	.617	.596	.659
	Std. Dev.	.193	.213	.161
<i>Beginning-of-term</i> : Interest in teaching and student learning	Mean	.715	.785	.727
	Std. Dev.	.211	.179	.238
<i>End-of-term</i> : Interest in teaching and student learning	Mean	.704	.724	.706
	Std. Dev.	.184	.174	.187
<i>Beginning-of-term</i> : Perceived value of reflection on teaching and learning	Mean	.563	.633	.651
	Std. Dev.	.288	.271	.227
<i>Beginning-of-term</i> : Beliefs about teaching and learning	Mean	.616	.618	.607
	Std. Dev.	.145	.152	.175
<i>End-of-term</i> : Beliefs about teaching and learning	Mean	.441	.428	.429
	Std. Dev.	.205	.172	.182

Note. * = $p \leq .10$, ** = $p \leq .05$, *** = $p \leq .001$; $n^2 = 56$ (Tenured/ tenure-track faculty), $n = 84$ (Other full/ part-time faculty), $n = 55$ (GTAs).

The mean “beliefs about student capabilities” response from GTAs was significantly higher than non-GTAs, at the beginning-of-term [$F(1, 237) = 7.668, p = .006$] and end-of-term [$F(1, 196) = 3.128, p = .078$]. These results mean that GTAs think their students are more capable than other types of faculty both at the beginning and the end of the term. In contrast, all instructor types decreased on this measure. This indicates

² When n (the sample population) is provided for a table, rather than for individual tests, I report the minimum n for any of the individual tests.

that over the course of Calculus 1, instructors of all rank lose confidence in their students' capabilities.

One explanation for this result may be a difference in teaching experience. Instructors with more experience may have more realistic, or perhaps more pessimistic, views of what students are capable of. This result contrasts what other researchers have found about GTA's beliefs about their students. For instance, in a study targeting GTAs' beliefs about the nature of mathematics and who can learn it, Gutmann (2009) found that GTAs tend to believe that only some students are capable of learning mathematics past precalculus. These findings add nuance to Gutmann's finding: while GTAs may not believe that every student is capable of learning calculus, they do so more frequently than other types of instructors.

For all other belief items, GTAs were not statistically different than non-GTAs, yet this was not surprising. For instance, one may conjecture that GTAs would be less interested in teaching and student thinking than other instructor types since they are often focused on courses and their research, instead of their role as instructors. GTAs are learning how to balance the competing demands of being students themselves and conducting research with teaching. As a group they do not express being less interested in teaching and student thinking than non-GTAs even though they have competing demands (e.g. completing their course work, conducting graduate research), and thus they prioritize teaching similarly to other instructor types.

Additionally, they expressed similar interest in student thinking as other instructor types even though they have different levels of teaching experience. Research into the knowledge needed for teaching indicates that Knowledge of Content and Students (KCS)

is especially critical (Ball, et al., 2008; Wagner et al., 2007). This element of knowledge comprises knowing how students may understand specific content, various solutions they may arrive at, struggles they have with the material, what examples students find interesting and understandable, and generally an interest in understanding student thinking. Teachers may gain this knowledge from reflecting on their teaching experiences, reading mathematics education research into student thinking, or from professional development programs that focus on student thinking (Ball, et al., 2008). Because GTAs often come into their roles as instructors with little experience on which to reflect and little (or no) knowledge of mathematics education literature, it seems natural that they express less interest in student thinking. Consistent with this hypothesis Speer, Strickland, and Johnson (2005) found that experienced graduate students often lack extensive knowledge of student learning of key ideas and have not developed strategies to support student learning of these topics, however it is possible for GTAs to develop rich knowledge of their students' mathematical understandings through professional development programs (Kung, 2005). The results from this study show that GTAs are equally interested in student thinking as non-GTAs, though it says nothing of their actual knowledge of student thinking.

These results indicate that graduate students express beliefs similar to the community of Calculus 1 instructors, a community that they are becoming a part of, though with a more inexperienced or novice perspective. Specifically, they view their students as more capable, both at the beginning and the end of the term, which is likely due to being less familiar with how typical Calculus 1 students do in class. However, graduate students express similar beliefs regarding their interest in teaching and student

thinking, the perceived value of reflection on teaching in their departments, and their beliefs about the teaching and learning of mathematics. One way to characterize a community are by their espoused beliefs (Wenger, 1998). Thus, these results indicate that graduate students are, overall, aligned with the community of Calculus 1 instructors with respect to these espoused beliefs.

Instructional Practices

The previous sections have shown that graduate students are similar in demographics to other Calculus 1 instructors, are more novice in this community as indicated by experience and academic qualifications (and as expected), and share similar, but slightly more optimistic, beliefs to other faculty. In this section I compare their actual practices and consider how these are or are not related to the other dimensions already examined. Specifically, I compare three components of instructional practices across instructor types: frequency of certain pedagogical activities, reported classroom discourse, and the nature of the tasks in which the students engage. There are a number of survey questions from the student end-of-term survey and the instructor end-of-term survey that address each of these three components. I use instructor reports when discussing aspects of instruction that do not vary from student to student. For instance, the amount of time students spend working in groups during class should not vary much within a class. In a separate analyses of a similar data set, Ellis, Kelton and Rasmussen (2014) found that the average student report on such items was not statistically different than the instructor report. I use student reports for items that should vary by student. These include items addressing the classroom discourse from the students' perspective,

including if: the instructor listened to their questions during class, he/she responded to questions by simply giving the answer, helped the student determine answers, and/or allowed enough class-time for students to understand difficult ideas.

Class Structure

Before comparing instructors across these various instructional practices, I examined the structure of their classes. I then conducted ANOVA and chi-square analyses for items that have non-zero data cells. Table 4.4 shows that the overwhelming majority of all instructors used a book chosen by the department, and teach in a face-to-face format. About 20% of GTAs taught a class that had a recitation taught by a TA, about 30% of other full and part-time faculty had a recitation section and almost 50% of tenure/ tenure-track faculty did [χ^2 (df = 2, n = 244) = 13.427, p = .001]. The average class size across all instructor types was between 37 and 71, though the high standard deviations show the class size varied within each instructor type. Classes taught by a GTA were significantly smaller than classes taught by a non-GTA [$F(2, 209) = 7.451, p$ = .007].

Table 4.4 Comparison of Instructional Practices– Classroom Structure

	Tenured/ Tenure- track	Other full/ part-time	GTAs
Instructor Reports			
<i>Beginning-of-term: The Calculus 1 textbook you use is:</i>			
A common textbook selected by the department.	66 (97.1%)	107 (100%)	72 (97.3%)
A textbook I chose from an approved list.	0	0	0
A textbook of my own choosing.	2 (2.9%)	0	0
<i>Beginning-of-term: What will be the primary means of instructor students?</i>			
face-to-face classroom	65 (95.6%)	105 (98.1%)	71 (95.9%)
online via distance learning	0	1 (0.9%)	0
hybrid between face-to-face and online distance learning	3 (4.4%)	1 (0.9%)	3 (4.1%)
<i>Beginning-of-term: Does your Calculus 1 course have recitation sections taught by teaching assistants? (Yes)</i>	33 (49.3%)	33 (32.0%)	15 (20.3%)
<i>End-of-term: At the end of the term, how many students were enrolled in each Calculus class that you taught?</i>			
Mean	71.77	51.76	37.47
Std. Dev.	77.49	47.23	54.47
n	61	87	62

Note. * = $p \leq .10$, ** = $p \leq .05$, *** = $p \leq .001$.

Frequency of Certain Pedagogical Activities

The previous analysis shows that GTAs teach smaller classes and have recitations less frequently than non-GTAs. In this section, I consider differences between the reported frequency of certain pedagogical activities: showing students how to solve specific problems, lecture, having students work individually on problems or tasks, having students work with one another, and having students give presentations. Additionally, instructors reported how frequently various technologies were used during class. Students responded to a similar set of questions and the average student response within a class was not significantly different than the instructor's report (Ellis, Kelton, & Rasmussen, 2013).

Table 4.5 shows a number of commonalities in the reported frequency of various pedagogical activities between instructor types, although there are also a number of stark differences. GTAs and non-GTAs showed their students how to work specific problems [$F(1, 208) = .001, p = .977$] and lectured with relatively high frequency [$F(1, 208) = 1.715, p = .192$] (on average near 5 for all instructor types, where 6 indicates that this occurred very often). All instructor types also reported having their students work individually on problems or tasks with medium frequency [$F(1, 207) = .399, p = .529$]. In addition to these similar instructional practices, GTAs had their students work together significantly more frequently than non-GTAs. Specifically, tenure-track and tenured faculty reported that their students worked together at the lowest frequency, an average of 2.22 compared to 3.15 among students taught by other full and part-time faculty and 3.55 among students taught by GTAs [$F(1, 208) = 8.148, p = .005$]. Similarly, GTAs had their students give presentations more frequently than non-GTAs, though this is still was reported infrequently across the board [$F(1, 206) = 3.248, p = .073$]. These results indicate that GTA instruction is more interactive than non-GTA instruction³. However, this did not occur at the expense of more direct instruction such as lecture.

³ This may be due to the differences in class size between GTAs and non-GTAs, rather than a difference in their views on teaching since I found no significant differences on their beliefs about teaching and/or student learning. This may also be partially attributable to a large number of graduate students from one institution that report similar and innovative instructional practices. In *Chapter 6*, I investigate the specific instructional practices of graduate students from that institution (identified as ‘Institution 2’.)

Table 4.5 Comparison of Instructional Practices– Frequency of certain pedagogical activities

		Tenured/ Tenure-track	Other full/ part-time	GTAs
Instructor Reports				
<i>End-of-term: During class time, how frequently did you: (1) not at all; (6) very often</i>				
Show how to work specific problems.	Mean	5.03	5.24	5.16
	Std. Dev.	1.21	1.11	1.08
Lecture.	Mean	5.32	5.10	5.42
	Std. Dev.	1.23	1.35	0.69
Have students work individually on problems or tasks.	Mean	2.32	3.21	3.00
	Std. Dev.	1.46	1.57	1.73
Have students work with one another.**	Mean	2.22	3.15	3.55
	Std. Dev.	1.57	1.80	1.90
Have students give presentations.*	Mean	1.35	1.78	1.94
	Std. Dev.	1.02	1.29	1.29
<i>End-of-term: How frequently were the following technologies used during class? (1) Never; (5) Every class session</i>				
Instructor demonstration with a graphing calculator.	Mean	1.31	1.42	1.45
	Std. Dev.	.654	.698	.533
Student use of a graphing calculator.***	Mean	1.46	1.98	2.46
	Std. Dev.	.734	1.217	1.311
Instructor demonstration with computer algebra system (e.g., Maple, Mathematica, MATLAB).	Mean	1.40	1.20	1.21
	Std. Dev.	.620	.402	.449
Student use of a computer algebra system (e.g., Maple, Mathematica, MATLAB).	Mean	1.04	1.17	1.11
	Std. Dev.	.187	.519	.367

Note. * = $p \leq .10$, ** = $p \leq .05$, *** = $p \leq .001$; n = 56 (Tenured/ tenure-track faculty), n = 81 (Other full/ part-time faculty), n = 61 (GTAs).

These analyses also reveal information regarding technology use among the three instructor types. In general, all instructors reported rarely using technology, both by instructors (demonstrating with technology) or used by students in class. However, GTAs had their students' use graphing calculators significantly more frequently than non-GTAs [$F(1, 199) = 15.521, p \leq .001$].

Classroom Discourse

The previous analyses showed that GTAs reported having their students work together, give presentations, and use a graphing calculator more frequently than non-GTAs. In this section, I examine various components of reported classroom discourse. I rely on instructor reports for aspects of classroom discourse that should not vary by student (except of course for the perception of these frequencies). These items include the frequency of whole-class discussion, the instructor asking the class questions, and having students explain their thinking during class. Of these three aspects of classroom discourse reported by the instructor, only the frequency of having students explain their thinking showed significant differences between GTAs and non-GTAs. GTAs reported having their students explain their thinking significantly more frequently than non-GTAs [$F(1, 206) = 4.669, p = .032$].

Table 4.6 Comparison of Instructional Practices—Instructor reports of classroom discourse

		Tenured/ Tenure- track	Other full/ part-time	GTAs
Instructor Reports				
<i>End-of-term:</i> During class time, how frequently did you: (1) not at all; (6) very often				
Hold a whole-class discussion	Mean	2.61	3.08	2.71
	Std. Dev.	1.78	1.74	1.30
Ask questions	Mean	5.13	5.14	5.11
	Std. Dev.	1.14	1.11	1.12
Ask students to explain their thinking**	Mean	3.43	3.97	4.26
	Std. Dev.	1.63	1.52	1.45

Note. * = $p \leq .10$, ** = $p \leq .05$, *** = $p \leq .001$; n = 56 (Tenured/ tenure-track faculty), n = 81 (Other full/ part-time faculty), n = 61 (GTAs).

I rely on student reports for aspects of classroom discourse that are not uniform within a class. Table 4.7 shows that students taught by GTAs reported statistically similar classroom discourse as students taught by non-GTAs. Overall, students report that GTAs

and non-GTAs allowed time for their students to understand difficult ideas [$F(1, 2491) = 0.177, p = .647$], and provided explanations that were understandable [$F(1, 2490) = 0.002, p = .965$]. Additionally, all students report rarely being lost and unable to follow the lecture or discussion [$F(1, 2381) = 0.369, p = .544$], and sometimes copying what was written on the board [$F(1, 2383) = 0.000, p = .984$].

Table 4.7 Comparison of Instructional Practices– Student reports of classroom discourse

		Tenured/ Tenure- track	Other full/ part-time	GTAs
Student Reports				
<i>End-of-term:</i> When my calculus instructor asked a question addressed to the whole class s/he: (1) waited for a student to answer; (4) answered the question is no one responded quickly	Mean	2.33	2.29	2.24
	Std. Dev.	1.00	0.94	0.95
<i>End-of-term:</i> When I asked a question about a problem I was having difficulty solving, my instructor: (1) solved the problem for me; (4) helped me figure out how to solve the problem	Mean	2.90	2.99	3.03
	Std. Dev.	0.89	0.91	0.91
<i>End-of-term:</i> My calculus instructor: (1) Strongly disagree; (6) strongly agree				
Asked questions to determine if I understood what was being discussed**	Mean	4.15	4.34	4.45
	Std. Dev.	1.32	1.25	1.15
Listened carefully to my questions and comments*	Mean	4.54	4.72	4.76
	Std. Dev.	1.27	1.15	1.17
Allowed time for me to understand difficult ideas	Mean	4.11	4.35	4.22
	Std. Dev.	1.38	1.29	1.32
Provided explanations that were understandable	Mean	4.31	4.64	4.51
	Std. Dev.	1.38	1.26	1.27
<i>End-of-term:</i> During class: (1) Never; (5) Every class session				
I contributed to class discussions.***	Mean	2.21	2.45	2.59
	Std. Dev.	1.12	1.21	1.17
I was lost and unable to follow the lecture or discussion.	Mean	1.98	1.87	1.95
	Std. Dev.	0.98	1.01	1.01
I asked questions.***	Mean	1.96	2.19	2.34
	Std. Dev.	0.96	1.05	1.00
I simply copied whatever was written on the board.	Mean	2.99	3.00	3.00
	Std. Dev.	1.37	1.38	1.33

Note. * = $p \leq .10$, ** = $p \leq .05$, *** = $p \leq .001$; n = 784 (Students of Tenured/ tenure-track faculty), n = 1196 (Students of Other full/ part-time faculty), n = 396 (Students of GTAs).

However, students' responses indicated significantly different aspects of classroom discourse across instructor types. Specifically, students of GTAs reported that their instructors asked questions to determine if students understood what was being discussed [$F(1, 2496) = 7.640, p = .006$], and listened carefully to student questions and comments [$F(1, 2486) = 3.111, p = .078$] more frequently than students taught by non-GTAs. Additionally, students of GTAs contributed to class discussions [$F(1, 2384) = 13.270, p \leq .001$] and asked questions [$F(1, 2375) = 17.616, p \leq .001$] more frequently than students of non-GTAs. Combined with the differences in instructional practices, these results indicate that GTAs are creating more active and engaging classroom environments than non-GTAs.

Nature of Tasks

There were a number of questions on both the student end-of-term survey and the instructor end-of-term survey that address the nature of the tasks that students engage in during and out of class. These questions detail the structure of homework and exams (e.g. common final, online homework, multiple choice questions or open ended, frequency of assignments, quizzes, and exams, etc.), and the content of homework and exams (e.g. required to explain thinking or not, word problems, relationship between homework problems and exam problems, graphical interpretation problems, proofs or justifications, etc.). I use the instructor reports because I expected these aspects of the course to not vary within a class.

There are significant differences across instructor types on both dimensions of the nature of tasks. Table 4.8 provides a comprehensive summary of the analyses regarding

the structure of tasks and Table 4.9 provides a summary of the analyses regarding the content. With respect to the frequency of assignments and exams, GTAs reported giving fewer exams [$F(1, 200) = 3.508, p = .063$], more quizzes [$F(1, 209) = 9.068, p = .003$], and the same amount of assignments compared to non-GTAs [$F(1, 208) = 1.560, p = .213$]. There were no significant differences in the reported format of assignments between GTAs and non-GTAs [$\chi^2 (df = 3, n = 210) = 2.021, p = .568$], nor for the use of a common final [$\chi^2 (df = 2, n = 210) = 2.591, p = .274$].

Table 4.8 Comparison of Instructional Practices– The nature of the tasks: Structure

		Tenured/ Tenure- track	Other full/ part-time	GTAs
Instructor reports				
<i>End-of-term:</i> How many exams, not including the final, did you give?*	Mean	3.42	3.06	2.80
	Std. Dev.	1.65	1.15	1.34
<i>End-of-term:</i> Indicate how often the following occurred: (1) Never; (5) Every class session you gave a short quiz**	Mean	1.85	2.07	2.37
	Std. Dev.	0.92	0.81	0.85
	Mean	2.70	3.05	3.15
	Std. Dev.	1.23	1.32	1.23
<i>End-of-term:</i> What was the format of the majority of the homework assignments?	multiple choice items	2(3.3%)	1 (1.1%)	2 (3.2%)
	free response questions	48 (80.0%)	68 (77.3%)	46 (74.2%)
	more or less equal amounts of both	6 (10.0%)	14 (15.9%)	12 (19.4%)
	not applicable	4 (6.7%)	5 (5.7%)	2 (3.2%)
	<i>End-of-term:</i> In my Calculus 1 course: a common final was used for all sections.		39 (65.0%)	75 (85.2%)

Note. * = $p \leq .10$, ** = $p \leq .05$, *** = $p \leq .001$; n = 59 (Tenured/ tenure-track faculty), n = 87 (Other full/ part-time faculty), n = 55 (GTAs).

From personal experience I expected GTAs to have less control over the content of their assignments and exams than non-GTAs. However, there were differences between reported content from students and instructors of GTAs compared to non-GTAs. Specifically, GTAs report asking their students to solve more complex or unfamiliar

word problems on assignments [$F(1, 196) = 5.068, p = .025$], and giving exams that contain less problems focused on skills and computations [$F(1, 207) = 6.465, p = .012$] and more complex or unfamiliar word problems [$F(1, 193) = 9.770, p = .002$] and problems focused on proofs or justifications [$F(1, 185) = 6.821, p = .010$].

Table 4.9 Comparison of Instructional Practices– The nature of the tasks: Content

		Tenured/ Tenure- track	Other full/ part-time	GTAs
Instructor reports				
<i>End-of-term:</i> On a typical assignment, what percentage of the problems focused on:				
skills and methods for carrying out computations (e.g., methods of determining derivatives and antiderivatives)?	Mean	52.07	48.39	45.08
	Std. Dev.	19.08	20.11	20.88
graphical interpretation of central ideas?	Mean	19.06	26.74	24.92
	Std. Dev.	9.25	16.34	15.47
solving standard word problems?	Mean	23.57	23.72	25.76
	Std. Dev.	9.23	14.48	13.42
solving complex or unfamiliar word problems?***	Mean	14.18	18.80	22.54
	Std. Dev.	10.13	16.03	19.53
proofs or justifications?	Mean	8.68	10.62	11.93
	Std. Dev.	7.08	10.53	15.52
<i>End-of-term:</i> On a typical exam, what percentage of the points focused on:				
skills and methods for carrying out computations (e.g., methods of determining derivatives and antiderivatives)?**	Mean	52.50	47.82	41.84
	Std. Dev.	20.05	21.96	21.44
graphical interpretation of central ideas?	Mean	19.64	23.37	22.13
	Std. Dev.	9.81	16.13	13.92
solving standard word problems?	Mean	22.54	23.91	24.92
	Std. Dev.	11.83	14.58	13.98
solving complex or unfamiliar word problems?***	Mean	10.20	12.98	19.49
	Std. Dev.	7.35	15.11	20.46
proofs or justifications?***	Mean	8.04	9.36	13.68
	Std. Dev.	7.22	10.61	15.66

Note. * = $p \leq .10$, ** = $p \leq .05$, *** = $p \leq .001$; n = 53 (Tenured/ tenure-track faculty), n = 81 (Other full/ part-time faculty), n = 57 (GTAs).

If GTAs are more frequently giving common finals, how does the nature of these finals differ so much from other instructor types? It is possible that this result speaks

more to the nature of exams written by GTAs rather than their common finals. It is also possible that although GTAs are giving common finals, they have control over the content of the homework, quizzes, and midterm exams and choose to make the content more conceptual.

Research frequently links tasks that encourage students to engage in high-level reasoning to increased student learning gains (Newmann et al., 2001; Silver, 1996; Stein & Lane, 1996). However, this research emphasizes not only the nature of the problems but also the way in which students are expected and supported to engage with them. Thus, connecting the nature of the tasks GTAs put on the homework and exams to the reported frequency of various instructional practices and classroom discourse, we see a more complete picture of GTA instruction compared to non-GTA instruction.

Summary of Instructional Practices

The reported frequency of certain pedagogical activities of GTAs were similar to that of non-GTAs with respect to traditional instructional practices, though GTAs complemented this instruction with more student-centered, or innovative, instructional practices. These practices engage students more interactively during instruction by having students work together, give presentations, explain their thinking, encouraging student questions and contributions to class discussions. The combination of these classroom interactions with the more conceptual and/or cognitively demanding nature of the tasks on which GTAs' report having their students work illustrates what researchers have labeled *ambitious teaching* (i.e. Jackson, Garrison, Wilson, Gibbons, & Shahan, 2013). Ambitious teaching is instruction that “should include frequent opportunities for

students to solve challenging mathematical tasks, to articulate their mathematical reasoning, and to make connections between mathematical ideas and representations” (Jackson et al., 2013, p. 647), and has been shown to have positive influences on student learning. However, implementing ambitious teaching is an intellectually demanding endeavor for the instructor that requires additional professional preparation. In a study articulating these challenges, Lampert and her colleagues (2010) note that: “Such deliberately responsive and discipline-connected instruction greatly complicated the intellectual and social load of the interactions in which teachers need to engage, making ambitious teaching particularly challenging –but fundamentally important – for novices to learn” (p. 130).

Graduate students can be viewed as both novice members of the community of Calculus 1 instructors, and as future, more central members of this community. Thus, it is encouraging that this group of instructors are more likely to implement more innovative, researched-based instructional practices that have previously been linked to increased student success. This is exactly what Seymour meant when identifying GTAs as “partners in innovation” in her 2005 book by that name. However, she pointed to the increased pedagogical preparation graduate students need in implementing such practices. Without such training these instructional practices may not be implemented in the intended way, and thus may not have the benefits for students that have been previously identified.

Student Success

In this section, I compare GTAs to other instructor types based on their students’ success. Before conducting this comparison, I first compare students’ incoming

preparation across instructor types. In this comparison I restrict the analyses to students from doctoral granting institutions, since (in this data set) GTAs are acting as the sole instructor at these institutions only. These institutions are typically more competitive institutions and thus have high quality students. Table 4.10 shows the average student SAT mathematics scores are all above 650, which is often used as a cut-off score for entry into Calculus 1. Interestingly, students of GTAs come in with significantly higher SAT math score [$F(1, 1013) = 4.370, p = .037$]. In addition to the SAT mathematics score, we asked students to self report on how well their high school mathematics courses prepared them to perform calculations without a calculator, solve word problems, factor expressions, solve equations, and solve inequalities. There were no significant differences on responses between students of GTAs compared to non-GTAs. Overall, students reported that their courses prepared them for each activity, with average reports over 4 (slightly agree) for each. Students reported being most prepared to solve equations and factor expressions, and least prepared (though still prepared) to perform calculations without a calculator and solve word problems. Thus, although student taught by GTAs some into Calculus 1 with significantly higher mathematics SAT scores, they self report being equally prepared as students taught by non-GTAs.

Table 4.10 Comparison of Student Success – Student preparation coming in

		Tenured/ Tenure- track	Other full/ part-time	GTAs
SAT mathematics score.**	Mean	666.52	665.41	681.16
	Std. Dev.	101.86	78.52	159
	n	295	560	72.61
My mathematics courses in high school have prepared me to: (1) Strongly disagree; (6) strongly agree				
Perform Calculations without a calculator	Mean	4.50	4.51	4.60
	Std. Dev.	1.38	1.36	1.28
Solve word problems	Mean	4.86	4.80	4.82
	Std. Dev.	0.94	1.07	1.12
Factor expressions	Mean	5.34	5.21	5.21
	Std. Dev.	0.83	0.96	0.94
Solve equations	Mean	5.51	5.40	5.41
	Std. Dev.	0.68	0.85	0.85
Solve inequalities	Mean	5.11	5.05	5.07
	Std. Dev.	0.92	0.92	1.03

Note. * = $p \leq .10$, ** = $p \leq .05$, *** = $p \leq .001$; n = 613 (Students of Tenured/ tenure-track faculty), n = 899 (Students of other full/ part-time faculty), n = 315 (Students of GTAs).

The previous analysis showed that students of GTAs enter with higher SAT math scores and report being more prepared to perform calculations without calculators and solve inequalities. I keep these differences in mind as I compare these students' success across five variables. These five variables are: persistence onto Calculus 2 among students who initially intended to take Calculus 2 (used as a proxy for STEM intention), pass rate, and three affective measures – change in confidence in mathematical ability ([end-of-term confidence] – [beginning-of-term confidence]), change in enjoyment in doing mathematics ([end-of-term enjoyment] – [beginning-of-term enjoyment]), and increased interest in taking mathematics. We chose these measures of success because many students enter Calculus 1 pursuing a STEM degree and change their major away from a STEM field because of a decreased interest or enjoyment in mathematics, and are thus driven out of the STEM community. Research into the reasons students switch out of STEM majors points to the calculus classroom environment, specifically poor instruction,

as an underlying commonality (Rasmussen & Ellis, 2013; Seymour & Hewitt, 1997; Thompson et al., 2007).

Table 4.11 shows there is a significant difference in the persistence of GTAs' students when compared to non-GTAs' students. Specifically, GTAs' students persist onto Calculus 2 (a proxy for STEM intention) at significantly lower percentages than non-GTAs, 79.9% compared to 88.2% and 86.3% [χ^2 (df = 1, n = 3097) = 21.15, $p \leq .001$]. Interestingly, there are no significant affective differences. All students lost confidence and enjoyment in mathematics, but there were no differences in the amount lost by students of different instructor types. There are a small number of students for whom we have final grade data (n = 587). Though the differences are not significantly significant, GTAs gave a passing grade to 94% of their students, while non-GTAs gave a passing grade to 90% of their students [χ^2 (df = 1, n = 587) = 1.734, $p = .188$]. Together these results suggest that students taught by GTAs are the least likely to persist onto Calculus 2, although they are receiving higher grades and reporting similar affective changes.

Table 4.11 Student success by instructor type

Measure of student success		Tenured/ Tenure- track	Other full/ part-time	GTAs
Persistence onto Calculus 2 among students who initially intended to take Calculus 2***		850 (86.3%)	1392 (88.2%)	426 (79.9%)
Percentage of students with passing grades.		161 (89.9%)	263 (90.1%)	109 (94.0%)
Change in confidence ([end-of-term] – [beginning-of-term]).	Mean	-0.44	-0.49	-0.51
	Std. Dev.	1.14	1.14	0.96
	n	543	760	263
Change in enjoyment ([end-of-term] – [beginning-of-term]).	Mean	-0.37	-0.36	-0.42
	Std. Dev.	1.14	1.11	1.12
	n	538	755	261
This class has increased my interest in taking more mathematics. (1) Strongly disagree; (6) strongly agree**	Mean	3.73	3.82	3.58
	Std. Dev.	1.39	1.40	1.40
	n	890	1382	462

Note. * = $p \leq .10$, ** = $p \leq .05$, *** = $p \leq .001$

Instructor Quality Summary

The above analyses suggest that instructor effectiveness is the most significant differences in any measure of instructor quality. Students taught by GTAs disengage from the STEM community in significantly higher frequencies than students taught by other instructor types, even though they come in more likely to succeed, pass the course in higher frequencies, and are typically in more innovative classes. In summary, compared to other instructor types GTAs:

- Are less educated, younger, and less experienced in teaching Calculus 1,
- Are slightly more diverse ethnically/racially, but similarly male dominated,
- View their students as more capable,
- Teach structurally very similar classes, with an average of around 40 students, face-to-face, using a department chosen text,

- Teach similarly with respect to traditional approaches to teaching, but implement more innovative practices,
- Have students solve more complex and novel word problems on homework and exams, and more proof and justification on exams,
- And have students changed their mind about taking Calculus 2 more frequently than non-GTAs' students.

These analyses articulate components of Calculus 1 instruction (by novice and more expert instructors) along a number of dimensions. In order to explore the question of how to prepare graduate students as Calculus 1 instructors, it is first necessary to articulate the practices of Calculus 1 instructors. After doing so, one can identify representations, decompositions, and approximations of these practices, and consider how to provide opportunities for novices to engage in these pedagogies of practice. The comparative, descriptive analyses in this chapter indicate that the practices of graduate students are more innovative than the practices of more expert Calculus 1 instructors. This finding supports Seymour's (2005) description of GTAs as "partners in innovation", but also highlights a difficulty in providing graduate students authentic experiences before they enter the classroom. Grossman et al. (2009) state that fieldwork apprenticeships can be problematic, given that "that practices in the field can often reinforce the status quo and even counter the teachings of the professional preparation program" (p. 2076).

One solution to this potential issue is to ensure that the practices novices are exposed to during fieldwork are the desired practices. One way to provide a type of fieldwork experience to graduate students would be to have them work as an assistant to

a Calculus 1 instructor, observing their class, helping to grade, teaching occasionally, working with students during office hours, etc. If an institution is interested in preparing graduate students to teach Calculus 1 in an innovative way, involving whole-class discussions, student presentations of their work, and novel and complex tasks, then graduate students should work with Calculus 1 instructors who are enacting these practices.

Alternatively, representations, decompositions, and approximations of more innovative practices allow for novice instructors to learn these practices in an institution where they may not be widely enacted. For instance, graduate students could be shown a written case description of an innovative classroom (a representation), watch a presentation describing the different types of questions to ask students in order to facilitate a meaningful whole-class discussion (a decomposition), and/or role-play as a group having a whole-class discussion, with graduate students alternating in the role of student and the role of instructor (an approximation). Such activities would allow graduate students to gain insights and experience in innovative practices, without the necessity of these practice occurring at their institution.

While more experienced faculty report more traditional practices than novice instructors, the students taught by more experienced faculty were much more successful than those taught by graduate students. This may be reflective of students' adversity to change, or a deviation from what they expect. In high school, students become accustomed to the majority of learning occurring in the classroom, where they are responsible for letting the knowledge be transmitted to them. Traditional undergraduate instruction aligns with these expectations, while more innovative instruction does not. In

order to account for the potential misalignment between students' expectations and innovative instruction, the instructor may need to explicitly address these differences and share with students why s/he is using more innovative practices.

An alternate explanation may be that graduate student were not sufficiently prepared to enact innovative practices. Graduate students come into their roles in Calculus 1 instruction with little teaching experience, and are left to draw on their own experiences as students. Mathematics graduate students were the most successful mathematics undergraduate students, and thus likely needed very different instruction than the students they are teaching. GTAs view their students as more capable than non-GTAs view their students and implement a more ambitious style of teaching, including more student-centered pedagogy, and novel and/or complex tasks. While similar instructional practices have been linked to student success both at the K-12 level (Boaler, 1998; Jackson et al. 2013) and the undergraduate level (Kung, 2011; Rasmussen, 2001), research indicates that *successful* implementation of student-centered pedagogy can be difficult to achieve and may require different knowledge or expertise than traditional instruction (Lampert, Beasley, Ghouseini, Kazemi, & Franke, 2010; Wagner et al., 2007). Thus, though graduate students may be a strong resource for implementing innovative instruction, they must be properly prepared to do so in order to be successful “partners in innovation”.

In *Chapter 5*, I describe three models for GTA professional development that support GTAs in Calculus 1 instruction, in general and specific to innovative instruction. In *Chapter 6*, I then explore the mathematical beliefs and instructional practices of graduate students coming from each of the models, consider how they relate to the

nationwide sample of graduate students considered in this chapter, and how their preparations to teach are related to their beliefs and practices.

CHAPTER 5: Models of Graduate Student Professional Development Programs

In this chapter I articulate a set of guiding questions for characterizing graduate student professional development models, and portray three examples of such models using these guiding questions. I use four guiding questions as a means for characterizing GTA-PD programs. These guiding questions emerged through thematic analysis (Braun & Clarke, 2006) of the case study data surrounding the professional development programs that exist at institutions with successful calculus programs. Braun and Clark describe thematic analysis as “minimally organiz[ing] and describ[ing] your data set in (rich) detail. However, frequently it goes further than this, and interprets various aspects of the research topic” (p. 79). These guiding questions function to both organize and describe the graduate student professional development program in rich detail, and further interpret aspects of a professional development program that are both necessary and sufficient in their characterization. These four guiding questions are:

1. What is the institutional and departmental context that the model is embedded in and supported by?
2. What is the (implicit or explicit) guiding philosophy of the model?
3. What are the structural components of the model?
4. What knowledge and practices are emphasized through this model, and how?

Differing answers to the four questions characterize different models of GTA-PD programs, and can be used by practioners and researchers. For instance, these

characterizations can be used by Department Chairs to develop a professional development program for graduate students, or to make changes to an existing program. These characterizations can also be used by researchers as a systematic way to describe and compare existing programs. In the following sections, I describe each guiding question and articulate a number of ways each question may be answered. I then provide three examples of different models of professional development programs, characterizing each by answering the four questions. In addition, I answer two additional questions that provide information specifically for the practitioner interested in implementing and/or evaluating a model.

5. What aspects are necessary to institute this model?
6. What are the affordances of this model, and what could be done to make it stronger?

The last two questions give the practitioner (Course Coordinator, Department Chair, etc.) additional information for developing or evaluating a program, and also information that may be used to convince other stakeholders (such as the Department Chair, Dean, or Provost) that such a professional development program is useful and appropriate.

Guiding Questions

What is the institutional and departmental context that the model is embedded in and supported by?

This question contextualizes the model in the institution and department. Once the programs are contextualized then one can begin to analyze which aspects of the GTA-PD program can be transferred to another institution/department without being altered and which will need to be adjusted to account for institutional/departmental differences.

Specific components of the institutional and departmental context include:

- institutional characteristics, such as the description (public, private, technical, etc.), the undergraduate population, any relevant institutional history, and any notable features of the institution (previously recognized for calculus success, part of case study, etc);
- information specific to the calculus program, such as how many students typically take Mainstream Calculus 1 in Fall, who typically teaches Calculus 1, if Calculus 1 coordinated, and if so by whom, and any relevant history surrounding the Calculus 1 program;
- information specific to the role of graduate students, such as the graduate student population, what role(s) GTAs are responsible for, and relevant history of the GTA program.

What is the (implicit or explicit) guiding philosophy of the model?

The next guiding question investigates the implicit or explicit philosophy that drives the professional development model. This philosophy may be explicitly stated in a TA Handbook, for example, or they may be intuited from other aspects of the program. The guiding philosophy includes the goals and objectives of the training program, as well as ideas regarding how graduate students come to learn how to teach and different perspectives on learning. Belnap and Allred (2009) have previously articulated a number of goals/objectives of TA professional development programs. These include:

- Familiarize GTAs with the university and department
- Familiarize GTAs with their job and its expectations, responsibilities, and benefits
- To help prepare to begin teaching by helping them anticipate and prepare for classroom problem administrative duties
- Become aware of different teaching and learning strategies
- Provide GTAs with hands-on teaching practice in order to develop classroom skills
- To provide opportunities to network with other GTAs

Other potential goals are to support graduate students make as they make the transition from student to instructor, or to help departments gain “buy-in” from GTAs as they implement a certain instructional approach. In addition to these goals or objectives, the guiding philosophy of the model includes the institution or department’s disposition towards teaching and learning, which tends to answer questions such as: How do students learn undergraduate mathematics? How do graduate students learn how to teach? What knowledge is needed to successfully teach Calculus 1? Answers to such questions guide

many aspects of a professional development program, including the timing, duration, and frequency, the topics covered, what kind of instructional practices graduate students are expected to implement, and how graduate students engage in the training (via watching presentations or by practice teaching, for instance).

What are the structural components of the model?

The structural components of a professional development program provide the architectural framework of the program. These pieces are designed based on constraints and restrictions from the institutional and departmental context, and are guided by the philosophy of the program designer. When someone describes a professional development program, often these are the aspects that they attend to, just as when one describes a new house they list the number of bedrooms and bathrooms, the floor plan, the wood floors, etc. However, the number of bedrooms and floor plan were constrained by the architect's budget, by the plot of land, and local zoning laws, and the choice of wood floors and layout were influenced by the owner and architect's vision.

The structural components of a professional development program include both informal components, such as weekly course meetings that provide opportunities for discussions surrounding teaching, and formal components, such as summer seminars or ongoing classes with the explicit purpose of providing PD to GTAs. Belnap and Allred (2009) articulated five components of formal professional development programs which can be used to describe the both informal and formal components of a GTA-PD program:

- timing of training,
- frequency of training,

- duration of training,
- topics covered, and
- overall design utilized by the program.

For the practitioner seeking to develop a new program, the structural features are likely the first components one may think of. These are, of course, *necessary* components of a GTA-PD program, but they are not *sufficient* and cannot exist without the articulation of the overarching philosophy and without considering the institutional/departmental context. Thus the structure should be considered only after considering answers to the first two guiding questions.

What knowledge and practices are emphasized through this model, and how?

As part of developing as an instructor, one develops knowledge and practices surrounding instruction. Thus, the professional development programs designed to prepare graduate students as instructors emphasize different types of knowledge and practices depending on the community within than institution. Sfard (1998) distinguishes between two metaphors for learning: *acquisition* and *participation*. Those who ascribe more fully to the acquisition metaphor attend to the knowledge that one acquires, and those that ascribe more fully to the participation attend to the development of practices that enable one to act in ways that are compatible with the norms and expectations of those they work with. Sfard emphasizes that these metaphors are complementary and each is at play as graduate students are prepared as Calculus 1 instructors or recitation leaders. As GTAs become members of their local communities of calculus instructors, they *acquire* specific skills, knowledge, and beliefs that allow them to *participate* in the

practices of their communities. Conversely, as one *participates* in various practices they *acquire* and refine specific knowledge, skills, and beliefs surrounding calculus instruction.

In order to characterize the types of knowledge emphasized through these programs, I draw on the extensive literature surrounding teacher knowledge. Shulman (1986) classically differentiated between various knowledge needed for teaching, introducing *pedagogical content knowledge (PCK)* into the mathematics education research lexicon. Pedagogical content knowledge is distinct from a blend of basic pedagogical knowledge and basic content knowledge and was introduced by Shulman in response to the wide-held belief that content knowledge alone was sufficient to teach. PCK is the particular form of content knowledge related to the aspects of content knowledge “most germane to its teachability”, including ways of representing content so that it is understandable to others (Schulman, 1986, p. 9). Ball, Thames, and Phelps (2008) extended this construct by further elaborating *Mathematical Knowledge for Teaching (MKT)* and have aimed professional development efforts at developing the various components of this knowledge. MKT is comprised of two main categories of knowledge:

- knowledge of the subject matter and its organizing components, referred to as content knowledge (CK);
- and the knowledge of how to teach this content so that it is comprehensible to others, referred to as Pedagogical Content Knowledge (PCK) (Shulman, 1986).

Two especially critical components of PCK are knowledge of how students understand and think about specific content, referred to as Knowledge of Content and

Students (KCS), and the knowledge of how to teach specific content so that students understand it, referred to as Knowledge of Content and Teaching (KCT) (Ball, et al., 2008).

Different professional development programs for GTAs necessarily focus on different types of knowledge depending on their goals and guiding philosophies, as well as depending on the department's needs and the needs of the graduate students. For instance, if graduate students typically come into their role as GTAs at a specific institution with extensive teaching experience but are less confident in their mathematical knowledge, a professional development program may choose to emphasize content knowledge related to teaching. If, instead, graduate students typically come into their role as GTAs at a specific institution with very strong mathematical content knowledge but little to no experience interacting with students, than a professional development program may choose to emphasize pedagogical knowledge and pedagogical content knowledge, but not content knowledge.

In order to characterize the types of practices emphasized and how, I draw on Grossman et al.s' (2009) *pedagogies of practice*. Grossman and her colleagues (2009) identified three concepts for describing ways to teach practices in professional education: representations of practice, decompositions of practice, and approximations of practice. Various professional development activities may serve the purpose of representing a practice, decomposing a practice, or approximating a practice, depending on how they are used. For instance, Videocases may be used either as a representation of practice or as an approximation of practice. As a representation, they allow the novice to explore the richness and complexity of a classroom setting without being in one. Novice teachers

may be asked to go further than simply viewing a Videocases by being instructed to reflect on the practices of the teachers, consider how they may have responded, and develop questions they would like to ask the teacher about their classroom practices. When used in such ways, the video cases serve not just as a representation of practice but also an approximation of practice by allowing the novice teachers to take on the role of teacher without being in the classroom.

In answering this guiding question, I consider how the program structure is designed to emphasize different types of knowledge and engage graduate students in different pedagogies of practice. As previously mentioned, the development of knowledge and engagement in practices are reflexively related, so I attend both to what knowledge is developed through various practices and how these practices are taught by emphasizing different knowledge.

Additional Questions for Implementation and Evaluation

What aspects are necessary to institute this model?

To answer this question, I consider what aspects of the institution and/or department allow the model to be enacted in the way it is, and which of these facets are necessary for it to be implemented. I also consider how variations of certain attributes of the institution and/or department would necessitate certain adjustments to the model.

What are the affordances of this model?

The affordances of a professional design program are the actions that are made possible by the structure of the program. Whether or not these affordances are strengths depends on the institution and department, and the needs of the stakeholders in the institution and department. One way to characterize the affordances and/or strengths of a GTA-PD program would be to compare the program to previously identified “successful” PD programs. The Apprenticeship Model exhibits all of the six traits consistently identified as components of successful PD programs at the K-12 level (Clarke, 1994; Elmore, 2002; Garet et al., 2001; Hawley & Valli, 1999; Kilpatrick et al., 2001). These six traits are professional development programs that:

1. Are sustained over a long period of time;
2. Focus on subject matter, both helping teachers understand the mathematics of specific content domains and students’ mathematical thinking in those domains;
3. Provide opportunities for “hands on” learning by modeling the type of instruction expected;
4. Are integrated into daily lives of teachers;
5. Provides teachers with feedback and assessment that they need to grow as teachers; and
6. Have support from other constituents, such as administrators and the school district.

One way I consider the affordances of a program is by articulating which of the above traits is the program exhibits. However, it is not necessarily true that what is a

strength for a professional development program at the K-12 level is a strength for a graduate student professional development programs. Thus, I additionally consider to what extent the structure of the program meets the needs of various stakeholders in the environment.

Three Models of GTA Professional Development

In this section, I provide *thick descriptions* (Ponterotto, 2006) of four GTA professional development programs at institutions that employ graduate students in the teaching of Calculus 1 (either as instructors or as recitation leaders) and whom have been determined to be more successful than other institutions. Thick descriptions are used in qualitative research to describe events or interactions in context, and “accurately describe observed social actions and assign purpose and intentionality to these actions, by way of the researcher’s understanding and clear description of the context under which the social actions took place” (Ponterotto, 2006, p. 540). I answer the following questions in each thick description:

1. What is the institutional and departmental context that the model is embedded in and supported by?
2. What is the (implicit or explicit) guiding philosophy of the model?
3. What are the structural components of the model?
4. What knowledge and practices are emphasized through this model, and how?
5. What aspects are necessary to institute this model?
6. What are the affordances of this model?

The four institutions that employ graduate students in the teaching of Calculus 1 implement three different models of GTA-PD that I refer to as: (1) *the Apprenticeship Model*; (2) *the Coordinated-Innovation Model*; and (3) *the Peer-Mentor Model* (the last of which is represented by two professional development programs). Two institutions primarily employ GTAs as course instructors, one of which uses the Apprenticeship Model and one that uses the Coordinated-Innovation Model. The other two institutions primarily employ graduate students as recitation leaders, and both use what I refer to as the Peer-Mentor Model for their GTA professional development. Table 5.1 provides a comprehensive overview of the four institutions, and the roles that GTAs play at each. In the paragraphs that follow Table 5.1, I describe each of the four institutions and three GTA-PD models and provide the thick descriptions that elaborate on each and answer the guiding questions.

Table 5.1 GTA Model Summary

	Apprenticeship model	Coordinated Innovation model	Peer-mentor model	
	Institution 1	Institution 2	Institution 3	Institution 4
Institutional Overview				
Undergraduates (Total)	5,000	25,000	25,000	30,000
Fall enrollment of Calculus 1	270	2,000	1,040	1,200
Math graduate students	20 Ph.D.; 18 MS	138	136 (55 are TAs)	9 Ph.D.; 27 MS; and 21 in Math Education (Ph.D. or MS)
Size of Calculus 1 class	45	30	240 - 320, recitations 40	240, recitations 40; small classes 35
Number of Fall Calculus 1 sections	6	66	4	large 4 small 6
GTA responsibilities				
Recitation Sections	None	None	Yes; Primary role	Yes; Primary role
Sole Instructor	Yes, 3 on survey	Yes, 23 on survey	Can, none on survey	Can, none on survey
Staff tutoring lab	Yes, typically staffed by UGs; staffed by grad. students who do not teach	Yes, typically staffed by UGs; staffed by grad. students who do not teach	Yes, part of office hours held here	Yes, part of office hours held here
Other	Act as TA for Calculus 1 instructors (grade, attend class, assist in general)		Senior TA	Senior TA

I refer to the professional development of GTAs at Institution 1 as the *Apprenticeship Model* because it is guided by the goal to apprentice graduate students into the role of instructors. The main components of the Apprenticeship Model are:

- A lesson-study inspired, three-unit class that takes place during the semester before the GTA is placed as a course instructor.

- A mentor instructor for whom the mentee acts as a teaching assistant in the class they will be teaching during the semester before the GTA is placed as a course instructor.
- Weekly course meetings once the once the GTA is placed as a course instructor.
- Observations and feedback once the GTA is placed as a course instructor.

Institution 1 is a small, public, technical institution, where both Masters and Doctoral students are involved in the teaching of Calculus 1. Calculus 1 is taught in small classes without recitation sections. Graduate students serve as course instructors, as teaching assistants (where they observe class, grade quizzes and exams, and help instructor class), and staff the tutoring lab. Institution 1 does not have recitation sections.

I refer to the professional development of GTAs at Institution 2 as the *Coordinated Innovation Model* because the calculus program at Institution 2 itself is coordinated by a staff of three instructors, Calculus 1 is taught using an innovative approach, and the professional development of GTAs is guided by these characteristics. This coordination includes a set weekly schedule, assignments, and exams, in addition to a strongly-recommended instructional approach. The main components of the Coordinated Innovation Model are:

- An intensive four-day training seminar that takes place the week before GTAs are placed as course instructors.
- Weekly course meetings once the GTA is placed as a course instructor.
- Observations and feedback once the GTA is placed as a course instructor.

Institution 2 is a large (undergraduate population greater than 20,000), public institution where Doctoral students and post-docs comprise the majority of the Calculus 1

instructors. Calculus 1 is taught in classes of less than 30 students, in two-hour time blocks, without recitation sections. Graduate students serve as course instructors and occasionally staff the tutoring lab.

The GTA professional development programs at Institution 3 and 4 share many commonalities and represent two instantiations of the same model. I refer to this as the *Peer-Mentor Model*. The main components of the Peer-Mentor Model are:

- An advanced GTA who designs and implements the professional development of GTAs.
- A one-day seminar before the GTAs are placed as recitation leaders.
- A seminar that occurs periodically throughout the semester.

Institution 3 is a large, public institution, where undergraduate and graduate students (MS and Ph.D.) are involved in the teaching of Calculus 1. Calculus 1 is taught in large classes with recitation sections. Graduate students primarily serve as recitation leaders for the large Calculus 1 class, but advanced graduate students can also serve as the course instructor –though they rarely choose to serve as the course instructor for Calculus 1. Undergraduates also serve as recitation leaders for Calculus 1, but are not required to participate in the professional development for this role that GTAs are required to participate in. Graduate student TAs also tutor in the tutoring lab as part of their responsibility as recitation leader. The second institution that implements the Peer-Mentor Model is Institution 4. Institution 4 is a large, private institution, where MS and Ph.D. students are involved in the teaching of Calculus 1 and Calculus 1 is taught both in large classes with recitation sections and small classes without recitation sections.

Graduate students serve primarily as recitation leaders for the large sections of Calculus 1, but may also be the course instructor for small classes.

Apprenticeship Model

What is the institutional and departmental context that the model is embedded in and supported by?

Institution 1 is a small, public technical institution with approximately 5,000 undergraduates. Institution 1 was selected as a case study institution because it had higher than average positive gains in each student success variable reported (increased interest, enjoyment, and confidence in mathematics), and had a large number of STEM-intending students and a large number of those students who persisted in their STEM intentions after completing Calculus 1. In a typical Fall semester, there are approximately 270 Calculus 1 students in 6 classes of 45 students. These courses are taught by lecturers, tenure/tenure track faculty, and graduate students, and are coordinated by a long-term lecturer who also serves as the TA-trainer and is in charge of placement. The coordination includes uniform assignments and exams. GTAs at Institution I serve as course instructors for Precalculus, Calculus 1, Calculus 2, and Instructor Statistics. GTA's may also work in the Mathematica Lab. All calculus students spend one day a week in a computer lab working on Mathematica assignments that are coordinated across sections. This is an uncommon assignment for GTAs, and is most often used for GTAs who are determined to not be ready to teach their own course after going through training.

The current GTA-PD program was developed by the current Department Chair when he was the Director of the Graduate Program. When he came into the role of graduate director, new graduate students had a 1.5 week orientation in the summer where they would give a few practice lectures and have sessions on how to grade, how to facilitate group work, etc. The Department Chair said of the program: “They packed a lot of good information, but it was a week and a half and a lot of them were teaching that first semester. So I participated in that and was just interested/concerned about how well they could really do with that kind of preparation.” With the support of the Department Chair, the department hired a Director of First Year Mathematics who developed a course for future graduate student instructors and the mentoring program. This person was involved in a Lesson Study professional development program with elementary teachers, and used ideas from Lesson Study to influence the structure of the course that GTAs must take before being course instructors. Though the person in the role of Director of First Year Mathematics has changed, the program still relies heavily on the original structure.

What is the (implicit or explicit) guiding philosophy of the model?

Institution 1 articulated their philosophy towards training graduate students as instructors in the “TA Handbook” which is distributed to all new GTAs. Their stated goal is to “*to better prepare our GTAs as instructors, so that both the students and the GTAs will experience success in their roles in the department.*” The mentoring program is viewed as a way to “transition” graduate students from the role of a student to the new role as an instructor, and has the following stated purposes:

1. to model good teaching practice,

2. to allow the GTA to become comfortable interacting with undergraduate students without the pressure of having full responsibility for a course,
3. to learn the policies of the department and university as they pertain to the classroom instructor and first year courses in the department,
4. and to provide a framing for thoughtful reflection and conversation about effectiveness pedagogical practices (TA Handbook p. 2).

The philosophy statement concludes by stating that the most important result of the year long mentoring program is that the new GTA should finish the year with “a sense that they are being fully supported in their role of an instructor in the department, and should continue to search for ways to improve their teaching in subsequent semesters.”

This stated philosophy makes it clear that the stakeholders at Institution I view the graduate student training program as a long-term support for graduate students, in preparing them not only as current instructors but also as future faculty members. By requiring graduate students to spend a semester apprenticing into the role of instructor, Institution I prioritizes the graduate students’ long-term development as an instructor, rather than their immediate value as paid instructors. This philosophy is reflected in the structure of the training program as well as the Department Chair’s justification for the cost:

Chair: For Ph.D. students I feel like the cost is very minimal because they're going to teach for 5 years, 10 semesters. Now they're going to teach for 9 semesters. You subsidize one semester to do this. For [Masters] students, there's no question that the cost is higher. Most of them will now teach for three semesters instead of four. We have enough economy to scale that we've never had to pinch pennies and we were able

to afford that into our budget. It had to absorb into the budget because nobody gave us any resources to do it. We just felt like it was important enough. The other side of the coin is that we probably have some students teaching successfully now who never would have taught successfully without that training. So for those masters students, I'm sure in some cases we're getting three semesters of competent teaching where as before we would have gotten 4 semesters of problematic teaching. So it's certainly not all cost from monetary point of view because if you have to pull somebody out of a classroom the second year, there's a cost to that too.

This statement not only supports the guiding philosophy of this model, but also provides strong justification for implementing such a model. The stakeholders at Institution I indicate a commitment to their undergraduate students' success as well as their graduate students' success, as current instructors and as future faculty. It is undeniable that graduate students are a cost-effective tool for instructing undergraduates, and that teaching positions are a good incentive for attracting graduate students. However, there is an implicit contract involving all constituents involved in these interactions: undergraduates intend to receive quality instruction from the graduate students teaching them, and the institution intends to provide quality instruction through the graduate students they are employing. The above statement indicates that the Department Chair is aware of these elements, and in order to successfully satisfy these contracts he supports the Apprenticeship Model by continuing to advocate for funds, employ the instructors who run the lesson-study class, and sustain a department culture that encourages and implements the mentoring.

What are the structural components of the model?

Graduate students are required to participate in a number of professional development activities, both prior to teaching and while they teach. All new GTAs must attend a one-day seminar led by the mathematics department, with some of this time spent doing practice teaching presentations. During these presentations faculty conduct workshops on topics including “Chalkboard Techniques,” “Cooperative Learning,” and “Grading Issues.” (Source: TA Handbook). Additionally, all first-year TAs are assigned a faculty mentor during the orientation session.

If a GTA has no prior teaching experience they act as a Teaching Assistant to a mentor. While the majority of GTAs begin with little to no teaching experience, there are occasionally graduate students with multiple years of experience. These students are placed in the role of classroom instructor in their first term. Everyone else must be successful in two components of PD before they are given their own course: (a) they serve as a teaching assistant to a faculty member who mentors them in teaching, and (b) they participate in a one-semester course called “Teaching College Mathematics” that is based on lesson study. As classroom instructor, the GTA is responsible for most aspects of the course. Specifically, they are responsible for preparing a course syllabus, preparing and delivering lectures, creating assignments, writing quizzes and exams, grading homework and exams, holding office hours, and determining grading scales. All GTAs are observed by a faculty member, and participate in weekly meetings with other course instructors.

Mentoring. Institution 1 provides extensive documents for both mentors and mentees on what each should expect from the mentoring component of GTA-PD. For

mentees serving as TAs for the mentor in their first term, the goal is to “prepare the TA to independently teach a course in the following semester, so it is to the TA’s advantage to take on as many responsibilities as is manageable” (Mentoring Handbook, p. 12).

Specifically, mentor and mentees are told that mentees are expected to:

1. Attend the assigned course every day the course meets.
2. While in class, observe the instructor and keep notes of ideas and techniques that you find effective, along with those that you have questions about.
3. When the instructor is using teamwork, walk about the classroom and help students/ groups in need of assistance.
4. Grade for the course. Particular duties should be discussed with the instructor.
5. Keep accurate class records for the work that you grade, and report any trends for the class or individual students to the course instructor.
6. Maintain your office hours, as agreed upon by you and your mentor.
7. Thoughtful reflection – After class, spend some time thinking about what you observed. What things did you think went particularly well? What things would you have done differently?
8. Attend a weekly meeting with your mentor. The time should be arranged with your mentor (Minimum of 1 hour per week, at a regularly scheduled time.) You should bring questions to these meetings.
9. Take on any other (reasonable) duties, as determined by the instructor
(TA Mentor Info, p. 2).

The above expectations are heavily influenced by and reflective of the guiding philosophy of Institution I. Not only are mentee graduate students expected to participate in the instruction with limited but authentic responsibilities, they are also guided to reflect on these experiences in order to begin developing the disposition of a reflective practitioner for their own long-term success as instructors. While these expectations are clearly conveyed to both mentors and mentees, there is no support for mentors in learning how to enact these requirements, nor are there structures in place to ensure that these requirements are enacted. Thus, the amount of actual mentorship depends on the mentor.

I spoke with two GTAs about their experiences teaching at Institution 1 and the preparation they received for teaching. Both were Masters students in their second year who were recently nominated for the university's outstanding teaching award. I also spoke with a group of first semester GTAs but there was a technical glitch in recording this conversation. Thus, I did a retrospective reflection of this interview. The first GTA I spoke with has an education degree and is certified to teach high school mathematics but never taught. Instead, she has many years of tutoring experience. She was tutored by the Calculus Coordinator in Calculus 1 her first semester at Institution 1 and has been teaching Calculus 1 on her own since; she is currently in her second semester of teaching. She reported having extensive mentoring from the Calculus Coordinator, but recognized that this was not uniform. When I spoke with the group of first year GTAs, they supported this by reported varying levels of mentoring.

GTA 1.1: ...it all depends on the mentor. Some of them, they only, they would have their graduate student teach twice, and then that was it, so they didn't get much experience. Some of them weren't allowed to grade

quizzes, some of them did. Some of them when they did teach, they had to go exactly like what their mentor said, 'you have to teach this lesson exactly this way.' So it all depends on who you got, that your experience could be very different.

For mentees who are teaching their own course in the first term the role of the mentor is to “provide a support system” (Mentoring Handbook, p. 11), and the expectations of both mentor and mentee are very different. When teaching their own course for the first time, GTAs are provided a detailed course syllabus, a timeline, daily problems to be assigned and collected, dates for the exams, and general course policies. The mentor will observe the GTA’s course regularly, assist the GTA in preparing for class as needed, and help write exams. This graduate student highlighted the gradual process of gaining more and more responsibility and ownership of her class.

GTA 1.1: Well, the first time I taught Calculus, I relied heavily on what my mentor had done, because I watched her teach calculus for a semester, and so I used her lessons. And then I got some lessons that another person, he's not here any more, but he got a job somewhere else, but he had taught calculus, so he gave me some of his lessons, so I started incorporating those ideas. I started expanding what I was doing, I started giving notes, just as a worksheet, to fill in the notes, to make it more structured. This semester, I started adding more conceptual questions, so I have been adding to, from what I started with and modifying it.

GTA 1.1: Yes [in her first semester there was more structure placed on how she was teaching], [her mentor] said, 'You have to give this many quizzes,' she said, she suggested I didn't do this, 'But you should have someone look at your quizzes every week to make sure that you're giving good quizzes.' Just have everybody double-check what you're doing, to make sure that you're doing a good job... and then she pulls back once she sees that you're doing okay.

The second GTA I spoke had over 30 years experience teaching AP calculus. She was assigned the role of course instructor her first semester as a student at Institution 1

because of her extensive teaching experience. She did not mention having a mentor during her first semester teaching, but has had her course observed twice a semester, and receives midterm evaluations as well as end of term evaluations from her students. When asked what she thought of the TA training program, she said “I think it's a great program, I don't know if it happens in other disciplines in the university, but I think that the focus on training TA's to teach is really good, I think it's excellent” and that she felt very supported. Also, she mentioned drawing on other professors for inspiration in teaching, and having multiple sources to go to in order to talk about teaching.

GTA 1.2: Probably just the other instructors here [are influences on her teaching], because I kind of know what students are experiencing in other courses. ... So trying to fit in with the rest of the Math Department, the way they teach, has changed what I do a little bit, I think for the better. And I know that if I were to go back and teach high school, I would take some of these ideas and bring them back. Also being a student and knowing what I like to get out of a class here, does impact what I give them, seeing it from both sides of the desk.

Class. The majority of GTAs are required to enroll in the lesson-study inspired course, called *Teaching College Mathematics* (hereafter referred to as the lesson-study course) during their first semester. The only GTAs that are exempt are those that begin with extensive teaching experience, like Eve. The course is 3 units and meets twice a week for discussion and once a week for a lab component focused on technology in the classroom. The text for the course is *Teaching Tips: Strategies, Research, and Theory for College and University Teachers*; Thirteenth Edition, Wibert McKeachie and Marilla Svinicki. The class is currently taught by a Senior Lecturer with a MS in Mathematics Education who is in charge of TA training as well as Placement and coordinating

Calculus 1. The course description is: “Survey key issues in undergraduate mathematics education, including course preparation, assessment, student learning, developing assignments, instructional strategies, technology, motivating students and institutional resources. The lab involves practical training in the computer algebra system used in the mathematics lab” (course catalog). There are typically between 5-10 new graduate students enrolled in the lesson-study course every fall, including Masters students and Ph.D. students, pursuing degrees in Mathematics and Statistics.

The modified version of lesson-study used in the course involves multiple iterations of developing a lesson together, practice teaching it to each other, giving feedback to one another, then teaching to a real class, and writing reflections on their teaching. One graduate student instructor summarized the experience as follows:

GTA 1.1: We collaborated together to create lessons. So let's say, 'Okay, we want to write a lesson for these sections in this book.' And we were doing the Pre-Calc book, because that's what most of us would end up teaching. So we would work together saying, 'Oh, this is what I think should be covered.' 'Well, come up with an example.' So we'd write our own, and then we would present it, we'd critique each other, and then we'll take what everybody did and we'll kind of mesh it together into one lesson, so that hopefully everybody would be consistent when they do teach it their next semester. So we'd mesh everything together, and then we'd practice that lesson with our mesh lesson, and then we would critique each other. So we did that several times with various sections.

Interviewer: How long does that process take? So you start with a unit, you develop some ideas, then you finally practice it. So how many classes, how many meetings does that span?

GTA 1.1: At least 2 weeks' worth, because we'd have about a week where we'd be creating our own, then we'd take a week or 2 to actually go through and watch everybody. And then we'd have another week where we modify it, and then another week or 2. So it's like 2 weeks for each portion

of it really... But then we would get through 3, we'd write like, it's 3 sets of these, but we do 2 sections each. So I guess 6 sections total that we did this for.

In addition to the practice teaching component, students read chapters from the text with related assignments. There is a strong emphasis on developing lessons that actively involve students, which is consistent with the pedagogical perspective of the Math department. For instance, one week students read a chapter on “Active Learning: Group Based Learning” and were assigned to “Design a group lesson for 4.4 in Hughes-Hallet. Include a one page summary of how you are going to implement and grade the lesson.”

The courses that graduate student teach are all coordinated, with respect to common homework, schedule, textbook, and exams. However, there is no prescribed instructional approach, such as lecture or group-work. When asked what would happen if she did not actively involve students during class, one GTA responded that the students would probably drop her class because they have come to expect being involved during classes at Institution 1, but that the course coordinator would allow her to teach how she wants.

GTA Placement. Near the end of the first semester the TA Trainer, Department Chair, and assistant to the Department Chair determine which graduate students are and are not ready to be a course instructor. This decision is made based on the graduate students' performance in the lesson-study inspired course and feedback from their mentor. When asked how she determines who is and who is not ready to be an instructor, the TA Trainer responded:

TA Trainer: *Whether or not they get to [teach] is based on the mentor's recommendation and how well they did in [the class] and the observations of anyone else that comes to watch them teach when they teach. So we take that into account. And there's just certain things, I mean I don't have a formal rubric probably because I've been a teacher for 25 years. You just kind of know that they can't go in the classroom.*

There are typically about one or two students every year that are determined to not be ready to be course instructors. For students who are not placed into a class, they are instead put into the Mathematica Lab or work as a grader. Additionally, they are re-mentored with the hope that they will eventually be ready to go into the classroom. If this does not work, then they will remain working as a Lab TA and/or grader. This also remains a possibility for graduate students who are placed into the classroom and then are determined to not be suitable course instructors, based on observations and/or student evaluations.

What knowledge and practices are emphasized through this model, and how?

The Apprenticeship Model provides novice graduate student instructors with many experiences in approximations, representations, and decompositions of practice (Grossman et al., 2009). The lesson-study course is designed to provide many different ways for graduate students to engage in the practices of teaching, including representations of practice, decomposition of practice, and approximations of practice. The lesson-study activities allow students to engage in approximations of practice with increasing level of authenticity, and the readings serve to both represent and decompose the practices of teaching. These approximations allow novice teachers to engage in the

practices of teaching within narrow boundaries, which “limit the difficulty of the task, helping novices hone in on dimensions of the practice that otherwise might get lost in the fray” (p. 2090). These experiences enable graduate students to develop pedagogical knowledge (such as how to structure a lesson so it is clear and engaging) and pedagogical content knowledge (such as which examples are better than others, where may students become confused) that are often developed through experience.

These components of Mathematica Knowledge for Teaching are most often fostered through experience in teaching, and have been identified as being especially critical when implementing more innovative instructional practices, such as fostering productive whole class discussions that leverage student thinking (Johnson & Larsen, 2012; Speer & Wagner, 2009). In an article examining one mathematician’s implementation of such an instructional approach, Speer and Wagner (2009) found that the mathematician was unfamiliar with student generate ideas and their ways of thinking, and in order to make sense of their thinking he needed to draw on his own Specialized Content Knowledge (SCK).

Many of the graduate students at Institution 1 are in the process of earning their Masters degree in mathematics, and may have not yet developed the extensive content knowledge needed to make sense of students’ thinking in the moment. Thus, it is especially beneficial for these students to be immersed in the classroom, experiencing students’ thinking, and experiencing their mentor’s own in-the-moment sense making and reactions to student thinking *before* they enter the classroom on their own. Further, by developing this knowledge, graduate students are able to participate in the lesson-study class and mentoring experience with greater and greater authenticity.

What aspects are necessary to institute this model?

There are many aspects of the Institution I, the department, and individuals within the department that make this program possible. First, there are a relatively small number of students enrolled in Calculus 1 each Fall term. Specifically, there are typically around 270 students enrolled in Fall Calculus 1, representing around 5% of the total undergraduate population. Calculus 1 courses are all taught by graduate students or Lecturers, and there are around six Calculus 1 courses each Fall, and around 35 graduate students in a typical year. There are enough teaching assistantships to support the graduate students, and a reasonable number of first time GTAs to run a class like the lesson-study inspired course (typically around 5-10 first year graduate students). Such a course could be run with more graduate students. In the observed year there were only seven graduate students enrolled in the lesson-study inspired course, and each student was able to present their prepared lesson each round of the lesson-study cycle. If there were more graduate students, not every student would be able to present every round, or perhaps they would break into smaller groups and present to one another rather than the whole class, or there may be multiple sections of this course. A larger number of graduate students would be able to support a larger number of undergraduate students, so the small number of undergraduate students at Institution I is not a necessary component in order to implement this model. Although these structural features of the institution are not necessary to implement the Apprenticeship Model, there are features of Institution 1 that are necessary. These involve the culture of the department and the institution.

The department places a high value on teaching, especially teaching first year courses. This idea does not belong to one individual, but is instead emblazoned on the GTA Manual: “The success of our undergraduate students, especially during their first year at Institution 1, is of utmost importance to those in the math department.” This emphasis is supported by the Department Chair, though not in a prescriptive way. For instance, during the weekly meetings with the course coordinators, he often shares innovative teaching techniques that he learned about from an MAA publication or meeting. By sharing the idea, he is making the other coordinators aware of new things to do in the classroom, but in no way does he tell them that they must implement these innovations.

Thus, instructors (both graduate students and faculty) feel supported to enact student-centered instruction and experiment in the classroom in ways that provide a sense of independence though while being supported through the coordination, weekly meetings, observations, and other instructors. This GTA-PD model is further support by the attention to the long-term success of graduate students as faculty members. This is necessary for the financial justification for the model and to ensure “buy-in” and continued support by faculty in the department to act as mentors.

What are the affordances of this model?

The Apprenticeship Model exhibits all of the six traits consistently identified as components of successful PD programs at the K-12 level. The Apprenticeship Model is sustained over the entire first year of teaching and continues as a support system throughout a GTA’s assignment, the lesson study inspired course is rooted in a specific

mathematical content area (typically PreCalculus), there are many opportunities for hands on teaching practice in both the course and the mentoring, the program is integrated into the lives of GTAs on (at least) a weekly basis, there are many opportunities for feedback and assessment of teaching through the lesson study course, and finally there is support and buy-in from the department administration.

While this model shares traits of successful programs at the K-12 level, and appears to be successful based on observation and student success, one aspect that could be improved upon is the support for mentors. The TA Trainer remarked that she “can't micromanage [the mentoring]” and only selects interested and/or “good” teachers to be mentors. This restricts the number of faculty that serve as mentors. If this program were to expand, more mentors would be necessary and thus more supports for mentors would be needed. Currently, mentors are given a handbook that clearly articulates the expectations for the mentoring, but there is no guarantee that they read it, nor that they stick to the expectations. Perhaps a way to foster more support without micromanaging the mentors would be to have periodic meetings for the mentoring faculty to discuss what activities their mentees should be engaging in, how the relationship is going, any difficulties or questions that have arisen, and what they would like their mentees to do moving forward.

Coordinated innovation Model

What is the institutional and departmental context that the model is embedded in and supported by?

Institution 2 has approximately 1500 students enrolled in Calculus 1 each fall. Every Calculus 1 course has 32 students enrolled, and thus there are around 50 Calculus 1 sections taught. GTAs teach the majority of these sections (in Fall 2012 35/50 instructors were first year GTAs). The remaining instructors are experienced GTAs and faculty (including the provost). All courses are coordinated by a team of three permanent faculty. All Calculus 1 courses are taught using an Inquiry Based Learning (IBL) inspired instructional method, which emphasizes student discovery, group work, and conceptual understanding (see <http://www.inquirybasedlearning.org/> for more information). A typical class consists of a 15-minute lecture, followed by students working on related problems in groups of four, followed by multiple groups presenting their solutions. Each session is 2 hours, so this sequence may be repeated a number of times during each class meeting. The course uses the Hughes-Hallet textbook that was designed to foster conceptual understanding and problem solving over procedures and skills. Calculus 2 is structured in a similar way, but Calculus 2 and 3 are different in that they have large lectures or 80 or more students and they use a different textbook series. All students at Institution 2 are required to take Calculus 1 and 3.

There is a large PhD program in mathematics at Institution 2 and all graduate students are funded through Teaching Assistantships, unless they obtain research funding. Graduate students at Institution 2 act as course instructors for pre-calculus, Calculus 1, or

Calculus 2. These courses are coordinated at Institution 2, including common midterms, a common final, common online homework, common written homework, and a suggested schedule. As the course instructor, GTAs are responsible for creating quizzes and grading exams. The schedule, homework, exams, and the final are developed by the coordinators. If a graduate student is determined to not be suitable as a course instructor (for language reasons or instructor quality reasons) they are placed as a tutor in the tutoring lab.

What is the (implicit or explicit) guiding philosophy of the model?

Institution 2 has an innovative approach to calculus and the GTA-PD model is designed to support GTAs in enacting this approach. While there is no explicitly stated guiding philosophy, the Coordinated Innovation model implicitly relies on a number of. Specifically, based on conversation with the multiple faculty involved in the development and implementation of the graduate student training, conversation with graduate students, observation of the training, and analysis of the documents for the training, I have identified the three following overarching goals of this GTA-PD program:

1. To familiarize GTAs with the logistics of their responsibilities as instructors at Institution 2;
2. To gain buy-in from the instructors about the main tenants of Institution 2's approach to calculus;
3. To provide a number of opportunities for GTAs to practice teaching and get feedback before stepping into the classroom.

As I describe in the following section, the Coordinated Innovation GTA-PD model operates based off of these guiding beliefs in a number of ways, and these beliefs

appear to be held by all facilitators of the GTA-PD as well as administrators that support the approach to calculus.

What are the structural components of the model?

The GTA-PD program at Institution 2 prepares GTAs to teach coordinated sections of Calculus 1 that are taught in an innovative way. The main component of the GTA-PD is a five-day training seminar that takes place the week before the semester begins. There are also weekly course meetings and periodic observations by faculty and experienced GTAs. In the following sections I detail each of the components of the “Coordinated Innovation Model.”

Summer Training. The training consists of five consecutive days during the week before the semester begins. In Fall 2012, there were around 30 new GTAs that participated in the training. The training is led by the three calculus coordinators and a number of faculty and experienced GTAs, who help organize and run sessions. This training encompassed multiple opportunities for graduate students to present a prepared lesson and get feedback, as well as a series of presentations that aimed to introduce graduate students to the specific approach to calculus and to convince graduate students why this approach is useful. In this section, I provide a detailed description of this week-long training.

The first day (Monday) started with a “Math Department Orientation” for all new graduate students only, followed by lunch with faculty. Then the professional development staff introduced themselves, students were told about the structure of the week and assigned a Calculus 1 section to present for the videotaped teaching and group

work demo, and the Department Chair gave a talk about the “Professional Responsibilities” of being an Graduate Student Instructor (GTA).

On Tuesday, students were split into groups of four (three new students and one facilitator) for “Short Individual Practice Teaching.” Each graduate student was videotaped giving a seven-minute lesson to the other students and a facilitator, followed by replaying the videos and a discussion. Institution 2 highly recommends Calculus 1 instructors to structure their class as a cycle of short lectures (less than 15 minutes) followed by time for students to work in groups on problems related to the lecture. The “Short Individual Practice Teaching” allows instructors to practice and get feedback the lecture component of this structure.

The facilitators were given explicit guidelines for how to run this session (e.g. “Keep the camera running: as the next person goes up in front, the person who has just finished goes to the camera to video tape the next presenter.”), what type of feedback to give (instructed to attend to “Material and Content” and “Technique and Delivery”) and how to facilitate a discussion among all instructors (“Begin with good things before addressing those things that didn’t go so well. Encourage all others to give feedback before you give any yourself.”). All of the GTAs I spoke to after the training week was complete identified this component of the training as the most useful.

GTA 2.1: So I also thought [the mini-lectures] were the most useful things for me. First of all, I think it's always useful when someone is diagnosing sort of your individual habits or mistakes or whatever, but also I thought just sitting and watching other people a lot of issues actually come up when teaching is actually being done that don't come up on a PowerPoint presentation when you're talking about teaching in abstract.

After the videotaped lessons and a lunch break, all GTAs listened to a presentation by three faculty about the structure of Calculus 1 and 2, the profile of the students in Calculus 1 and 2, and Institution 2's approach to calculus. This approach entails a course that is structured to focus on interaction in a group setting and to include group work in order to achieve a dialogue between students and instructors. The content focuses on developing conceptual fluency of the material rather than procedural fluency, including emphasizing graphical understanding and real-world examples. This content focus is supported by the Hughes-Hallet text, and complemented by interactive classes, technology, and multiple forms of evaluation. A large part of the training is focused on "selling" this approach to Calculus to the GTAs so they will in turn "sell" it to their students. This presentation is one of three specifically aimed at introducing Institution 2's approach to calculus to GTAs and getting buy-in. After a break, GTAs were split into two groups given the same presentation: "Cooperative Learning Techniques and Interactive Classroom Modeling." The purpose of this presentation was to introduce the GTAs to the interactive classroom format by modeling this type of environment. After modeling the environment the facilitator asked the GTAs to reflect on their experiences in this environment (e.g. How is this different from the experience of seeing someone explain the answers? Why might we use cooperative learning/ group work in class?). After this reflection, there was a presentation about "Why we use cooperative learning" and encouraged GTAs to voice their concerns about using cooperative learning and how they might mitigate these concerns.

Wednesday started with "Extended Practice Teaching." The GTAs were broken up into four groups of about six students and one faculty facilitator, and each group went

to one of the actual classrooms that they teach in. Each GTA gave a 12-minute lecture and other students asked questions as though they were students. After each extended lecture the Course Coordinator for Calculus 1 gave feedback and other graduate students added feedback as well. In general, the graduate students appeared much more comfortable than the previous day, in their teaching as well as in asking each other questions and giving feedback to one another. These extended lectures are purposefully twelve minutes because the suggested format of a class is comprised of multiple iterations of approximately twelve minutes of lecture followed by group work. After these extended lectures and a break, all GTAs attended an hour-long presentation about “Most Things You Worry About Never Happen” that addressed how to deal with difficult students. Next was a presentation about “How to IBL?” that addressed techniques and suggestions for an interactive classroom. After a break there were Technology Breakout Sessions that discussed technology use and availability. Thursday began with “Running an Interactive Classroom” where a subset of instructors gave and managed an in-class group assignment. This was another opportunity for practice teaching where instructors were placed into groups to mimic a classroom environment and focused on the group-work component of class instead of the lecture component. Every instructor came prepared to lead the group-work activity, but not all instructors were chosen to demonstrate. All instructors who were not presenting were given student roles, such as “work very slowly on the problem, by yourself. When the instructor comes by, ask questions to check that each step of your work is correct.” The facilitators were given explicit guidelines about how to run the session, how to facilitate the discussion after instructors present, examples of specific things to look for to bring up in discussion (e.g.

“Did the instructor interact with the groups and determine where they were and what they were stuck on?), and goals for the session (including “give instructors practice thinking on their feet” and “provide instructors with experience using the book in the context of an active learning Institution 2 classroom”).

The GTAs with whom I spoke said this practice teaching session was not as useful as the practice lecture from Tuesday because many of the instructors goofed off in their roles as students. One of the GTAs I spoke with was able to present her group-work and get feedback, and she said this was useful. One of the GTAs suggested that it would have been more useful had they been split into smaller groups so that everyone could present and get feedback.

GTA 2.2: In fairness I think they could have broken us up into smaller groups if they wanted us to all go. I think it was more about demonstrating to everyone using a few people as examples. And the people who did go I thought by in large like got very good feedback in terms of they usually had one thing that kind of stuck out totally to the entire class as like a way that they weren't really in control and I don't know. You know, it was still quite useful I think.

After the practice group-work sessions, there was a presentation about “Grades, Ethics, and Values” discussing how to handle the instructor-student relationship. After this there was a presentation about “Setting up and running out-of-class homework teams” discussing how to form teams, team roles, etc. After a lunch break, there was a presentation about “Understanding Student Thinking” that drew on feedback from Institution 2’s “efforts to probe students’ conceptual understanding. Part of this presentation was a short video clip of a Calculus 1 student reasoning about a complex

problem a month into the term. Many students seemed very impressed with the student's thinking, and expressed in the focus group that this was an especially interesting component of the training.

Based on the facilitators' notes from the instructors' practice lecture (on Tuesday) and practice group-work (on Thursday) they assign graduate students to precalculus, Calculus 1, Calculus 2, or (rarely) to work in the tutoring lab. In Fall 2012, 35 brand new GTAs were assigned to Calculus 1 and the other 15 sections of Calculus 1 were taught by the course coordinators, a few faculty members, and experienced GTAs or post-docs.

Calculus 1 Coordinator: So we all meet as a group and sort of, we have a list of names and like a sort of space to right comments and then we're writing comments for each person and normally that helps us place them into the right course. So if we have someone who we think would do better in the 105 setting then we'll sort of mark that for a 105 or 115 and there occasionally are people who we don't think are ready for the classroom and we have places in our math lab that we can give them and it's not always, it's not always that they would be bad it's just sort of sometimes it's throwing them into a class might not be fair to them, really is often then case.

On the last day there was a presentation by the Center for Research on Learning and Teaching about classroom dynamics. Then GTAs were given their assignments, and then there were course meetings to discuss initial course logistics.

In summary, this training is highly structured and well planned. It is planned jointly by the Course Coordinators with support and input from a number of other faculty members and experienced GTAs. Because there are a number of facilitators running the training, there are explicit guidelines for facilitators so that the sessions all run as planned. Many of the materials are re-used year after year, with small additions or

changes made based on the facilitators' experiences and feedback from the GTAs. Of the GTAs that I spoke with, there was consensus that the practice teaching components were very useful, but that the presentations were much less useful.

Coordination. There are three coordinators for the Calculus sequence that share the responsibilities. In addition to being coordinators, they teach the course that they are coordinating. Their coordinator responsibilities include: (a) running the Graduate Student Instructor (GTA) training; (b) observing all instructors; (c) writing the written homework; (d) create the exams; and (e) run a weekly meeting for all new instructors. coordinator chose a co-coordinator to assist with these responsibilities. The co-coordinators are experienced GTAs who are funded for a semester of work, often third-year graduate students who is selected or sometimes volunteer for the position. The co-coordinator is responsible for writing the written homework assignments and helping to write the exam, help conduct observations, and help run the week-long summer training.

All of the GTAs we spoke to noted that they had freedom in the classroom. They are provided a very rigid schedule, the exams are common, the homework assignments are common, the physical classroom structure forces students into groups of four, but still the GTAs feel that they have freedom to run class the way they want. If they deviate too much from the schedule or the suggested instructional format, this will come out during observations, midterm evaluations, or students' performance on the exams. A number of GTAs also mentioned that one benefit to this coordination was that in their students' minds the GTAs are "on their side" and "someone higher up" make decisions about what is on the homework, exams, and the structure of the class.

Weekly Meetings. There are weekly course meetings led by the course coordinator that are required for all first time instructors (GTAs and post-docs) to attend and experienced instructors can choose to attend. These course meetings previewed upcoming materials, address common student difficulties with upcoming materials, and other logistics (such as exam grading schedules). One GTA described these meetings as addressing logistical, practical things as well as “how we're going to teach this section, notice this section is hard for students, make sure you emphasize this thing.” New GTAs knew that these meetings served as a place to address issues with running class, such as with group-work or specific content issues. For instance, one new GTA said that the practice training surrounding group-work was less helpful than the practice lecture, but that he felt comfortable knowing that the weekly meetings were available to address any issues that came up:

GTA 2.1: Yeah, I feel like most of the other things because we're going to be having these weekly course meetings like you'll actually do group work for the first week and you realize what all these problems are and they'll actually be in front of you and not sort of like fabricated and then you can talk about them. And I think that will be a lot more useful when it happens.

A number of questions came up during the observation of the weekly meeting that addressed both logistical issues and student thinking. Experienced instructors do not choose to attend often, although there were a number of experienced instructors that attended during our visit. Multiple graduate students said that the meetings are longer than needed and that the information could be conveyed via email. However, the observed weekly meeting seemed to function not only as an opportunity to cover the

logistics of the week, but also a venue for informal discussions about student thinking and difficulties.

Observations. Many instructors pointed to how helpful the observations were. Every Calculus 1 instructor is observed at least once during the semester, with the new GTAs observed first. During the observation, the observer attends to how the material is presented, the interactions between the students and the instructor, and the instructor's control over the class. The team of observers is comprised of the coordinators, the co-coordinators, and other instructors familiar with Calculus 1 (including experienced GTAs). After the observations the observer gives feedback to the instructor and their comments are recorded in a database. The observers are told to attend to both the notes that students in the class would be taking based on the board work, the quality of the lecture component, and the quality of the group-work component. Typically more improvement is needed on the group-work component:

Calculus 1 Coordinator: I'll typically just takes notes on the left side of the page, exactly what I see on the board, and on the right side of the page I'll write comments. I'll try to synthesize those into something that's sort of readable for the instructor that I'm visiting, so that they have not just, I always try to give them at least half a dozen good comments with specific details about what it was I really liked and then normally there are lots more detailed comments about just things they could improve in the class and other kinds of suggestions. And normally, I can't think of a visit where I said, oh the group work went perfect in that class, so normally there's tons of comments about group work, about improving your relationship with the class, about making your lecture better and a lot of the really hard part about the format is the transition from lecturing to group work and then going over problems and then getting back to lecturing again.

Based on these observations, students' performance on the first midterm, and the midterm evaluations some instructors are observed a second time, or at least offered a second visit.

Other Resources. There are a number of ongoing professional development/ instructor support resources available to GTAs in addition to the weekly course meetings. One of these resources is the course coordinator, who answers GTA emails about student issues, logistical questions, and in general serves as a resource for questions about teaching. When I asked a group of GTAs to reflect back on the training after they had taught for a few months to rate how prepared they were, they said they felt mostly prepared but ran into problems with students that they weren't prepared for, such as cheating or long-term illness. When I asked how they dealt with these situations now, they all said they talked to the course coordinator. Another resource are the lessons plans that are made available to all GTAs. There are lesson plans for the entire course for precalculus and up through the first midterm of Calculus 1. Additionally there is a problem bank for quizzes. This is a bank of problems put together by past instructors, and available as needed for current instructors.

What knowledge and practices are emphasized through this model, and how?

The main emphasis of this training is on developing specific pedagogical knowledge surrounding the student-centered instruction recommended by Institution 2. This includes instructing graduate students on the decomposed components of the recommended instructional approach and giving them practice and feedback in implementing approximations of these components. In addition to this type of

knowledge, there is some emphasis on developing knowledge of students' thinking surrounding the type of calculus problems that are part of this approach to calculus. This comes in the form of watching a few videos of students solving problems during the week-long training and during the weekly meetings where GTAs ask questions about student difficulties and get feedback with how to respond. However, this type of knowledge could (and should) be emphasized more.

During the Coordinated Innovation professional development program, GTAs at Institution 2 get multiple opportunities to practice teaching. This experience is embedded within a week-long summer training where graduate students have two opportunities to present the lecture component of their instruction and one opportunity to present the group-work component of their instruction. This training decomposes the expected instructional approach into the lecture component and the interactive component, and gives graduate students opportunities to enact these practices with limited authenticity. These experiences primarily enable graduate students to develop pedagogical knowledge surrounding the specific instructional approach recommended by Institution 2.

Multiple authors within the undergraduate mathematics education community have identified the difficulties in implementing student-centered instruction and the role that lacking Mathematical Knowledge for Teaching plays in these difficulties (Johnson & Larsen, 2012; Wagner et al., 2007). Speer, Wagner, and Rossa found that much of the difficulty the instructor (a research mathematician) had implementing the Inquiry-Oriented Differential Equation curriculum was due to his lacking special mathematical knowledge of student thinking and common difficulties (Knowledge of Content and Students). Johnson and Larsen (2012) similarly found that an instructor's ability to

effectively implement an Inquiry-Oriented Abstract Algebra curriculum was constrained by her knowledge of content and students, which specifically affected her ability to listen interpretively and/or generatively to her students' mathematical contributions.

This specific type of knowledge may be gained from teaching experience, reading mathematics education research into student thinking, or from professional development programs that focus on student thinking (Ball, et al., 2008). The graduate students that teach at Institution 2 typically have little teaching experience to reflect on and little (or no) knowledge of mathematics education literature. Thus, it would be especially beneficial for this professional development program to focus more on student thinking and how to leverage student thinking in one's teaching in order to develop the knowledge and practices surrounding implementing innovative instruction.

What aspects are necessary to institute this model?

The Coordinated Innovation Model is itself necessitated by the large number of Calculus 1 students taught in small classrooms using innovative instruction. However, these components are not necessary to implement the model. Institution 2 is responsible for teaching a larger-than average number of Pre-calculus, Calculus 1, and Calculus 2, and the Coordinated Innovation Model could easily be implemented at institutions with the same or fewer undergraduates. This model relies on having an about 30-1 ratio of undergraduates taking Calculus 1 and GTAs. Additionally, this model relies on a team of faculty and experienced graduate students who believe in the approach to calculus and are interested and able to contribute to the training of GTAs. The week-long seminar is very time and resource intensive, with one of the primary resources needed being

facilitators. Of course, another major resource is financial, which in turn requires the support and ability of administration.

This GTA-PD model is highly connected to Institution 2's innovative approach to calculus. Thus, while a structurally similar GTA-PD could be instituted surrounding a more traditional approach to calculus, many of the component of the Coordinated Innovation Model would not be necessary. Specifically, there would not need to be an emphasis on gaining instructor "buy-in" to teach in a more traditional way. However, instructors would still benefit from having many opportunities to practice teaching and getting feedback, and having weekly meetings to support their instruction and provide opportunities for informal discussion.

What are the affordances of this model?

Institution 2 is responsible for teaching a large number of students in Calculus 1, and has set up a system where these students are taught in a research-based, innovative approach, rather than in large lectures as is often done when with a large Calculus 1 population. In order to maintain small classes, Institution 2 primarily employs graduate students as course instructors, and in order to maintain consistently with respect to the approach to calculus, Institution 2 has a highly coordinated calculus program. The Coordinated Innovation Model prepares new GTAs as course instructors in this unique environment, very likely an environment initially unfamiliar to the graduate students as well as the undergraduates enrolled in these courses. The Coordinated Innovation Model succeeds in introducing GTAs to Institution 2's approach to calculus and successfully provides a number of opportunities for GTAs to practice teaching and get feedback. The

GTAs reported that these opportunities to practice teaching were extremely helpful and that they felt prepared to go into the classroom and teach in the intended approach.

One area that Institution 2 could improve upon is the emphasis on gaining buy-in from instructors about the unique approach to calculus. Not all GTAs felt “convinced” that Institution 2’s approach to Calculus 1s the best way to teach, and others did not feel that they needed to be convinced – rather that they trusted the motivation for teaching in a certain way and did not question its utility.

GTA 2.3: I would say that I haven't really found the components of this week outside of our morning sessions of teaching like I haven't found those to be very useful. I don't think that it has made me more prepared to deal with inquiry-based learning situations.

Thus, with respect to the goals articulated above and my discussions with the GTAs, the training does a good job accomplishing goals (1) and (3), but not goal (2) and it is an open question if this needs to be one of the goals of the program.

Perhaps one way to address the goal of gaining instructor “buy-in” without getting the negative feedback I heard would be to “show instead of tell.” During the summer training there was a short video clip of a Calculus 1 student reasoning about complex problems one month into the semester. All of the GTAs I spoke with after the training said this was a very interesting part of the training, that they “were impressed with what the student said”, they “could have watched a pretty long amount of [videos]”, and that the video served as evidence for enacting the instructional approach encouraged through the Coordinated Innovation model.

GTA 2.3: It's like this promise of this extremely rewarding thing where you have this student who is not a star student and is like a pretty good student, but a month later is able to have a very intuitive understanding of what is going on.

These students further appreciated the experience of interacting (albeit through a video recording) with a real Calculus 1 student rather than fellow graduate students and faculty acting as students. In essence, these graduate students appreciated how the videos approximated the practice of interacting with a student as s/he solved a problem, though in a fairly inauthentic way. Thus, perhaps in addition to more time spent showing videos of student, Institution 2 could also bring in real students for the graduate students to interact with. This may be unrealistic to occur during the summer training, but a feasible addition to weekly meetings.

This suggestion additionally addresses the potential knowledge deficit identified above. Institution 2 recommends a specific student-centered instruction, and mathematics education literature has identified that a major barrier in effectively implementing this form of instruction is the instructors' limited knowledge of content and students, including knowledge of students' thinking in a specific domain. One way to foster this knowledge is by watching students solve problems out loud (in video format or in person), and responding to and reflecting on their thinking in an authentic way, as is done in professional development for Cognitively Guided Instruction (CGI).

Peer-Mentor Model

There are two institutions that employ graduate students primarily as recitation leaders and employ the Peer-Mentor Model GTA-PD program. In the following

description of the Peer-Mentor model, I articulate the characteristics of each institution that characterize the model. I then leverage the variations of each institution's implementation of the model to discuss the affordances, areas for improvement, and necessary traits of an institution needed to employ the model.

What is the institutional and departmental context that the model is embedded in and supported by?

Institution 3

Institution 3 is a large, public university with almost 25,000 undergraduates. Due to the general requirements, almost all undergraduates must take the calculus sequence. There are two calculus tracks, the "10 series" and the "20 series." The 20 series is typically geared toward STEM intending students. For instance, an English major would still have to take Calculus 1 – Calculus 3, but would take the 10 series instead of the 20 series. In a typical fall term, there are about 1,040 students enrolled in 20A, the mainstream Calculus 1 intended for STEM majors. Calculus 1 is taught by visiting faculty and tenure/ tenure track faculty. Occasionally a graduate student will teach the course. There are typically four sections of Fall Calculus 1, with between 240 and 320 students. These courses have recitation sections of 40 students led by Teaching Assistants (TAs). Calculus 1 is coordinated by a full-time faculty member when it is taught in Fall (on sequence), but not when it is taught in Winter or Spring (off sequence). When it is coordinated, there are uniform assignments and exams across all sections. Tenured faculty can "opt out" of this coordination but rarely do so.

At Institution 3 both undergraduates and graduate students serve as TAs for calculus. Their responsibilities are the same, but the TA Trainer says that he may “ask a little more of the graduate TA.” These responsibilities include running a recitation section of 40 students, grading a portion of the common exams, holding office hours, and in some cases holding a review session before an exam. Graduate students are given two recitation sections and undergraduates are initially given one. If they do receive positive student evaluations they are given two in subsequent terms. Graduate students who have finished their course work and “Advance Candidacy” are able to teach their own upper level courses as “Associate Instructors” (AI) rather than as a TA. They can be an AI for calculus courses as well as upper division mathematics courses.

Recitation sections were repeatedly described as running as “question/answer sessions” and serving the purpose of “filling in the gaps” from lecture. TAs are not required to attend lecture and report learning what is being covered in class by looking at the homework assignments and feedback from students. Both undergraduate and graduate students hold one office hour per recitation section. Graduate students are required to hold half of their office hours in the Calculus Lab and undergraduates hold all of theirs in the Calculus Lab, an open tutoring center specifically for calculus run by hired undergraduate tutors and the TAs. While TAs hold their office hours in the Calculus Lab they are expected to help their students as well as other calculus students. TAs are also responsible for grading exams and the final, but there is a hired grader for the homework.

Institution 4

Institution 4 is a large, private university with around 30,000 undergraduates. There are currently 34 tenured-tenure track faculty members and 5 visiting or temporary faculty. The Department of Mathematics offers a bachelors, masters, and a doctoral degree in mathematics. There is a separate department for Mathematics Education, and faculty and graduate students from Mathematics Education are involved in the teaching of calculus in addition to faculty and graduate students from Mathematics. There are currently over 300 mathematics majors and there are typically between 30-40 graduate students. Calculus 1 is a 4-credit course that meets for 5, 50-minute sessions per week. It is offered in both small class size and large lecture with recitation formats. For example, in the Fall 2012 there were 4 different small class sections with approximately 30 students per section and there were 4 different lecture sections ranging from 150-200 students that met three times per week plus two recitation sections with up to 40 students. A different instructor taught each of the different lectures and small size sections. In 2008 they introduced large sections. Prior to this, GTAs taught the small sections of Calculus or College Algebra. In Spring and Summer there are only small classes because of the smaller demand, and in this case the GTAs often teach. The textbook for Math 112 is *Single Variable Calculus: Early Transcendentals* by Stewart.

At Institution 4, graduate students are involved in Calculus 1 in two ways. The most common way is as a lab (recitation) leader for the large sections. The less common way is as the full instructor for the smaller sections. For the large section, students meet for lecture 3 days a week and in recitation twice a week. In addition to running the lab section, graduate students are also responsible for grading and recording grades. What

occurs in recitation varies from GTA to GTA and instructor to instructor. The observed sections ran like Q&A sessions, but some graduate students also spoke of providing their students with worksheets and being asked by their supervising professor not to run class in a Q&A format. Some supervising professors observe their Teaching Assistants, some have their TAs come to their class, some have weekly meetings with their TAs, some tell them exactly what to do during lab, and some do none of these. Graduate student Teaching Assistants are expected to work 15-20 hours per week, and come from both the Mathematics Education masters program and the Mathematics masters and PhD program, depending on which department the supervising professor is from (mathematics GTAs work for mathematics professors; mathematics education GTAs work for mathematics education professors).

What is the (implicit or explicit) guiding philosophy of the model?

At both Institution 3 and Institution 4 the guiding philosophy for the model is not explicitly stated in any one location, but discerned from a number of sources. The professional development programs appear to be motivated by similar goals and orientations at each institution. Specifically, the Peer-Mentor model appears to be driven by the following goals:

1. Familiarize GTAs with their job and its expectations, responsibilities, and benefits;
2. To help graduate students anticipate and prepare for classroom problem administrative duties; and

3. To provide ongoing support as issues arise (mainly through the Senior TA as the point of contact).

In addition to these goals, the Peer-Mentor model is driven by the disposition that a more experienced GTA is not only capable of preparing and facilitating seminars for GTA-PD, but also is a better point of contact for GTAs than a faculty member. This role is viewed as a benefit to both the novice GTAs as well as for the experienced GTA in transitioning to the role of faculty member.

What are the structural components of the model?

Institution 3

At Institution 3 the TA training involves seminars throughout the term, observations of their teaching, and evaluations. The primary component is the Senior TA who is responsible for preparing and running the seminars, observing TAs, and in general serving as a point of contact for the TAs. There is a website for TAs that is run by the Senior TA and thus the maintenance relies on who is in the position. The website was well maintained and provided advice for getting feedback on teaching, and answers to commonly asked questions.

Senior TA. The main component of the TA Professional Development program at Institution 3 is the Senior TA position. The Senior TA is a fifth year PhD Mathematics student who has experience as a TA and was selected to be a Senior TA by the Graduate Vice-Chair. As Senior TA, they do not teach or work as a TA for any classes; the position of Senior TA is their sole responsibility with respect to their TA appointment. Senior TAs are responsible for:

- Scheduling TAs based on their requests, availability, and abilities;
- Monthly meetings with the Graduate Affairs Committee, discussing “what’s going on with graduate life”, including the cleanliness of GTA offices;
- Planning and running the 2-hour long TA training seminars that occur 3 times in the first quarter and 1-2 times the following quarters;
- Observing all first time TAs and providing feedback;
- Being available to help solve problems that arise with TAs;
- How to support and deal with TAs that get very low evaluations;
- Running the Open House for potential incoming graduate students;
- Training the new Senior TA.

Senior TAs are chosen during their third year and enter into the position during their fourth year as an incoming Senior TA (also referred to as a Junior TA). The incoming Senior TA participates in all aspects of the Senior TA position so that he or she can learn what the role entails. While participating in these activities, the incoming Senior TA still has their own TA responsibilities as a TA for a course. The incoming Senior TA during my visit described his responsibilities as doing very little:

Junior TA: In my role as Junior TA, I've done very little. I've been waiting in the wings and observing and helping Timothy pass ideas. Mostly being sort of Timothy's right hand man.

The Senior TA role comes with a high degree of autonomy relative to regular TAs. In addition to the structured roles of the Senior TA outlines above, there is support and encouragement for the person in the role to implement new ideas. For example, the

current Senior TA and the incoming Senior TA together decided to have the TAs observe each other and give feedback. When I asked how this idea came about, the Junior TA said that it has been in the works for some time but just finally being enacted:

Junior TA: That's a good question. It's sort of been digested over time through the Senior TA line and I guess over the years people have been getting feedback that the TA observations are really helpful, how can we do more of those and this is a way that makes it relatively easy for the Senior TA. They don't have to do a lot more work. We used to have a TA training meeting where established TA's would come in and say this is what I do in my section. It's not nearly as instructive to hear what someone has been doing as it is to see what someone's been doing. That's been tumbled around for a while and people have said, " This is the right solution." Work on it for a couple years and then evolve it again.

Seminars. There are three 2-hour mandatory seminars during the first quarter for first time GTAs. The first seminar takes place just before the term begins, and the emphasis of this seminar is to prepare GTAs for the first day of class. The main goal of the first session is to make sure TAs are comfortable and confident walking into class on the first day. One TA described the training as not memorable but sufficient:

Junior TA: Just having the introduction say, this is what it is going to be like, everything is going to be fine, don't worry, was very helpful. I don't know that I remember any of the particular information they told me that day, but it was enough to get me in and happy.

Based on my observation of what was discussed during this seminar, I would identify it as acting as a representation of practice, albeit a brief representation. The senior TA gave a narrative of what the recitation section looks like, what their role as instructor is, and gave them materials that would prepare them for the first day. The

senior TA remarked that the first session always happens, and the following seminars do not necessarily always take place.

Senior TA: The first quarter [the seminar] definitely happens and you have one meeting that tells you what to talk about, how to get in touch with your instructor, what to be prepared for as far as workloads, what's expected of you, what's not expected of you, and these kind of things. Then just like a sheet of ideas to run through on the first day, like go over old Algebra facts that people mess up a lot, or new Calculus facts like what they might be learning in this lecture. Just to give them ideas so that the first few sections can run as smoothly as possible, even if it's their first time ever in front of the board in this situation.

Undergraduate TAs are recommended to attend the summer seminar but it is not mandatory. Typically, they have a ten minute conversation with the senior TA regarding how to run their recitation and are provided documents. The one undergraduate TA I spoke with described the preparation she received as very minimal:

TA 3.1: There is some sheet that they give us. It has general things like what to expect, or what to do on your first day. I don't remember now what it says. I remember the main thing that I got from it like it says at the bottom don't dismiss your class early because it will set a bad precedent for the rest of the quarter...That was the one thing that I really remember. Ben Wilson was the Senior TA and he said to me basically think about your favorite TA and model your discussions after that, so that's pretty much what I did.

The undergraduate TAs do not attend any ongoing training. They can ask the Senior TA if they have questions, and they are evaluated by their students at the end of the term. They are not observed leading recitation. When asked about her final comments

bout the calculus program at Institution 3, the undergraduate TA I spoke with mentioned the lack of training she received, and how it is in the TA's hands to ask for more support:

TA 3.1: I think the only thing that I wanted to say was about the training. How I basically got none. If I had asked for more help I probably could have gotten it, but I don't think that the majority of people ask for help on TA-ing.

GTAs participate in required seminars during the first semester, and other ongoing training is determined by the senior TA.

Senior TA: The second training then goes over more on grading exams. This will happen a week or 2 before they grade their first exam, right around that time so that they know. We run through a few examples. Put on some transparencies go through different ways students have answered questions, how they would grade it and tell them that it certainly does not have to be uniform amongst all them, but their own specific grading technique has to be uniform and make rubrics so that there's consistency. So if a student 2 weeks down the road asks for a re-grade they are able to pull out the rubric and remember why they got the grade they did. The third training speaks more to final exam grading, how long you have to hold onto exams, and when things will be returned. But by this time most people are feeling pretty comfortable.

These meetings primarily serve to focus TAs' attention to the decomposed activities of proctoring and grading exams. These meetings also provide an opportunity for TAs to investigate student thinking by looking at records of students' solutions and discussing how they would grade them, which approximates the practice of evaluating student thinking in class and on exams.

Observations. Both undergraduate and graduate TAs are observed at least once while teaching their recitation section. This may be done by the professor leading the class that they are leading the recitation for, or may be done by the Senior TA. They meet with the observer after and get feedback. This is viewed as a non-evaluative observation, and may occur more frequently if a TA needs more feedback. This is the primary form of TA training for undergraduate TAs, and the undergraduate TA said it was very valuable to get this feedback.

GTA Placement. All graduate students are funded through a Teaching Assistantship unless they have research funding, which is not common. The senior TA is in charge of making a draft assignment for all TAs based on their requests, schedules, the instructor of the course, and the senior TA's knowledge of the student. The Senior TA often tries to pair more experienced TAs with less experience instructors, such as visiting professors, and less experienced TAs with more experienced instructors. Once the senior TA develops a draft of the assignments the TA assignment committee approve it, or make adjustments as they see fit. Graduate students are able to TA for upper division courses as well as lower division courses, and many more experienced GTAs request upper division courses because they are more interested in the content and upper division courses count for the twice the time that lower division courses do. If a graduate student is doing a poor job as a TA and they do not show interest in improving, then they may be given a reduced TA load (for example they may only TA for one class rather than 2) and thus receive a reduced stipend.

Undergraduate students interested in working as a TA must submit an application and have earned A's in the Calculus sequence, completed the proof course, and earned an

A in either Abstract Algebra or Analysis. The undergraduate TA described the undergraduate TA selection process as “going by the grades” and that the majority of undergraduate TAs were suited to lead recitations.

Institution 4

GTAs in the mathematics department at Institution 4 receive a two-day training through the mathematics department and prepared and led by the Senior TA. There is also a one-day training for GTAs run by the university that none of the GTAs we spoke to reported utilizing. GTAs in the mathematics education department reported having no training, but many of them had teaching degrees or credentials. They used to train the mathematics and mathematics education GTAs together but each department decided that their students had different strengths and needed different things from the training.

Senior TA. In the mathematics department, there is a Senior GTA position that is responsible for running a two-day summer workshop for mathematics GTAs. This position is held by a PhD mathematics student who has worked as a GTA for a number of years. Interested GTA's turn in an application consisting of an essay portion and a few letters of recommendation. Their students' responses to the mid-course evaluations are also taken into consideration. The Senior GTA is given freedom to design the contents of the workshop with approval from the TA Trainer. This workshop is for all new mathematics GTAs and is designed to prepare new GTAs for the first day of recitation. In Fall 2010, there were 12 new mathematics GTAs (both MS and PhD students) that participated in this seminar. When asked about his role as Senior GTA and what he did during the two-day session, the Senior TA said:

Senior TA: Okay, so what they do there is they had, you apply for the position for coordinating the TA training and then what you do is you identify and put together a number of workshops that were things that you would think new TA's would need to know. I did ones on communicating effectively. We had the videotape session again, answering difficult student questions, coordinating office hours, preparing a lesson and a couple other ones... Things that would get people ready for their first recitation section.

Additionally, the Senior TA said that he met with the professors teaching during Fall for whom the GTAs would be running recitation sections for, and got input for what the GTAs needed to do during the first session. The Senior TA then shared this with the new GTAs and had them put together a sample lesson plan. From this, they divided the lesson plan into 15-minute segments and used this for the practice teaching. GTAs were videotaped delivering these 15-minute lessons and then given feedback by their peers, a mathematics education faculty member, and the Senior GTA. Thus by the time the term started, all of the first time GTAs “had what they were going to do that first recitation section all prepared.”

Each year there is a new Senior GTA who designs a two-day seminar. When asked how much is reused each year, the Senior TA said that the new person would “certainly be able to take the schedule. With maybe some minor modifications, probably 60-70% [of what he had done] if they chose to.” When asked why this needs to be redone every year instead of reusing the materials with minor tweaks, the Senior TA voiced that part of the reason is to provide the Senior GTA ownership of the role:

Interviewer: *Why does it need to be re-done every year?*

Senior TA: *Let's see, I mean whoever gets it next year, I guess the blunt answer is I guess it doesn't, but certainly whoever's running the seminar next year is going to have their own insights into what's affective in teaching and what's not. I can only go on what my personal experience was and what I feel the most important things in teaching are.*

Interviewer: *So maybe part of it is just gives more ownership to the person?*

Senior TA: *Yeah.*

The specific structure of the Senior TA position at Institution 4 is different from the position at Institution 3. Specifically, at Institution 3 this role extends throughout the entire year and involves developing and leading the professional development program, and in general being a resource for graduate students and the departments throughout the year. At Institution 4, the responsibilities of the Senior TA consist exclusively of developing and implementing the summer training for TAs. At Institution 3, there is a structured system in which the new future Senior TA is apprenticed into the role which ensures cohesion from year-to-year, and reduces the amount of “new” development the Senior TA must do. At Institution 4 no such system exists, and thus the Senior TA redesigns the training program each year.

Mathematics Specific PD. The primary training that mathematics GTAs receive is the two-day seminar described above that is designed and run by the Senior GTA. This seminar is for new mathematics GTAs only, and prepares them to run a recitation section. There is no extra training provided for GTAs that become sole instructors. In addition to this seminar, there is a University wide seminar that is optional for all new GTAs to attend, including mathematics and mathematics education. This one day seminar was described as “broad” by a number of GTAs and the TA trainer. One mathematics

education GTA described the contents as “Be nice to your students, don't tell them what each other's grades are' and things like that.”

There is also an ongoing seminar run by the TA Trainer that is optional. At the time of the visit it was unclear if this was still being run. The TA Trainer described this seminar as being comprised of:

basic teaching techniques though, some of them are just basic board skills, communication skills, you can see 'dealing with problems in office hours,' 'how to write a good lesson plan,' 'How to Review Your Lesson Plan and Give Yourself Feedback,' assess your teaching, as well as having people observe and getting different kinds of assessment; 'Grading,' really basic skills, one each week.

Although the ongoing seminar was mentioned by the TA Trainer, none of the GTAs (mathematics or mathematics education) mentioned that this seminar was a part of their training. It is possible that other GTAs attend, but because it is optional it does not seem to be widely attended.

The only ongoing type of professional development that is required across all mathematics GTAs is a faculty observation every semester. Although there was little oversight for what occurred after the observations, faculty were encouraged to “meet with GTAs to point out the mostly positive things they'd done, and then pick 2-3 things that they recommend for improvement.” Additional observations were done as needed for GTAs that were struggling more than others, and during this follow up the TA Trainer would specifically attend to improvement on the 2-3 things originally pointed to as areas for improvement. GTAs were not warned for when this observation would occur.

The primary way GTAs are assessed on their teaching is through a mid-course evaluation. The mathematics department sends them to all of the GTA's students and the

anonymous feedback is given to the GTA's. A number of the GTAs said this feedback was helpful. When asked if the current preparation for mathematics GTAs was successful and if there was anything more that could be done, there were mixed responses. The Senior TA said that the training prepared him to step into the classroom on the first day and made him aware of everything he needed to do in the role, but that what a TA takes out of the training may vary because "certainly there's personal responsibility on the new TA's part as to how much time and effort their willing to put into that." The Course Coordinator for calculus said that the training was mostly successful but that he felt that the TAs "need some practice" and sitting in on someone else's TA recitation section before being a TA would be helpful.

Mathematics Education Specific PD. The training for mathematics education GTAs is minimal, and exists separately from the training for Mathematics GTAs. There appears to be a perspective that, because the mathematics education students come in with interest in education and often experience teaching, they need little training to be TAs. However, some students voiced difficulty initially in both remembering the content they were expected to teach and knowing what the format of a recitation section is. For instance, a mathematics education GTA for Calculus 1 said:

GTA 4.1: I think that one of the hardest things for me when I was teaching 112, I hadn't even taken it since high school, and so I couldn't remember the things that we talked about, or why it mattered to talk about this now, and how that fit into the grand scheme of things. And so the 1st time around, it was really hard for me to know what things I should emphasize and what things are okay to let slide and things like that because I didn't quite remember what was coming up next. So then when I had the whole picture, the next semester was a lot easier.

She added that she would have felt more prepared if had she had a mentoring experience similar to one she had for a mathematics education course. In this mentoring experience, she sat in on the class for one semester before she taught it. She said this was very helpful, but was unsure if it could be implemented in Calculus 1.

Depending on the instructor that the GTAs are working for, there may be weekly meetings to discuss what is happening in class and in discussion section. While this is true for both mathematics and mathematics education GTAs, during the visit only the mathematics education GTAs said that they participated in weekly meetings. These meetings function mainly to discuss what will be covered in class and how to run the recitation sections, but also provide a space to discuss student thinking:

GTA 4.2: We'll often say, 'I realized students were making this misconception, so this is how I presented it in class, and it seemed to go well.' Or we might say, 'I gave them this question, and they got really confused.'

Overall, the mathematics education GTAs appeared to feel successful as recitation leaders or instructors on record, after gaining experience as recitation leaders, even though their training to do so was minimal.

GTA Placement. All incoming mathematics and mathematics education graduate students get funding for grading, leading a recitation section, or being a course instructor. These assignments are intentionally assigned so that more experienced graduate students are course instructors (if they have requested to be one) and the least experienced or those who have not been successful in other roles and placed as graders.

GTAAs are evaluated on their teaching based on student evaluations and observations. All graduate students are initially guaranteed funding through a TA fellowship. If a GTA is “failing at teaching” they would have to write a formal letter addressing how they're going to work on their teaching which would be reviewed by the GTA trainer and the chair of the graduate committee. If their teaching did not improve, they would lose funding. The TA Trainer said that the college has removed funding for students who were not doing a good job teaching because “funding is not based on being a grad student, it's based on teaching or interacting with students, so if they aren't doing it, they don't get funding.”

What knowledge and practices are emphasized through this model, and how?

The Peer-Mentor model is driven by a need to prepare novice graduate students to run a recitation section and utilizes a more experienced graduate student as the main resource for preparing and supporting novice graduate students. The primary type of knowledge that is emphasized in this model is pedagogical knowledge: how to structure a recitation section, how to grade exams, how to prepare a lesson, and how to run office hours.

There are some informal opportunities in both instantiations of the Peer-Mentor model for graduate students to develop PCK. At Institution 3 there is a meeting before the first midterm where graduate students looked at past student solutions of exams problems and analyzed why they did what they did and how to grade the problem. This activity provides GTAs an opportunity to approximate the decomposed practice of grading and making sense of a student solution. While the main goal of this session appeared to be to

train graduate students how to grade exams, this activity also provided graduate students with an opportunity to discuss and analyze student thinking. At Institution 4, discussions surrounding common student misconceptions or difficult student questions came up during the weekly meetings with the mathematics education faculty. Although the nature of these discussion depends on the instructors involved, these meetings provide the opportunity for GTAs to develop PCK, specifically knowledge of content and students.

For the Peer Mentors themselves, the process of developing the training programs and facilitating them provides very authentic opportunities for them to develop the practices of faculty. They are able to take steps into the role of faculty by acting as an advisor to more novice graduate students, and this position clearly serves as a way to help graduate students develop a sense of professional identify as an undergraduate instructor and member of this community.

What aspects are necessary to institute this model?

At both Institution 3 and Institution 4 the primary role of graduate students is as recitation leaders, and the primary goals of the GTA-PD are to prepare GTAs for the first day of class and to provide an ongoing support system as needed. The GTA-PD programs appear to successfully accomplish these goals in a resource efficient way, and the Senior TAs seem well equipped to prepare and facilitate the PD activities. It is unlikely that a Senior TA would be as well equipped to prepare graduate students to be course instructors, or to facilitate a GTA-PD program with other goals, such as transitioning graduate students from the role of student to the role of instructor. As such, this model is

likely to be most successful implemented at institutions where GTAs primarily serve as recitation leaders rather than course instructors.

This model also relies heavily on having experienced GTAs that would be interested in serving in this position. In speaking with a number of current and past Senior TAs, these individual's appear to be more interested in teaching (as compared to research) and know that serving in the role of Senior TA will be a beneficial career move in preparing them for a faculty position that is more focused on teaching. Thus, in order to implement this model an institution must have graduate students interested in pursuing careers focused on teaching as opposed to only research-intensive positions.

What are the affordances of this model?

The main PD components of the Peer Mentor model are the initial seminar preparing GTAs for the first day of class and ongoing opportunities for support and/help as needed once GTAs are in the classroom. By utilizing an experienced GTA for the planning and implementation of these main activities, the Peer Mentor model is a very resource efficient program. While there are faculty supervisors, the Senior TA is paid to facilitate many of the time-intensive activities that other faculty may not have time for. This aspect of the Peer Mentor program makes it especially well-suited for institutions that do not have the resources available to run a 5-day intensive seminar or a semester long lesson-study type class.

Additionally, the Peer Mentor provides an opportunity for more experienced graduate students to apprentice into the role of faculty, not just as instructor. In their role as Peer Mentor, these graduate students authentically engage in many service-oriented

practices that are part of faculty positions. These practices include developing and implementing the GTA professional development, as well as serving as a teaching resource for more novice GTAs.

However, there are a number of ways that this model was implemented at Institution 3 or Institution 4 that could be improved upon. At both institutions there is a sense of “reinventing the wheel” with each new Senior TA. While allowing the Senior TA to develop their own materials and have a large amount of autonomy in their role provides a sense of ownership, this needs to be balanced with being efficient with resources. There could be more carry-over from year to year, perhaps in the form of a set of materials that do not change. This would still allow for the Senior TA to individualize the PD activities, though in a more systematic and resource efficient way.

Summary and Conclusions

I began this chapter by introducing the four guiding questions that characterize a GTA professional development program, and by reviewing potential answers for these questions. I then gave examples of three existing GTA-PD models and characterized them by answering the guiding questions. These three programs are currently being implemented at institutions with Calculus 1 programs that have been linked to students’ positive affect towards mathematics, high percentages of students who persist in their STEM intentions, and/or students’ conceptual understanding in Calculus 1, and where graduate students are heavily involved in the teaching of Calculus 1. Thus, while I am not identifying the professional development programs themselves as successful, they do

prepare graduate students to participate in the teaching of Calculus 1 at institutions with successful Calculus 1 programs.

For the practitioner, the guiding questions provide an entry point into thinking about how to develop a new program. Additionally, these guiding questions can be used to demonstrate to stake holders the variety of possibilities for GTA professional development programs, and how far beyond giving graduate students a textbook and a syllabus institutions can go in preparing graduate students to teach or lead a recitation. The three models provide examples of existing programs that answer the guiding questions in different ways, and go a long way in offering a relatively complete package of a professional development program that could be implemented at their institution. Because of the individualized nature of institutional and departmental needs, these models provide a starting base that can be improved upon, adjusted, and individualized to fit the institutional and departmental context and the philosophy of the stakeholders involved. The fifth and sixth questions are especially useful in identifying components of existing programs that may be useful and how to best individualize the program to fit the specific needs of an institution.

For the researcher, the guiding questions partition graduate student professional development into four areas for more targeted investigations: the institutional and departmental context of a professional development program, the guiding philosophy of the program, the structure of the program, and the knowledge that a graduate student may learn in the program. After providing an in depth review of GTAs' roles in undergraduate mathematics education, Belnap and Allred (2009) state: "We need research that builds a knowledge base for not just telling us whether a [professional development for graduate

students] program had a specific impact, but *why* and *how* (p. 36, emphasis added)”. The four targeted areas point to dimensions of a professional development program that may be connected to the reasons a program may or may not have had a specific impact on graduate students.

Additionally, this structure provides a systematic way to compare existing professional development programs to one another. Much of the current research into graduate student professional development describes one program in depth and discusses the benefits of this specific program (e.g. Alvine et al., 2007; Hauk et al., 2006; Luft et al., 2004). Such research is very important to show the community detailed descriptions of existing programs and to begin to identify measures of their success. However, because there is no existing criteria for what is discussed when describing an existing program, it is difficult to compare and contrast the merits of one programs versus another, an issue for both the practitioner and the researcher.

In developing my characterization I identified guiding questions through thematic analysis. These guiding questions emerged from the data set and were also influenced by the literature. A primary influence was Belnap and Allred’s (2009) existing classification of GTA-PD programs. This classification helped me focus on specific facets of the programs I was seeking to describe, though it did not capture many important facets of the programs. Here I highlight the benefits of their classification and discuss ways that my characterization may answer different needs than the existing classification.

Belnap and Allred conducted a mixed methods study that surveyed over 200 Masters or Doctoral granting institutions and developed a classification of GTA-PD programs into four categories: *Orientation programs*, *Transitional programs*, *Refresher*

*programs, and Establishment programs*⁴. I found this classification to be beneficial in describing many components of professional development programs, spanning all four of my guiding questions. These include elements of the institutional and departmental context (such as how many graduate students are appointed as teaching assistants, and what the role of the teaching assistant is), the structure of the formal professional development program (such as the timing, duration, frequency of the PD activities), the stated goals of the program, and the topics covered in the program. However, I found that these components did not characterize all aspects of the programs that I wanted to describe, and this may be due to the methodology used by Belnap and Allred. These authors asked someone informed about the Teaching Assistant training program to describe the formal TA preparation programs via an online questionnaire. This data collection allowed the authors to analyze 20 programs, but restricted their analysis to the elements of the programs that were reported by the institutional contact.

In developing my own characterization for graduate student professional development programs, I found that there were traits of these programs that I was able to infer through case study analysis that were not captured in Belnap and Allred's classifications. I found their classification useful in describing elements of the institutional and department context, such as the typical number of GTAs and their responsibilities, though I found that this did not allow me to capture the relevant history of the professional development program or of the calculus program itself. Similarly, while the stated goals were helpful in understanding the purpose of the PD program, it

⁴ For more discussion on each of these categories, see Chapter 2.

did not capture the overarching philosophy of the program, and while the topics covered were helpful in understanding what happened during the training, it did not highlight the types of knowledge that may be developed through the training.

Thus I view Belnap and Allred's (2009) classification of professional development programs to be a useful way to characterize a large number of programs and a helpful initial characterization of the structural components of a programs. But in order to gain a holistic understanding of a professional development program, in a way rich enough for a practitioner to implement a version of it or for a researcher to deeply investigate it, more nuanced elements of the programs must be part of the characterization.

Such nuance is enabled by the connections I have made in this characterization to Grossman et al.'s (2009) *pedagogies of practice* and to *Mathematical Knowledge for Teaching* (Ball, et al., 2008). These theoretical connections allow me to articulate not just what the components of a graduate student professional development program are, but also how they are being used to help graduate students develop the knowledge and practices involved in Calculus 1 instruction.

The guiding questions put forth in this chapter have allowed me to richly characterize three existing graduate student professional development programs. The questions themselves begin to identify critical dimensions of GTA-PD programs and the relationships between these dimensions. In *Chapter 7*, I explore these dimensions and the relationships between them in much greater detail. Before doing so, I first dig deeper into the three existing models by investigating the beliefs and practices of GTAs coming from each model (*Chapter 6*).

CHAPTER 6: Instructor Quality Comparison Across GTA-PD Models

In this chapter, I investigate two components of instructor quality among GTAs from each of the three models described in *Chapter 5*: beliefs and instructional practices. The decision to not focus on student success for these analyses is multifaceted. First, from a practical perspective I do not have the data to explicitly connect student success to GTAs coming from different PD models. The responses from the survey data are too limited to make any connections between GTAs coming from the three models and their students' success. Second, it is nearly impossible to isolate the impact of GTAs on students' experience from the case study data, as the role of the GTA was not a component of the focus group interviews with students. Finally, the decision to not attempt to connect student success to GTAs' training and professional development experiences is secondarily driven by a desire to not further perpetuate the *process-product* paradigm. Instead of linking the process of graduate student professional development to the product of their students' success, I emphasize the potential impact each of these models had on influencing graduate students' beliefs and practices, and thus their integration and enculturation (or not) into the undergraduate instructional community.

Overview of Data Sources

For each of the three models (Apprenticeship, Coordinated Innovation, and Peer-Mentor) I first explore GTAs' beliefs about mathematics and then their instructional practices, attending to the specific impact of their training when possible. Along each of

these two dimensions, I draw from three potential data sources, although not each data source is available for each model. The three data sources are: (1) the beginning and end-of-term instructor surveys, (2) the follow-up GTA survey, and (3) interviews and observations from the case study site visits. Before investigating GTA beliefs and practices from each model, I provide an overview of each data source, and which of the three data sources I draw on for each model and why.

Instructor Survey

As part of the main CSPCC study, we sent a survey to instructor of Calculus 1 at the beginning of the term (about three weeks into the term) and the end of the term (about three weeks before the end of the term). These surveys are respectively referred to as the beginning-of-term survey and the end-of-term survey. These surveys were only sent to the instructor on record and did not include recitation leaders. Thus, I only have responses to these surveys from Institution 1 (which implemented the Apprenticeship model) and Institution 2 (which implemented the Coordinated Innovation model). I do not have this data from Institutions 3 and 4, because at these institutions graduate students are seldom the course instructor for Calculus 1 and instead serve primarily as recitation leaders.

Beliefs. As a reminder, there were 14 questions on the Instructor Start of Term (IST) survey and 6 questions on the Instructor End-of-term (IET) survey that addressed beliefs (see Appendix for a list of the questions). These items were conceptually grouped and aggregated based on these groupings. Figure 6.1 summarizes these aggregate

variables that target important components of instructors' beliefs about doing, teaching, and learning mathematics.

Variable	Survey	0	1
Beliefs about student capabilities	Beginning-of-term	students are not capable or prepared	students are capable and prepared
	End-of-term	students were not capable or prepared	students were capable and prepared
Interest in teaching and student learning	Beginning-of-term	not interested in improving his/her teaching or in student thinking and that knowledge of student thinking is not helpful for improving teaching.	interested in improving his/her teaching or in student thinking and that knowledge of student thinking is helpful for improving teaching.
	End-of-term	not interested in improving his/her teaching or in student thinking and that knowledge of student thinking is not helpful for improving teaching.	interested in improving his/her teaching or in student thinking and that knowledge of student thinking is helpful for improving teaching.
Perceived value of reflection on teaching and learning	Beginning-of-term	instructor thinking their institution, department, or colleagues does not value the scholarship of teaching and learning	instructor thinking their institution, department, or colleagues value the scholarship of teaching and learning
Beliefs about teaching and learning	Beginning-of-term	Traditional/ folk views of teaching and learning	Progressive/ expert views of teaching and learning
	End-of-term	Traditional/ folk views of teaching and learning	Progressive/ expert views of teaching and learning

Figure 6.1 Summary of aggregate beliefs variables

For each of these beliefs variables, values closer to 0 align with “folk” views of mathematics (i.e. “only some people are capable of doing mathematics”, “there is only one correct solution for mathematics problems”, etc.), while responses closer to 1 align with an “expert” view of mathematics (Carlson, 1997).

Instructional Practices. To illustrate the instructional practices from graduate students who taught as course instructors, I rely on three components of instructional practices: frequency of certain pedagogical activities, reported classroom discourse, and

the nature of the tasks in which the students engage. There are a number of survey questions from the student end-of-term survey and the instructor end-of-term survey that address each of these three components. I use instructor reports when discussing aspects of instruction that do not vary from student to student. For instance, the amount of time students spend working in groups during class should not vary much within a class. I use student reports for items that should vary by student. These include items addressing the classroom discourse from the students' perspective, including if: the instructor listened to their questions during class, he/she responded to questions by simply giving the answer, helped the student determine answers, and/or allowed enough class-time for students to understand difficult ideas.

Case Study Data

As part of the case study data collection, I conducted semi-structured interviews with graduate students, observed graduate student classes (both the main course instructors and recitation sections), and collected relevant course materials, such as homework and quizzes. Because one's beliefs about doing, teaching, and learning mathematics are interrelated to their practices of doing, teaching, and learning mathematics, I do not attempt to separate them. Instead, I discuss the espoused beliefs and instructional practices (stated and observed) together. This is consistent with Leatham's (2006) perspective that beliefs need to be understood as a system comprised of both evoked beliefs and inferred beliefs based on actions. I draw on interviews, observations, and collected course data to characterize this system. In the Appendix I provide the entire interview and observation protocols.

GTA Follow-up Survey

A follow-up survey was sent to the GTAs at the four institutions that were selected for the case study and employed graduate students in the teaching of Calculus. This includes graduate students who served as course instructors as well as those who lead recitation sections. Thus, I have responses to this survey from each of the four institutions. This survey was sent a few months following the site-visits, and the responses were anonymous.

Beliefs. Six questions from the instructor beginning and end-of-term surveys related to beliefs were modified and included on the GTA follow-up survey. A number of these questions were phrased so that the folk-like beliefs were put in contrast to the expert-like belief. These questions were expanded into two questions: one in which GTAs were asked how much they agreed with a folk-like beliefs and one in which they were asked how much they agreed with an expert-like belief. For example, on the Instructor beginning-of-term survey, Instructors were asked to respond to the question:

From your perspective, a student's success in Calculus 1 PRIMARILY relies on their ability to: (*0=solve specific kinds of problems; 1=make connections and form logical arguments*)

On the GTA Follow-up survey this question was modified so that graduate students were asked to what extent they agreed with the following two prompts (1=strongly disagree; 6=strongly agree):

A student's success in Calculus 1 PRIMARILY relies on their ability to solve specific kinds of problems.

A student's success in Calculus 1 PRIMARILY relies on their ability to make connections and form logical arguments.

The graduate student follow-up surveys also included elaborations on questions and new questions. Figure 6.2 reproduces the beliefs questions from the GTA follow-up survey, shows any related question from the Instructor survey, and relates them to the aggregate beliefs variables from the Instructor survey.

Instructor survey aggregate variable	GTA follow-up question	Original Instructor survey question
Beliefs about student capabilities	All students in Calculus 1 at my university are capable of understanding the ideas in calculus.	All students in beginning calculus are capable of understanding the ideas of calculus. (0=strongly disagree; 1=strongly agree)
Interest in teaching and student learning	How strong is your interest in: participating in activities that raise your awareness of how students learn key ideas in calculus?	How strong is your interest in: participating in activities that raise your awareness of how students learn key ideas in calculus? (0=not at all; 1=very strong)
	How strong is your interest in: teaching Calculus 1?	How strong is your interest in: teaching Calculus 1? (0=not at all; 1=very strong)
	How strong is your interest in: teaching more advances math classes (e.g. Linear Algebra, Real Analysis, Abstract Algebra, etc.)?	
	How strong is your interest in: improving your own teaching?	
	How strong is your interest in: conducting research in mathematics?	
	How strong is your interest in: conducting research in mathematics education?	
	How strong is your interest in: working in industry (i.e. a non-academic position?)	
Beliefs about teaching and learning	When students make unsuccessful attempts when solving a Calculus 1 problem, it is <i>a natural part of solving the problem</i>	From your perspective, when students make unsuccessful attempts when solving a Calculus 1 problem, it is: (1= <i>a natural part of solving the problem</i> ; 0= <i>an indication of their weaknesses in mathematics</i>)
	When students make unsuccessful attempts when solving a Calculus 1 problem, it is <i>an indication of their weaknesses in mathematics</i>	
	My role as a calculus instructor is PRIMARILY to <i>work problems so students know how to do them</i>	My primary role as a calculus instructor is to: (0=work problems so students know how to do them; 1= help students learn to reason through problems on their own.)
	My role as a calculus instructor is PRIMARILY to help students learn to reason through problems on their own.)	
	A student's success in Calculus 1 PRIMARILY relies on his or her ability to <i>solve specific kinds of problems</i>	From your perspective, student's success in Calculus 1 PRIMARILY relies on their ability to: (0= <i>solve specific kinds of problems</i> ; 1= <i>make connections and form logical arguments</i>)
	A student's success in Calculus 1 PRIMARILY relies on his or her ability to <i>make connections and form logical arguments</i>	
	A student's success in Calculus 1 PRIMARILY relies on his or her ability to <i>make connections and form logical arguments</i>	

Figure 6.2 Beliefs questions from GTA follow-up survey related to Instructor survey questions

Instructional Practices. Graduate students were asked two questions on the follow-up survey related to their instructional practices, both of which were based off questions from the Instructor survey. Additionally, students were asked to the extent that they agreed that they felt prepared to teach Calculus 1. Although this is not directly related to their instructional practices, I include this question in this section as it may provide insight into how their practices are related to their preparation.

GTA follow-up question	Original Instructor survey question
How would you describe your teaching of Calculus 1? (Very innovative, somewhat innovative, somewhat traditional, very traditional)	How would you describe your teaching of Calculus 1? (Very innovative, somewhat innovative, somewhat traditional, very traditional)
Please describe what you mean by innovative or traditional. (open ended responses)	
In my teaching of Calculus 1, I intend to show students how mathematics is relevant.	In my teaching of Calculus 1, I intend to show students how mathematics is relevant.
I feel prepared to teach Calculus 1.	

Figure 6.3 Instructional practices questions from GTA follow-up survey related to Instructor survey questions

Apprenticeship Model

I draw on all three data sources to discuss the beliefs and practices of graduate students at Institution 1 and how the Apprenticeship model influenced their development. However, the number of graduate students that were part of each data sample was relatively small (between one and three). In a typical year, there are typically around 35 graduate student instructors. Thus, there was a response of between 3-8%, depending on the data source. While this is a small representation, these graduate students are all disjoint (i.e. no one graduate student is represented in any of the two data sets). The

following analyses indicate that GTAs coming from Institution 1 have high expectations of what they are capable of, and teach in a traditional but interactive way using novel and complex problems to support their students in meeting their high expectations. The Apprenticeship Model does not only support graduate students in developing (or sustaining) these views and practices, but it also appears to support graduate students in developing a professional identity as Calculus 1 instructors.

Instructor Survey

There were three graduate student instructors that filled out the beginning-of-term survey and one who filled out the end-of-term survey, thus I do not conduct any tests of significance to see how these GTAs' beliefs and practices compare to those of GTAs from other institutions. I do provide the responses from all GTAs (as provided in Chapter 4) for a reference.

Beliefs. Table 6.1 shows the responses of the graduate student(s) from Institution 1 to the beginning and end-of-term aggregate beliefs variables. For reference, Table 6.1 also shows the responses from all GTAs. Note that these GTA responses *include* the responses from graduate students from Institution 1. When comparing the beginning-of-term responses of the three graduate students from Institution 1 to all GTAs' responses, we see: slightly lower beliefs about student capabilities, slightly higher interest in teaching and student learning, slightly higher perceived value of reflection on teaching and learning, and very similar beliefs about teaching and learning. When comparing the end-of-term response of the one graduate student from Institution 1 to all GTAs'

responses, we see: slightly higher beliefs about student capabilities, lower interest in teaching and student learning, and slightly lower beliefs about teaching and learning.

Table 6.1 Beliefs about mathematics among GTAs from the Apprenticeship model

		Apprenticeship	All GTAs
<i>Beginning-of-term</i> : Beliefs about student capabilities	Mean	.788	.833
	Std. Dev.	.068	.071
<i>End-of-term</i> : Beliefs about student capabilities	Mean	.750	.659
	Std. Dev.	-	.161
<i>Beginning-of-term</i> : Interest in teaching and student learning	Mean	.852	.727
	Std. Dev.	.170	.238
<i>End-of-term</i> : Interest in teaching and student learning	Mean	.500	.706
	Std. Dev.	-	.187
<i>Beginning-of-term</i> : Perceived value of reflection on teaching and learning	Mean	.706	.651
	Std. Dev.	.169	.227
<i>Beginning-of-term</i> : Beliefs about teaching and learning	Mean	.600	.607
	Std. Dev.	.087	.175
<i>End-of-term</i> : Beliefs about teaching and learning	Mean	.400	.429
	Std. Dev.	-	.182

Due to the very small sample sizes of this population, it is impossible to make inferences about the relationship between this sample and the population of graduate students at Institution I. However, this data provides one point of reference that will be used in conjunction with the two other data sets to paint a picture of the beliefs of graduate students who were trained under the Apprenticeship model.

Instructional Practices. Table 6.2 shows the reported pedagogical activities of the one GTA from Institution 1 that filled out the end-of-term survey. This one graduate student reported to show students how to work specific problems and lecture often, while (s)he had students work together, used technology in class, and had students give presentations rarely.

Table 6.2 Comparison of Instructional Practices– Frequency of certain pedagogical activities

Instructor Reports		Apprenticeship	All GTAs
<i>End-of-term: During class time, how frequently did you: (1) not at all; (6) very often</i>			
Show how to work specific problems.	Mean	5.00	5.16
	Std. Dev.	-	1.08
Lecture.	Mean	5.00	5.42
	Std. Dev.	-	0.69
Have students work individually on problems or tasks.	Mean	3.00	3.00
	Std. Dev.	-	1.73
Have students work with one another.	Mean	2.00	3.55
	Std. Dev.	-	1.90
Have students give presentations.	Mean	1.00	1.94
	Std. Dev.	-	1.29
<i>End-of-term: How frequently were the following technologies used during class? (1) Never; (5) Every class session</i>			
Instructor demonstration with a graphing calculator.	Mean	2.00	1.45
	Std. Dev.	-	.533
Student use of a graphing calculator.	Mean	2.00	2.46
	Std. Dev.	-	1.311
Instructor demonstration with computer algebra system (e.g., Maple, Mathematica, MATLAB).	Mean	1.00	1.21
	Std. Dev.	-	.449
Student use of a computer algebra system (e.g., Maple, Mathematica, MATLAB).	Mean	2.00	1.11
	Std. Dev.	-	.367

Discourse. Table 6.3 shows the discourse practices of graduate student from Institution 1 as reported by the instructor him/herself. This one graduate student reported to ask the class questions often, ask students to explain their thinking a medium amount, and rarely hold a whole-class discussion.

Table 6.3 Comparison of Instructional Practices—Instructor reports of classroom discourse

Instructor Reports		Apprenticeship	All GTAs
<i>End-of-term: During class time, how frequently did you: (1) not at all; (6) very often</i>			
Hold a whole-class discussion	Mean	2.00	2.71
	Std. Dev.	-	1.30
Ask questions	Mean	5.00	5.11
	Std. Dev.	-	1.12
Ask students to explain their thinking	Mean	4.00	4.26
	Std. Dev.	-	1.45

There were 22 students from the one GTA who responded to the end-of-term survey for students. On this survey, students were asked to report on a number of questions that addressed the classroom discourse. Note that all 22 students are from the same instructor, since the survey was only sent to students whose instructor filled out the end-of-term survey. Thus, any variation in these reports an indication of a perceived difference within the same classroom as opposed to students being in a different classroom. Ellis, Kelton, and Rasmussen (2014) have previously reported that variation among student reports of certain pedagogical activities within the same classroom is significantly related to a student's intention to continue studying calculus. As shown in Table 6.4, these reports indicate that students from this instructor felt that s/he often asked question to determine that they understood what was being discussed, listened carefully to questions and comments, allowed time to understand difficult ideas, provided explanations that were understandable, and when their instructor asked a question s/he waited for a student to answer. Additionally, students from this class reported that they rarely contributed to class discussions but were rarely lost and unable to follow.

Table 6.4 Comparison of Instructional Practices– Frequency of certain pedagogical activities

Student Reports		Apprenticeship	All GTAs
<i>End-of-term:</i> When my calculus instructor asked a question addressed to the whole class s/he: (1) waited for a student to answer; (4) answered the question is no one responded quickly	Mean	2.23	2.24
	Std. Dev.	0.87	0.95
<i>End-of-term:</i> When I asked a question about a problem I was having difficulty solving, my instructor: (1) solved the problem for me; (4) helped me figure out how to solve the problem	Mean	3.09	3.03
	Std. Dev.	0.75	0.91
<i>End-of-term:</i> My calculus instructor: (1) Strongly disagree; (6) strongly agree			
Asked questions to determine if I understood what was being discussed	Mean	4.55	4.45
	Std. Dev.	1.06	1.15
Listened carefully to my questions and comments	Mean	4.73	4.76
	Std. Dev.	0.83	1.17
Allowed time for me to understand difficult ideas	Mean	4.18	4.22
	Std. Dev.	1.10	1.32
Provided explanations that were understandable	Mean	4.32	4.51
	Std. Dev.	1.25	1.27
<i>End-of-term:</i> During class: (1) Never; (5) Every class session	Mean		
I contributed to class discussions.	Std. Dev.	2.55	2.59
		0.96	1.17
I was lost and unable to follow the lecture or discussion.	Mean	1.64	1.95
	Std. Dev.	0.85	1.01
I asked questions.	Mean	2.23	2.34
	Std. Dev.	0.87	1.00
I simply copied whatever was written on the board.	Mean	2.68	3.00
	Std. Dev.	1.36	1.33

Taken together, these results begin to characterize the instructional practices of the small sample of graduate students from Institution 1. Specifically, the in-class practices appear fairly traditional, as indicated by the high reports of lecture and showing students how to work problems. However, this is complemented by opportunities for explorations into student thinking, as indicated by student reports of frequently explaining their thinking during class, asking questions, and being asked questions by the instructor to determine if the students understood what was being discussed.

interpretations of central ideas, 40% solving standard word problems, and 20% solving complex word problems.

Table 6.6 Comparison of Instructional Practices– Content

Instructor reports		Apprenticeship	All GTAs
<i>End-of-term: On a typical assignment, what percentage of the problems focused on:</i>			
skills and methods for carrying out computations (e.g., methods of determining derivatives and antiderivatives)?	Mean	20.00	45.08
	Std. Dev.	-	20.88
graphical interpretation of central ideas?	Mean	20.00	24.92
	Std. Dev.	-	15.47
solving standard word problems?	Mean	30.00	25.76
	Std. Dev.	-	13.42
solving complex or unfamiliar word problems?	Mean	30.00	22.54
	Std. Dev.	-	19.53
proofs or justifications?	Mean	0.00	11.93
	Std. Dev.	-	15.52
<i>End-of-term: On a typical exam, what percentage of the points focused on:</i>			
skills and methods for carrying out computations (e.g., methods of determining derivatives and antiderivatives)?	Mean	30.00	41.84
	Std. Dev.	-	21.44
graphical interpretation of central ideas?	Mean	10.00	22.13
	Std. Dev.	-	13.92
solving standard word problems?	Mean	40.00	24.92
	Std. Dev.	-	13.98
solving complex or unfamiliar word problems?	Mean	20.00	19.49
	Std. Dev.	-	20.46
proofs or justifications?	Mean	0.00	13.68
	Std. Dev.	-	15.66

Case Study Data

There were two graduate students from Institution 1 that were interviewed during the case study visit. Neither of these students were at Institution 1 at the time of the Instructor survey, and thus there is no overlap between the graduate students who filled out the Instructor survey and those who took part of the case study. The first graduate student from Institution 1 was a second year Masters student who has an education degree and is certified to teach high school math but never taught. Instead she has many

years of tutoring experience. She was mentored by the TA Trainer/ Calculus Course Coordinator in Calculus 1 her first semester and has been teaching Calculus 1 on her own since.

When asked what she wanted her A students to learn compared to her C students, this GTA articulated an interesting difference in the idea of applicability. She expressed that she wants her A students to recognize problem solution strategies and apply them to novel problems. Conversely, she wants her C students to recognize formulas and rules and be able to apply them.

GTA 1.1: My A students, I want them to see that they can apply this, not just the cookie-cutter stuff, but be able to apply it on their situations, have that knowledge and say, 'Oh, this is similar to something that we've done, I can do this.' The C students, I want them to be able to, if nothing else, know the rules and all the derivatives and be able to do them. They may not be able to synthesize anything and apply things, but as long as they can do the rules, you know, then at least they have something that they can build off of.

When asked what she saw as her role in helping students achieve those skills, she responded that she likes “to try to make them explore on their own.” She elaborated that she gives worksheets that have similar problems to what they did in class but not exactly the same. When students are having difficulties, she said that she tries “to help them with those issues, to solve those problems.” This description is consistent with what I observed during the site visit. Specifically, during this visit I noted that related rates were presented very procedurally with no mention of why one would need an equation or why you take the derivative. However, students seemed engaged and many asked questions during class.

This GTA indicated that her practices were highly influenced by the Apprenticeship Model training. She said that her instructional practices were specifically encouraged during the class and she additionally learned a lot from her mentor with respect to how to ask questions and create an interactive environment.

GTA 1.1: That training was definitely more on, 'We want to get the students involved and do worksheets.' So the idea of the training was, 'Okay, you want to start, make organizer notes, make sure you hit the key points, and then make sure they have a chance to practice the stuff before they leave the classroom.' So that you can make sure they are starting to ingrain it before they leave. So the training that we got was, 'We're going to practice writing lessons, plan, make sure our lesson is maybe within 20 minutes, and then write worksheets on top of that.' So it was definitely encouraged that that's the way that you are going to teach is give notes and then have a worksheet.

GTA 1.1: I think I've learned a lot about the kind of thinking that goes into stuff. Because in the class, we all kind of, it was all us grad students coming up with the thinking. But as the mentor, when I was being mentored, I can find out [my mentor's] thinking, how she was thinking things through, and as an experienced person. And it's like okay, you get this other way of thinking, as opposed to somebody who hasn't had much experience, how we commonly think.

These findings are consistent with the survey responses regarding instructional practices, specifically the somewhat traditional emphasis on skills and routine word problems, complimented by encouraging students to explore problems on their own. This is especially interesting considering that there were two years in between the Instructor survey and the case study interviews, and the graduate students involved in each were different. Although the number of graduate students that responded to each of the individual components of the data collection at Institution 1 was relatively low, this triangulation of data strengthens the findings.

The second GTA was also a second year Masters student who has over 30 years experience teaching AP calculus. She was placed into the role of course instructor her first semester as a student because of her extensive teaching experience. She did not mention having a mentor during her first semester teaching, but had her course observed twice a semester, and received midterm evaluations as well as end of term evaluations from her students.

She described her class as a “more of a dialogue than a lecture” because they work on problems in groups or individually and then come together as a class and discuss the problems, typically repeating this process multiple times throughout one class. She said that she likes to motivate lessons with “something that’s real” but that this is easier for some content, such as related rates, than others, such as derivative rules. During the observed class, this GTA began class with a “Tootsie Roll Pop Problem” where two students collected data before class on the radius of a tootsie-roll pop after x seconds. During class, students were shown the data and asked “Does the radius decrease the same amount every 30 seconds?”, “What is the average rate of change?”, “What is the approximate instantaneous rate of change?”, and “At what rate is the volume of the tootsie-roll pop changing when it is $\frac{3}{4}$ of the original volume?” She then had students work on more standard related rates problems involving a ladder sliding away from a wall.

When asked what she wanted her A and C students to get out of class, she responded that she wanted them all to be A students and had high expectations. She also acknowledged that not all students placed in her class were capable of being A students, and attributed this to incorrect placements.

GTA 1.2: *I want all my students to be A students! I want them all to understand the concepts, to be able to apply them fluidly. I don't like to think that I have, that I expect you to be a C student. I expect you all to learn everything to the most, to the highest degree you can. I have high expectations of every student. I know some will not measure up. But I have expectations that they will all learn as much as they possibly can and be prepared to move on to the next level, and to be able to think and reason about what they've learned.*

She said that she also has many students who have already taken calculus in high school, and have surface understanding, they know the mechanics, but they don't necessarily understand what's going on.” She says that because of these students, she tried to “really engage them in thinking about it and trying to explain it, to try and deepen that so that they will be ready to move on.”

The practices of these two GTAs are certainly not identical, but both encourage a combination of developing procedural fluency and conceptual understanding. Both GTAs pointed to the department culture as supporting their instructional practices, specifically encouraging an interactive environment:

GTA 1.1: *I think [the success of the calculus program at Institution 1] is partly the atmosphere here. Like all the professors that are teaching calculus really enjoy teaching it. And they enjoy working with the students, they just enjoy teaching. And so then the students can respond to that. And I think because we're also so involved, we make sure they're doing the homework, we have the office hours, we're talking with them. I just feel like it's just somewhat the culture here, that's how the professors are, we talk with the students and we just interact with them*

GTA Follow-up Survey

There were two GTAs who responded to the GTA follow-up survey from Institution 1. These students were both in the process of earning a Masters in Mathematics and had each taught Calculus 1 once before. Based on the one email provided, at least one of these graduate students was different than the two who were involved in the case study interviews.

Beliefs. Table 6.7 shows the mean responses and standard deviations from these two graduate students. There are a number of questions where their answers align (as indicated by a standard deviation close to 0) and others where their answers do not align. For instance, these two students both indicate strong interest in teaching Calculus 1, and weak interest in teaching more advanced mathematics classes. These responses reflect the culture at Institution 1 for which Calculus 1 is a respected course to teach. Additionally, graduate students are never placed as course instructors for classes higher than Calculus 2, so it is possible that these students had never considered teacher a higher level mathematics course as a graduate student.

Table 6.7 GTA Follow-up survey – Beliefs: Apprenticeship Model

	Mean (Std. Dev.)
Beliefs about student capabilities (1=strongly disagree; 6=strongly agree)	
All students in Calculus 1 at my university are capable of understanding the ideas in calculus.	3.50 (2.12)
Interest in teaching and student learning (1=strongly disagree; 6=strongly agree)	
How strong is your interest in: participating in activities that raise your awareness of how students learn key ideas in calculus?	2.50 (2.12)
How strong is your interest in: teaching Calculus 1?	4.00 (0.00)
How strong is your interest in: teaching more advanced math classes (e.g. Linear Algebra, Real Analysis, Abstract Algebra, etc.)?	2.00 (0.00)
How strong is your interest in: improving your own teaching?	3.00 (1.41)
How strong is your interest in: conducting research in mathematics?	2.50 (2.12)
How strong is your interest in: conducting research in mathematics education?	2.00 (1.41)
How strong is your interest in: working in industry (i.e. a non-academic position?)	2.00 (1.41)
Beliefs about teaching and learning (1=strongly disagree; 6=strongly agree)	
When students make unsuccessful attempts when solving a Calculus 1 problem, it is <i>a natural part of solving the problem</i>	5.00 (0.00)
When students make unsuccessful attempts when solving a Calculus 1 problem, it is <i>an indication of their weaknesses in mathematics</i>	3.00 (0.00)
My role as a calculus instructor is PRIMARILY to <i>work problems so students know how to do them</i>	3.50 (0.71)
My role as a calculus instructor is PRIMARILY to help students learn to reason through problems on their own.	5.50 (0.71)
A student's success in Calculus 1 PRIMARILY relies on his or her ability to <i>solve specific kinds of problems</i>	3.00 (1.41)
A student's success in Calculus 1 PRIMARILY relies on his or her ability to <i>make connections and form logical arguments</i>	3.50 (0.71)

These two students also agreed that making unsuccessful attempts when solving a problem is a natural part of solving the problem (a more expert-like belief) while they slightly disagree that unsuccessful attempts are an indication of a student's weakness. Similarly, both students agreed that their primary role as an instructor is to help students reason through problems on their own, and were neutral in response to their primary role being to work problems so that students know how to do them.

Instructional Practices. Table 6.8 shows the responses from the two graduate students from Institution 1 on the three questions related to instructional practices. The

first question addresses how prepared the graduate students felt they were to teach; both students agreed that they were prepared to teach. There was disagreement regarding the degree to which the GTAs intended to show students the relevance of Calculus 1, resulting in a mean response of 3.50 and a standard deviation of 2.12. Lastly GTAs were asked how they would describe their teaching of Calculus 1, where 1 represented very innovative, 2 represented somewhat innovative, 3 represented somewhat traditional, and 4 represented very traditional. Both GTAs from Institution 1 responded with a 3, representing somewhat traditional.

Table 6.8 GTA Follow-up survey – Practices: Apprenticeship Model

	Mean (Std. Dev.)
I feel prepared to teach Calculus 1. (1=strongly disagree; 6=strongly agree)	5.00 (0.00)
In my teaching of Calculus 1, I intend to show students how mathematics is relevant. (1=strongly disagree; 6=strongly agree)	3.50 (2.12)
How would you describe your teaching of Calculus 1? (1=Very innovative, 2=somewhat innovative, 3=somewhat traditional, 4=very traditional)	3.00 (0.00)

When asked to describe what they meant by “somewhat traditional”, one of the two GTAs from Institution 1 did not respond, and the other responded: “*slopes -> derivatives -> optimization -> reimann [sic] sums -> antiderivatives & integration.*” Based off of the limited data from the GTA follow-up survey and the response rate, it is difficult to make any inferences about the actual instructional practices of the GTAs at Institution I. This data point does, however, contribute to the overall picture of instructional practices at this institution.

Apprenticeship Model Summary

The previous mixed methods analysis reveals a number of emergent themes in the mathematics educational beliefs and instructional practices of graduate students at

Institution 1. As previously mentioned, there were a relatively small number of graduate students represented in each of the three data sources. However, the graduate students in each data source are distinct, and thus I can use simultaneous triangulation (Morse, 1991) to identify points of convergence during the data interpretation stage.

Responses to each of the three data sources indicate that GTAs at Institution 1 view their students as capable of succeeding, hold them to high expectations, and view their role as instructors as supporting students in meeting these high expectations. The reported pedagogical actions that instructors report taking to satisfy this role vary, but generally indicate an interactive-lecture environment and cognitively rich tasks. These practices were supported by the department culture at Institution 1, which was reported to emphasize the importance of teaching and to be supportive of more innovative instructional practices. All GTAs reported being prepared for their role as course instructor, either through their own extensive teaching experience, or from participating in the Apprenticeship professional development program.

It is important to highlight that the graduate students that I spoke with articulated a large amount of ownership of their instruction, and appeared to identify as instructors (rather than hired help). As Grossman et al. (2009) note, “part of professional preparation involves the construction of a professional identity” (p. 2059). For the GTA who was an experienced high-school teacher, she came into her role as a Calculus 1 instructor with a professional identity of teacher, but not within the undergraduate environment. The department context supported her in feeling as though she was a part of this community in a way that she could share with and learn from other instructors. The Masters student I spoke with came into her role as GTA with no prior teaching experience and no

professional identity as a teacher. She pointed to the mentor experience and the lesson-study class as preparing her for her role as instructor, and it was clear while speaking with her that these experiences supported her in developing an identity as an undergraduate instructor.

Coordinated Innovation Model

I draw on all three data sources to discuss the beliefs and practices of graduate students at Institution 2 and how the Coordinated Innovation model influenced their development. There are a large number of graduate students who are represented in each data source, likely due to the average number of graduate students in a typical year (135). The following analyses indicate that GTAs coming from Institution 2 enact the instructional practices encouraged by the Coordinated Innovation model, although they do not report all of the views that undergird this instructional approach. The Coordinated Innovation model succeeds in preparing a large number of novice graduate students in implementing a novel and innovative instructional approach. Further, these GTAs report that they would likely continue to implement such approaches in other small classes outside of Institution 2, and they develop (or sustain) many more expert-like beliefs regarding teaching, learning, and doing mathematics.

Instructor Survey

There were 23 GTAs from Institution 2 that responded to the start-of-term survey and 18 that responded to the end-of-term survey. There were 47 GTAs from other institutions that responded to the start-of-term survey and 27 that responded to the end-

of-term survey. In this section, I compare the responses of these GTAs and their students to the responses from all other GTAs and their students and conduct significance tests on these comparisons.

Beliefs. Table 6.9 shows the responses of the graduate students from Institution 2 to the beginning and end-of-term aggregate beliefs variables. When comparing the beginning-of-term responses of the three graduate students from Institution 2 to all other GTAs' responses, we see: significantly higher beliefs about student capabilities [$F(1, 69) = 10.270, p = .002$], significantly less interest in teaching and student learning [$F(1, 73) = 9.203, p = .003$], significantly higher perceived value of reflection on teaching and learning [$F(1, 72) = 8.446, p = .005$], and slightly more expert-like beliefs regarding teaching and learning [$F(1, 70) = 3.911, p = .052$]. When comparing the end-of-term response of the graduate students from Institution 2 to all other GTAs' responses, we see: significantly higher beliefs about student capabilities [$F(1, 55) = 6.202, p = .016$], significantly less interest in teaching and student learning [$F(1, 54) = 7.649, p = .008$], and similar beliefs about teaching and learning [$F(1, 54) = 2.085, p = .155$].

Table 6.9 Beliefs about mathematics among GTAs from the Coordinated Innovation model

		Coord. Inn.	Other GTAs
<i>Beginning-of-term:</i> Beliefs about student capabilities	Mean	.870	.815
	Std. Dev.	.054	.072
<i>End-of-term:</i> Beliefs about student capabilities	Mean	.733	.623
	Std. Dev.	.142	.159
<i>Beginning-of-term:</i> Interest in teaching and student learning	Mean	.609	.781
	Std. Dev.	.277	.199
<i>End-of-term:</i> Interest in teaching and student learning	Mean	.611	.751
	Std. Dev.	.197	.166
<i>Beginning-of-term:</i> Perceived value of reflection on teaching and learning	Mean	.759	.601
	Std. Dev.	.203	.221
<i>Beginning-of-term:</i> Beliefs about teaching and learning	Mean	.665	.579
	Std. Dev.	.167	.174
<i>End-of-term:</i> Beliefs about teaching and learning	Mean	.467	.395
	Std. Dev.	.209	.154

Note. * = $p \leq .10$, ** = $p \leq .05$, *** = $p \leq .001$.

These results together characterize a graduate student instructor population that express mathematically related beliefs that are significantly different from the overall sample population of GTAs. The graduate student instructors from Institution 2 view their students as more capable at the beginning and end of the term than other GTAs but are less interested in teaching and learning even though they report being in an environment that places higher value on teaching and learning. This characterization is especially interesting given that one of the main goals of the PD program was to get GTAs to “buy-in” to the specific approach to Calculus 1.

Instructional Practices. Table 6.10 shows the reported pedagogical activities of the GTAs from Institution 2 that filled out the end-of-term survey. When comparing the responses of the three graduate students from Institution 2 to all other GTAs’ responses, we see: significantly less time spent lecturing [$F(1, 61) = 4.128, p = .047$], and significantly more time spent having students work in groups [$F(1, 61) = 46.757, p \leq .001$] and give presentations [$F(1, 61) = 17.054, p \leq .001$]. Interestingly, this did not

result in any differences in the amount of time spent showing students how to work specific problems [$F(1, 61) = 1.531, p = .221$] or having students work individually on problems or tasks [$F(1, 60) = 0.916, p = .342$]. This reported characterization is consistent with the approach to calculus that is highly encouraged through the Coordinated Innovation model.

Table 6.10 Comparison of Instructional Practices– Frequency of certain pedagogical activities

Instructor Reports		Coord. Inn.	Other GTAs
<i>End-of-term: During class time, how frequently did you: (1) not at all; (6) very often</i>			
Show how to work specific problems.	Mean	4.95	5.26
	Std. Dev.	0.97	0.88
Lecture.*	Mean	5.16	5.53
	Std. Dev.	0.83	0.59
Have students work individually on problems or tasks.	Mean	2.68	3.14
	Std. Dev.	1.67	1.76
Have students work with one another.***	Mean	5.42	2.72
	Std. Dev.	0.69	1.65
Have students give presentations.***	Mean	2.84	1.53
	Std. Dev.	1.71	0.80

Note. * = $p \leq .10$, ** = $p \leq .05$, *** = $p \leq .001$.

Discourse. Table 6.11 shows the discourse practices of the graduate students from Institution 2 as reported by the instructors. When comparing the responses of the three graduate students from Institution 2 to all other GTAs' responses, we see significantly more time spent having whole-class discussions [$F(1, 61) = 7.848, p = .007$] and students are asked to explain their thinking significantly more frequently [$F(1, 61) = 8.022, p = .006$]. There were no significant differences between in the amount of time the instructor spent asking questions [$F(1, 61) = .078, p = .780$]. Again, these results support the classroom environment encouraged through the Coordinated Innovation model.

Table 6.11 Comparison of Instructional Practices—Instructor reports of classroom discourse

Instructor Reports		Coord. Inn.	Other GTAs
<i>End-of-term: During class time, how frequently did you: (1) not at all; (6) very often</i>			
Hold a whole-class discussion.**	Mean	3.37	2.42
	Std. Dev.	1.30	1.20
Ask questions	Mean	5.05	5.14
	Std. Dev.	1.03	1.17
Ask students to explain their thinking**	Mean	5.00	3.93
	Std. Dev.	0.88	1.53

Note. * = $p \leq .10$, ** = $p \leq .05$, *** = $p \leq .001$

There were 145 total students from the 18 GTAs who responded to the end-of-term survey for students from Institution 2, and 304 students coming from the 47 other GTAs. On this survey, students were asked to report on a number of questions that addressed the classroom discourse. As shown in Table 6.12, students taught by GTAs from Institution 2 report significantly different classroom discourse than students taught by GTAs from other institutions. These reports add detail to the reported discourse by instructors. Specifically, GTAs from Institution 2 were reportedly more likely than other GTAs to wait for a student to answer a question rather than answer the question if no one responded quickly [$F(1, 429) = 5.654, p = .018$]. Students taught by GTAs from Institution 2 report asking more questions in class [$F(1, 395) = 3.468, p = .063$] and contributing to class discussion significantly more often [$F(1, 396) = 9.319, p = .002$]. When a student asked a question about a problem they were having difficulty solving, graduate student instructors from Institution 2 were reportedly more likely to help the student solve the problem instead of solving the problem for the student [$F(1, 428) = 13.357, p \leq .001$]. Additionally, students taught by GTAs from Institution 2 more strongly agreed that their instructor allowed time to understand difficult ideas [$F(1, 418)$]

= 9.606, $p = .002$] and that their instructor provided explanations that were understandable [$F(1, 417) = 2.812, p = .094$].

Table 6.12 Comparison of Instructional Practices– Student reports of classroom discourse

Student Reports		Coord. Inn.	Other GTAs
<i>End-of-term:</i> When my calculus instructor asked a question addressed to the whole class s/he: (1) waited for a student to answer; (4) answered the question is no one responded quickly**	Mean	2.07	2.31
	Std. Dev.	0.91	0.96
<i>End-of-term:</i> When I asked a question about a problem I was having difficulty solving, my instructor: (1) solved the problem for me; (4) helped me figure out how to solve the problem***	Mean	3.27	2.92
	Std. Dev.	0.78	0.93
<i>End-of-term:</i> My calculus instructor: (1) Strongly disagree; (6) strongly agree Asked questions to determine if I understood what was being discussed	Mean	4.58	4.40
	Std. Dev.	1.10	1.16
Listened carefully to my questions and comments	Mean	4.87	4.71
	Std. Dev.	1.01	1.22
Allowed time for me to understand difficult ideas**	Mean	4.53	4.09
	Std. Dev.	1.21	1.34
Provided explanations that were understandable*	Mean	4.67	4.44
	Std. Dev.	1.10	1.33
<i>End-of-term:</i> During class: (1) Never; (5) Every class session I contributed to class discussions.**	Mean	2.87	2.48
	Std. Dev.	1.07	1.19
I was lost and unable to follow the lecture or discussion.	Mean	1.93	1.95
	Std. Dev.	0.94	1.05
I asked questions.*	Mean	2.48	2.28
	Std. Dev.	0.95	1.01
I simply copied whatever was written on the board.	Mean	2.83	3.07
	Std. Dev.	1.26	1.35

Note. * = $p \leq .10$, ** = $p \leq .05$, *** = $p \leq .001$

Taken together, these results begin to characterize the instructional practices of the sample of graduate students from Institution 2. Specifically, the in-class practices align strongly with the encouraged instructional approach at Institution 2. This approach includes a balance between direct instruction (showing students how to solve problems and lecture) with group-work, whole class discussion, and student presentations. Additionally, the overall classroom environment is more interactive, with both students

and the instructor asking questions, and allowing time for students to explain their thinking and for the class to investigate difficult ideas.

Nature of tasks. The last component of instructional practices that I investigate from the Instructor survey is the nature of the tasks. As shown in Table 6.13, there are no differences in the number of exams or quizzes given by graduate student instructors from Institution 2 compared to others GTAs, though 100% of GTAs from Institution 2 report having a common final compared to 72.1% of other GTAs [χ^2 (df = 1, n = 62) = 6.575, p = .010]. Additionally, GTAs from institution do have students turn in homework significantly more frequently compared to other graduate student instructors [$F(1, 54)$ = 20.019, $p \leq .001$].

Table 6.13 Comparison of Instructional Practices– Nature of Tasks

Instructor reports		Coord. Inn.	Other GTAs	
<i>End-of-term:</i> How many exams, not including the final, did you give?	Mean	2.72	2.84	
	Std. Dev.	2.11	0.76	
<i>End-of-term:</i> Indicate how often the following occurred: (1) Never; (5) Every class session				
	you gave a short quiz	Mean	2.47	2.33
		Std. Dev.	0.61	0.94
students turned in assignments (either hard copy or online)***	Mean	4.00	2.77	
	Std. Dev.	1.29	1.00	
<i>End-of-term:</i> What was the format of the majority of the homework assignments?				
	multiple choice items		0	2 (4.7%)
	free response questions		14 (73.7%)	32 (74.4%)
	more or less equal amounts of both		5 (26.3%)	7 (16.3%)
	not applicable		0	2 (4.7%)
<i>End-of-term:</i> In my Calculus 1 course: a common final was used for all sections. **		19 (100%)	31 (72.1%)	

Content. Table 6.13 also shows that the assignments from all GTAs were typically either all free response questions or a combination of multiple choice items and free response questions. Table 6.14 shows in much more detail the content of the

assignments and assessments. Compared to the assignments of other GTAs, the assignments of GTAs from Institution 1 to have significantly fewer problems focusing on skills and methods for carrying out computations (32% versus 51%) [$F(1, 58) = 11.837, p = .001$], and significantly more problems focusing on a graphical interpretation (36% versus 20%) [$F(1, 58) = 20.291, p \leq .001$], solving a complex or unfamiliar word problem (38% versus 18%) [$F(1, 58) = 26.757, p \leq .001$], and proofs or justifications (18% versus 9%) [$F(1, 56) = 4.781, p = .033$]. All GTAs similarly reported about 25% of the assignments focusing on routine word problems [$F(1, 58) = 704, p = .405$]. These patterns held for assessments, with GTAs from Institution 2 reporting to give exams composed of approximately 26% problems focused on skills and methods, 34% graphical interpretations, 24% standard word problems, 40% complex word problems, and 20% proofs and justifications. The assignments and assessments from Institution 2 compared to those of other GTAs reportedly are comprised of more cognitively demanding tasks (complex word problems, graphical interpretations, and proofs and justifications). Such tasks have been connected to student learning gains (Silver, 1996; Stein & Lane, 1996) and student confidence (Halcrow & Dunnigan, 2012; Morrel, 2007), especially when such tasks are complemented by the engaging classroom environment reportedly supported by GTAs at Institution 2 (Newmann et al., 2001).

Table 6.14 Comparison of Instructional Practices– Content

Instructor reports		Coord. Inn.	Other GTAs
<i>End-of-term:</i> On a typical assignment, what percentage of the problems focused on:			
skills and methods for carrying out computations (e.g., methods of determining derivatives and antiderivatives)?**	Mean	32.63	51.00
	Std. Dev.	12.40	21.58
graphical interpretation of central ideas?***	Mean	36.32	19.50
	Std. Dev.	18.02	10.61
solving standard word problems?	Mean	27.89	24.75
	Std. Dev.	13.98	13.20
solving complex or unfamiliar word problems?***	Mean	38.42	15.00
	Std. Dev.	23.63	11.32
proofs or justifications?***	Mean	18.33	8.97
	Std. Dev.	24.55	7.54
<i>End-of-term:</i> On a typical exam, what percentage of the points focused on:			
skills and methods for carrying out computations (e.g., methods of determining derivatives and antiderivatives)?***	Mean	25.79	48.57
	Std. Dev.	16.77	19.58
graphical interpretation of central ideas?***	Mean	33.68	16.90
	Std. Dev.	13.83	10.47
solving standard word problems?	Mean	23.68	25.48
	Std. Dev.	11.16	15.17
solving complex or unfamiliar word problems?***	Mean	40.00	9.75
	Std. Dev.	23.09	8.62
proofs or justifications?*	Mean	20.00	10.77
	Std. Dev.	19.40	12.85

Note. * = $p \leq .10$, ** = $p \leq .05$, *** = $p \leq .001$.

Based off student and instructor reports of the frequency of certain pedagogical activities, classroom discourse, and the nature of problems on assignments and assessments, the instructional practices of graduate students from Institution 2 appear to be in line with what was encouraged through the Coordinated Innovation model. Interestingly, these graduate students report viewing their students as more capable, and being less interested in teaching and learning than other graduate students. One may expect an instructor who encourages a student-centered, cognitively demanding instructional environment (such as described by GTAs from Institution 2 and their students) to be highly interested in their students thinking and/or teaching. Instead, it

appears that these instructors implement such instruction even though they are not as interested in teaching and learning as other GTAs.

Case Study Data

During the site visit to Institution 2 five individual more experienced GTAs were interviewed in addition to a second focus group interview with a group of five first-time GTAs that I spoke with during the summer training. In this section I draw on data from the interviews during the site visit, observations, and collected course documents.

Among the ten GTAs I spoke with (5 experienced and 5 new), there were some consistencies in their espoused beliefs and their described instructional practices, such as what different students should get out of class and the structure of class. However, there were also areas where there was more significant variation among the GTAs, such as what their role as instructor is.

When asked what the instructors wanted their A versus C students to get out of class, many responded that A students already came in exposure to calculus and so they wanted them to get a deeper understanding of it, and C students need to develop procedural fluency.

GTA 2.1: I just want the A students to have a reach a deeper understanding of it, and I want the C students to have a reach a deeper understanding of it later.

GTA 2.2: I mean the A students typically tend to be people that have seen a little bit of Calculus before and so my goal for them is just that they on this second pass, they really get the concepts more. They see what's going on in addition to being able to do the computations... The C students... I guess I'd say that in the end of the day they at least see some vague ideas

about the concepts. Ultimately I think what winds up happening with those students often is that they at least remember how to do the computations and the concepts remain very hard for them, but definitely my goal would be to have them leave having some rough notions about conceptually what's going on.

GTA 2.3: I would like my C students to be able to chug through computations and take derivatives and maybe have gained some understanding of like how to reason through a problem. I would like the A students to have gained much more of an understanding of how to reason through a problem and maybe even a fine understanding of sort of how to develop a series of something.

GTA 2.4: So, for the A students, hopefully, I kind of, for those people who are already pretty good at this, I want to try to get them to thinking of taking more mathematics, try to cultivate an interest, right. And for the C, D, E students, the focus here is just to get them to pick up the essential skills, how do, how to do calculus.

Throughout the interviews, GTAs shared other, more idiosyncratic, perspectives on teaching and learning. One experienced GTA expressed the belief that “if you don't understand the theory, then you're not going to understand the Calculus 1 ideas.” He also expressed that one of the more difficult things about teaching pre-calculus and Calculus 1 is when students struggle with things that he never struggled with.

When I asked the group of first-year GTAs what their role as instructor is, their responses varied widely, and did not appear to correspond to what the training emphasized. Their responses included:

GTA 2.5: I tell them some facts, it's very hard for them to understand what this fact means until they've done a bunch of examples and they need to be guided to do the examples I think.”

GTA 2.6: I feel like my main job is not to explain much of anything. I feel like I'm more of a scheduler and the clarifier if they happen to be wrong.

GTA 2.7: Provider of counterexamples... They don't typically have rigorous enough definitions to be able to actually figure out what's always true and what's often true in the case of the nice functions that they see.

Overall, GTAs expressed running class in a format very consistent with what was (strongly) encouraged through the training program: a combination of lecture and group work. There appeared to more variation with respect to how much time graduate student instructors had their students present problems at the board. One GTA expressed that she chose not to have her students present at the board often because “when students present and they're not prepared they just sort of mutter into the chalkboard and no one pays attention to them.” Most of the GTAs I spoke to attributed their teaching style to the training.

GTA 2.7: I would say the group work was influenced by, definitely influenced, by the training because I normally I would have a lot of students working individually, but during the training one of the messages was that that is not feasible for the instructor to supervise or at least not nearly as much. And there were a few of my students who like it's very clear that the group work is really helping

GTA 2.5: As far as teaching calculus in a small class this is a really good way to do it...I mean I think it's really successful and I think I probably would have not have, if I just designed how to teach Calculus class done it this way or especially how to teach my own Calculus class, so I think the training's useful because it instills a philosophy which I, I think naturally I would have just asked questions at the board and like made sure that people sort of vaguely knew what was going on. If they were giving the right answers at the board then I would have been happy.

This description of the classroom environment is very consistent with what was observed. The observed classes were a combination of lecture and a cycle of students working on problems in groups or individually (depending on the class or the students)

and then discussing the problems as a class. The nature of the questions varied from class to class, with some more short answer responses (i.e. what is the answer to 4c?) and other more open ended (i.e. did anyone solve this problem differently?). Students worked on cognitively demanding tasks, and overall students appeared engaged.

GTA Follow-up Survey

There were 21 GTAs who responded to the GTA follow-up survey from Institution 2. The majority of these students were in the process of completing a PhD in mathematics (81%) and were currently teaching for the first time (71.4%).

Beliefs. Table 6.15 shows the mean responses and standard deviations from graduate students from Institution 2. For all of these questions, responses between 1 and 3 represent disagreement (or lack of interest), and responses between 4 and 6 represent agreement (or interest). On average, GTAs from the Coordinated Innovation model believe that all students in Calculus 1 at their university are capable of understanding the ideas in calculus. This result is consistent with the findings from the Instructor survey. When asked to respond to how interested they were in a variety of activities, these GTAs were most interested in conducting mathematics research, improving their own teaching, and teaching more advanced classes, like Linear Algebra and Real Analysis. These GTAs were less interested in conducting mathematics education research, working in industry, teaching Calculus 1, and participating in activities that raise their awareness of how students learn key ideas in calculus.

Table 6.15 GTA Follow-up survey – Beliefs: Coordinated Innovation Model

	Mean response (Std. Dev.)
Beliefs about student capabilities (1= <i>strongly disagree</i> ; 6= <i>strongly agree</i>)	
All students in Calculus 1 at my university are capable of understanding the ideas in calculus.	4.75 (1.07)
Interest in teaching and student learning (1= <i>not interested at all</i> ; 6= <i>very interested</i>)	
How strong is your interest in: participating in activities that raise your awareness of how students learn key ideas in calculus?	2.19 (1.12)
How strong is your interest in: teaching Calculus 1?	2.29 (0.72)
How strong is your interest in: teaching more advanced math classes (e.g. Linear Algebra, Real Analysis, Abstract Algebra, etc.)?	3.05 (0.87)
How strong is your interest in: improving your own teaching?	3.10 (0.93)
How strong is your interest in: conducting research in mathematics?	3.57 (0.68)
How strong is your interest in: conducting research in mathematics education?	1.57 (0.68)
How strong is your interest in: working in industry (i.e. a non-academic position?)	2.29 (1.12)
Beliefs about teaching and learning (1= <i>strongly disagree</i> ; 6= <i>strongly agree</i>)	
When students make unsuccessful attempts when solving a Calculus 1 problem, it is a natural part of solving the problem	4.95 (1.00)
When students make unsuccessful attempts when solving a Calculus 1 problem, it is an indication of their weaknesses in mathematics	2.45 (1.00)
My role as a calculus instructor is PRIMARILY to work problems so students know how to do them	3.25 (1.40)
My role as a calculus instructor is PRIMARILY to help students learn to reason through problems on their own.	5.40 (0.82)
A student's success in Calculus 1 PRIMARILY relies on his or her ability to solve specific kinds of problems	3.55 (1.40)
A student's success in Calculus 1 PRIMARILY relies on his or her ability to make connections and form logical arguments	4.70 (1.30)

These findings align with the findings from the Instructor survey, but provide additional insight. Specifically, GTAs' responses to both the Instructor survey and the GTA follow-up survey indicate low interest in student thinking and teaching Calculus 1. The GTA survey additionally shows that this group of graduate students is instead interested in teaching upper-level mathematics courses and/or conducting research in mathematics. These practices are aligned with the practices of a research mathematician. This finding adds nuance to the previous results, and additionally indicates that this body of graduate students likely do not envision themselves as becoming part of a community

surrounding the teaching of Calculus 1. Thus, it is problematic to look at their enculturation into this community if it is not a community they are looking to become a part of. Rather, this is a community that they *must* be a part of in order to receive funding while they earn a doctorate degree in mathematics that will enable them to become part of the community they want to join: that of research mathematicians.

Table 6.15 also shows that this group of graduate students believe that their role as an instructor is primarily to help students learn to reason through problems on their own, that students' success in Calculus 1 primarily relies on their ability to make connections and form logical arguments, and that when students make unsuccessful attempts at solving mathematics problems, this is a natural part of solving the problem. These beliefs more strongly align with an expert view of mathematics, and more specific align with a community of educators typically interested in teaching and student thinking. This group of graduate students express beliefs that are seemingly in opposition: they are not interested in student thinking or teaching Calculus 1, but they view their students as capable of making connections and forming logical arguments and that their job as the instructor is to help them reason through these problems.

Instructional Practices. Table 6.16 shows the responses from the graduate students from Institution 2 on the three questions related to instructional practices. These responses indicate that GTAs from Institution 2 felt prepared to teach and intend to make mathematics relevant when they teach.

Table 6.16 GTA Follow-up survey – Instructional Practices: Coordinated Innovation Model

	Mean response (Std. Dev.)
I feel prepared to teach Calculus 1. (1=strongly disagree; 6=strongly agree)	5.00 (1.08)
In my teaching of Calculus 1, I intend to show students how mathematics is relevant. (1=strongly disagree; 6=strongly agree)	4.55 (1.28)
How would you describe your teaching of Calculus 1? (1=Very innovative, 2=somewhat innovative, 3=somewhat traditional, 4=very traditional)	2.24 (0.77)

When asked to describe their teaching, GTAs from Institution 2 on average reported a somewhat innovative teaching style, with two-thirds of the GTAs reporting that their teaching was very or somewhat innovative. When asked what they meant by either “innovative” or “traditional”, their responses indicated varying degrees of “buy-in” or ownership to the approach. For instance, one GTA who responded that his/her teaching was somewhat innovative said that “The group work aspect seems new, although I'm not sure how effective it is.” Conversely, of the four GTAs who described their teaching as somewhat traditional, three mentioned “following” the model/ textbook/ syllabus. The fourth responded that s/he teaches “primarily with standard lecture style, but I build off of the intuition and involvement of the students. In general, my lectures are more reactionary and spontaneous, and less planned.”

Coordinated Innovation Model Summary

There were a large number of graduate student instructors from Institution 2 that responded to each of the data sources. While there may be some overlap between the respondents to any of the courses, this sample still provides an in depth look into the beliefs and practices of GTAs from this institution. Findings from each of the three data sources point to a number of consistent themes. The body of graduate students that teach

Calculus 1 at Institution 2 do not, overall, express much interest in teaching Calculus 1. Instead, their interests lie in teaching higher level mathematics and/or conducting research in mathematics. The appointment of teaching Calculus 1 is viewed more as a requirement than an opportunity to do what they want to do in their career. The GTAs consistently report enacting the recommended instructional practices of this institution's approach to Calculus 1. These include a combination of short lectures with whole-class discussions, students working in groups on cognitively demanding tasks, and student presentation of work. These practices were almost uniformly reported, with some variation reported on the frequency of student presentations.

Overall, it appears that the Coordinated Innovation model was highly effective at preparing graduate students to enact the innovative approach to calculus. While many of the graduate students involved in this study responded that they were not particularly interested in teaching calculus or in student thinking, they did express fairly expert-like beliefs about teaching and learning mathematics and generally felt positively toward the instructional approach that was encouraged. Further, when asked if they would continue to implement such practices outside of Institution 2 (such as in their future careers as faculty), GTAs responded that they would continue many of the practices if they could teach in small courses. Thus, based off of the multiple data sources, it is apparent that while graduate students at Institution 2 do not necessarily internalize all of the beliefs that underpin this institution's approach to calculus (such as the usefulness of understanding student thinking in improving one's own teaching), the Coordinated Innovation model successfully prepares GTAs to implement the main tenants of this approach and develop (or sustain) many positive beliefs related to teaching and learning mathematics.

Peer-Mentor Model

Institutions 3 and 4 primarily employed graduate students as recitation leaders, rather than as course instructors, especially in relation to Calculus 1. There were no graduate student instructors who filled out either the beginning-of-term or end-of-term survey coming from either institution. Thus, in order to characterize the beliefs and practices of graduate students who participated in the Peer-Mentor model and how this model influenced their beliefs and practices, I draw on the case study data and the GTA follow-up survey. At Institution 4 both Mathematics and Mathematics Education graduate students were involved in the teaching of Calculus 1. However, only the Mathematics graduate students participated in the Peer-Mentor professional development. In the following section, I distinguish between GTAs from Institution 3, Math GTAs from Institution 4, and Math Education GTAs from Institution 4.

The following analyses indicate that GTAs coming from Institution 3 and Mathematics GTAs coming from Institution 4 identify more with the research community than with the teaching community, though they generally report enjoying their roles as GTAs and view this role as being a support for students. The Peer Mentor model prepares GTAs to feel comfortable in their role as recitation leaders, and supports graduate students in supporting their Calculus 1 students. The involvement of Mathematics Education GTAs in the community of calculus instructors at Institution 4 appears to have influenced the practices of the Mathematics GTAs, as some report slightly more innovative instructional practices (similar to those reported by the Mathematics Education GTAs) than represented during their training.

Case Study Data

In this section I provide descriptions of the espoused beliefs and practices from graduate students coming from Institution 3 and 4. I find it useful to first overview each institution individually, and then identify commonalities. The primary reason for this is to authentically situate the findings within the correct institutional and departmental context.

Institution 3. During the site visit to Institution 3, I spoke with two experienced graduate student instructors, one of whom was the current Senior TA and the other the apprenticing (future) Senior TA. Both graduate students were completing PhDs in Mathematics and had previously led recitation sections for Calculus 1. The future Senior TA was currently leading a recitation section for Calculus 1.

When asked what qualities in his own instruction he has tried to pass down to new TAs, the current Senior TA responded that the main things are treating students with respect, being organized about what he writes on the board, and in general being approachable for students and a resource for them. He explained that sometimes students have the disposition that they have to battle against their professor to get a good grade, and view the TA on their side. Thus, he said another aspect of his instruction that he tries to pass on is communicating to students that both he *and* their professor are on their team.

GTA 3.1: If you're going at this as a team and if they already feel this sort of comradery toward the teaching assistant then you can kind of pass some of that on to the professor as well and they feel more comfortable talking to the professor.

Both GTAs described the recitation sections as primarily functioning as problem solving sessions, where they were the ones predominantly responsible for presenting

solutions. One graduate student said that he spends recitation “going over homework questions and trying to just clarify concepts whenever possible” and that in some ways students view him as “the hero” because they come in with questions and he helps them get answers. This is supported by the fact that recitation sections are not mandatory, so typically students go to recitation when they need help. While both students reported running recitation as a question/answer session, they both encouraged student contributions for solving the problems, and expressed the importance and benefit for students to see partial incorrect solutions as part of the recitation section.

GTA 3.1: I try to tell incoming TA's you don't have to do everything right. It's actually, I think, advantageous to the students to see if you're going down a path and as long as it seems like it might go correctly: your integrating by parts, verses U-Substitution, verses this thing. You go down the wrong path, well you do that and I bet half the other students have done this in the class as well. Sometimes it's nice to go down 2 different paths and show them what went wrong here or what went right here and why they want to go back and forth. I think very often students come in thinking that if the don't go the right direction the first time then it's frustrating, they give up, and can never do this problem. Where if, while you prepare yourself for section and you notice some of the problems you had or if you go the wrong direction, if you can kind of present both sides if they can see where you went wrong, where they might of thought and gone wrong, and what went through your mind when you switched back over to this side and why would you choose this avenue verses this one.

GTA 3.2: The best possible situation for me is that I write down a question and then I say, "How do we start this?" and I get ideas from the class. So long as I keep getting ideas from the class I keep going and I'll go down the right path, I'll go down the wrong path it doesn't really matter... I'm happy to go get stuck, see what happens, and make a lesson out of that.

Institution 4 - Mathematics GTAs. During the site visit I spoke to two students in the Mathematics department, who were directly involved in the Peer-Mentor

professional development program. These students report much more traditional instruction than the GTAs from the Mathematics Education. Specifically, these graduate students described their instruction as a combination of lecture and showing students how to solve problems with “initiation-reply-evaluation” (IRE) style questioning (Mehan, 1979).

GTA 4.1: I'll kind of try to base what I'm doing on what the lecture the day before had been. I'll look over the homework and see if there's anything extra that needs to be talked about that maybe [the instructor] didn't quite get to in lecture and I'll try to prepare it around that. Most of the time I'm just doing example problems where the students are, I'll put it up and then I'll ask, 'Okay, what's the next step? What do I do here? Why am I doing this?'

GTA 4.2: I tell them to write numbers on the board for their homework. So they come in and as they come in or right when we're getting started, they put homework numbers on the board, people can put checks or things to note which ones they really want to see. And we start with those first, and we try and do as many homework problems as we can.

These students also implicitly identified their role as being a resource for students and responding to what students want.

GTA 4.1: I just try to really emphasize what it is being talked about yesterday or the day previous and the real advantage I feel there is being a lot closer to them in age, as a TA I don't have to be quite as technical. I can explain really this is what's going on in English versus this other language of mathematics, which I'm comfortable with, but they're not.

GTA 4.2: For me I think it's kind of hard because the students want to do problems because they want to do their homework or they have questions. And it's hard to find a balance between, 'I want to strengthen your understanding of some principles or introduce some new principles or

things that I think are going to be a problem for you,' versus explaining these specific problems that you need to get done.

When asked about more student-centered instructional approaches, this graduate student said that this was something he avoided because building off of students' thinking can take a lot of time and may confuse people. The Senior TA said that recently he had been running his lab sections more interactively, which includes “[looking at students] more and just ask[ing] them questions while I'm doing the problem, seeing what was difficult for them, just trying to get that interaction going.”

Institution 4 - Mathematics Education GTAs. During the site visit to Institution 4, I also spoke with 6 graduate students who were either currently involved with teaching Calculus 1 or had been when the CSPCC surveys were sent out. Four of these graduate students were in the process of completing their Masters degree in Mathematics Education, and thus were not part of the Peer-Mentor professional development. Instead, as reported in *Chapter 5*, these students indicated that much of their preparation to teach came from their readings and experiences as part of the Mathematics Education degree. Additionally, some of these students had weekly meetings with the Mathematics Education professor teaching Calculus 1 where they would discuss common student difficulties in the class and various approaches to teaching.

Two of the Mathematics Education GTAs had previously lead recitation sections for Calculus 1, one was currently leading a recitation section for Calculus 1, and one was currently teaching a small, evening section of Calculus 1. Two of the graduate students were completing their PhDs in Mathematics, and one of these two had been the Senior TA during the previous summer and thus was responsible for developing and running the

summer training program for mathematics GTAs. Both Mathematics GTAs were currently running recitation sections for Calculus 1.

Both lab sessions and class sessions (one Mathematics Education Masters student was teaching a small section of Calculus 1 in the evening) were described as a combination of lecture, group-work, and student presentations. Lab sections were specifically described as *not* running as typical question-answer sessions, and instead served as a review of what happened in lecture with time spent working on complex tasks. Some time was spent working on homework problems that many students had difficulty on (after the homework was returned to the students), but when homework problems were solved they were solved and presented by students.

GTA 4.3 (lead recitation sections): So we would talk about some of the problems that I had just handed back, and then maybe talk about something from the lecture the day before and show some geometers sketchpad document about whatever's happening or something like that. And then talk about problems or things that might help them on their homework. Like I tried to do the homework before and know what problems were going to come up.

GTA 4.6 (lead recitation sections): So I would say like maybe 20 to 30 percent of the time, maybe more than that, maybe 40 percent of the time, somewhere around there, I would re-teach something if I thought it was confusing because we would attend lecture. You just kind of watch and be like, I don't think they're getting this, or just from past experience realizing, oh like they always have trouble with the degrees or whatever they're doing. So re-teach it but then, what I would have them do is I would have everyone write up on the board as I walked in, the questions that they didn't understand from the homework...I would break them into 7 groups and each group would get a problem. They would do the problem together, put it on the board and then they'd have to present it to the class. Explain how they did it.

GTA 4.5 (leads recitation sections): But [the instructor] has us prepare a task, and he'll like choose a task and then we'll prepare it, and it's group

work basically, and almost every time it's kind of the standard what you read about, 'groups are going to work together, and then at the end will come together and present ideas.'

During these conversations, multiple Mathematics Education GTAs mentioned that the “tasks” were very important to their instruction. When asked what types of tasks they prepared, one GTA responded that:

GTA 4.5: They're often problems that relate to what he talked about the day before in lecture on Monday. But they bring up counter-examples or bring up, like if you talked about the Mean Value Theorem, it might focus on why it needs to be continuous on this interval and different on this interval, and look at some examples and try to, stuff like that.

During the site visit one recitation section was observed, taught by GTA 4.3, and ran as she described. The GTA who was teaching her own section described class as having more lecture than she would like, but that she is still new to teaching and wants to make sure she gets through the material needed on the common exams.

GTA 4.4: It's a higher-speed course. I want to teach well, I want to teach with good teaching methods, and I think the plain, bland typical teaching isn't necessarily the best... but I want to start with something that works and make small changes in how I teach, rather than trying to do big changes at once. Because I figure if I fall behind, I can't shove the test back for these students, I don't have that kind of control. So I want to be respectful of their learning. So sometimes it's more lecture, and I'm the only one talking. But I try usually to ask a lot of questions. So I try to, maybe it's not always motivate things but make the proofs make sense. But I try to make connections. And try and connect to intuition also.

These GTAs expressed that students are held to high expectations in the department, but are given supports to succeed and thus often meet this high expectation.

One GTA said that all of her students could have succeeded in her course, but that it is up to them to take advantage of the resources made available. When asked what they wanted her A versus C students to get out of class, one GTA responded that they should be able to answer typical Calculus 1 questions *and* explain why they can answer them that way, instead of saying 'I don't know, that's what you told us.' She said her instructional approach supports this because when students work in groups they must explain things to one another, and during presentations they have to explain to the whole class, so they are used to explaining their thinking.

GTA 4.5: They'll try to explain it to each other. And then they'll explain it to me or whoever asks them a question. And I think that's helpful, to help them reason about it. Because just saying, 'This is what we learned to do,' doesn't help anyone understand and I think they know that.

Case Study Summary. Based on the case study data coming from graduate students from Institution 3 and Institution 4, it appears that the mathematics graduate students from Institution 4 are more similar in their beliefs and in the practices to the graduate students from Institution 3. These students indicate that their recitation sections ran mostly as interactive question/answer sessions. These GTAs indicated that their role was primarily to be a resource for their students, and that they try to show students not only complete and correct solutions, but also possible incorrect solutions on the path to solving a problem correctly.

The Mathematics Education GTAs from Institution 4 expressed different beliefs about mathematics and mathematics education, and reported very different instructional practices. Specifically, these students reported *not* running recitation section as a question

and answer session, but instead as a time for the GTA to reteach anything that was confusing and then have students work on challenging, open-ended problems in groups, often presenting their solutions.

GTA Follow-up Survey

There were 42 GTAs who responded to the GTA follow-up survey from the two intuitions that implemented the Peer-Mentor model. Two thirds of these students were in the process of completing a PhD in mathematics, 26.2% were completing a Masters in Mathematics, and the remaining 7.1% were completing a Masters in Mathematics Education. This sample of graduate students had mixed prior teaching experience, with 13 teaching for the first time and 15 having done so 5 or more times. At both institutions GTAs primarily serve as recitation leaders though are able to be course instructors. This survey did not identify which role(s) the respondents were serving.

Beliefs. Table 6.17 shows the mean responses and standard deviations from graduate students from Institution 3 and Institution 4, where GTAs from Institution 4 are grouped by Mathematics or Mathematics Education. All GTAs agreed that students in Calculus 1 at their university are capable of understanding the ideas in calculus, with the Mathematics Education GTAs agreeing the most strongly. There are interesting differences when it comes to the three groups' reported interests. Overall, Mathematics GTAs from Institution 4 aligned with the interested of GTAs from Institution 3. These students expressed interest in teaching more advances math classes (e.g. Linear Algebra, Real Analysis, Abstract Algebra, etc.), improving their own teaching, and conducting research in mathematics. They reported less interest in participating in activities that raise

their awareness of how students learn key ideas in calculus, teaching Calculus 1, working in industry (i.e. a non-academic position), and conducting research in mathematics education. Mathematics Education GTAs from Institution 4 expressed more interest in conducting research in mathematics education and participating in activities that raise their awareness of how students learn key ideas in calculus, and less interest in working in industry, conducting research in mathematics, and teaching more advanced math classes. These reported interests indicate that students from Institution 3 and Mathematics students from Institution 4 align themselves more closely with the community of research mathematicians, and are more similar to the interests of GTAs from the Coordinated-Innovation Model. Conversely, Mathematics Education graduate students from Institution 4 align with a different community, and are slightly more similar to the interests of GTAs from the Apprenticeship Model.

Table 6.17 GTA Follow-up survey – Beliefs: Peer-Mentor Model

	Institution 3 (N=30)	Institution 4 – Math (N=6)	Institution 4 – Math Ed. (N=3)
Beliefs about student capabilities (1=strongly disagree; 6=strongly agree)			
All students in Calculus 1 at my university are capable of understanding the ideas in calculus.	4.10 (1.61)	5.00 (0.89)	5.67 (0.58)
Interest in teaching and student learning (1=strongly disagree; 6=strongly agree)			
How strong is your interest in: participating in activities that raise your awareness of how students learn key ideas in calculus?	2.47 (0.84)	2.83 (0.75)	3.33 (0.58)
How strong is your interest in: teaching Calculus 1?	2.72 (0.99)	3.00 (0.63)	3.00 (1.00)
How strong is your interest in: teaching more advances math classes (e.g. Linear Algebra, Real Analysis, Abstract Algebra, etc.)?	3.53 (0.62)	3.17 (0.75)	1.67 (0.58)
How strong is your interest in: improving your own teaching?	3.50 (0.67)	3.50 (0.55)	3.67 (0.58)
How strong is your interest in: conducting research in mathematics?	3.34 (0.83)	3.67 (0.52)	2.00 (1.00)
How strong is your interest in: conducting research in mathematics education?	1.78 (0.79)	2.33 (1.37)	4.00 (0.00)
How strong is your interest in: working in industry (i.e. a non-academic position?)	2.28 (0.88)	2.17 (0.98)	1.67 (1.16)
Beliefs about teaching and learning (1=strongly disagree; 6=strongly agree)			
When students make unsuccessful attempts when solving a Calculus 1 problem, it is <i>a natural part of solving the problem</i>	4.90 (0.96)	5.17 (0.98)	5.67 (0.58)
When students make unsuccessful attempts when solving a Calculus 1 problem, it is <i>an indication of their weaknesses in mathematics</i>	2.17 (1.11)	2.17 (1.17)	1.00 (0.00)
My role as a calculus instructor is PRIMARILY to <i>work problems so students know how to do them</i>	3.37 (1.19)	3.00 (1.10)	2.00 (0.00)
My role as a calculus instructor is PRIMARILY to help students learn to reason through problems on their own.	5.27 (0.87)	5.33 (0.52)	5.00 (0.00)
A student's success in Calculus 1 PRIMARILY relies on his or her ability to <i>solve specific kinds of problems</i>	4.00 (1.34)	3.67 (0.82)	3.33 (1.53)
A student's success in Calculus 1 PRIMARILY relies on his or her ability to <i>make connections and form logical arguments</i>	4.27 (1.17)	5.33 (0.82)	4.33 (1.16)

Table 6.17 also shows that overall, each of the three groups of graduate students believe that their role as an instructor is primarily to help students learn to reason through problems on their own, and that when students make unsuccessful attempts at solving

mathematics problems, this is a natural part of solving the problem. It is interesting to note that, although the mathematics education GTAs indicate very different interests, their espoused beliefs regarding mathematics and mathematics education are very similar to mathematics GTAs coming from Institution 3 and Institution 4.

Instructional Practices. Table 6.18 shows the responses from the graduate students from the Peer-Mentor model on the three questions related to instructional practices. These responses indicate that GTAs from the Peer-Mentor model felt prepared to teach and intend to make mathematics relevant when they teach.

Table 6.18 GTA Follow-up survey – Instructional Practices: Peer-Mentor Model

	Institution 3 (N=30)	Institution 4 – Math (N=6)	Institution 4 – Math Ed. (N=3)
I feel prepared to teach Calculus 1. (1=strongly disagree; 6=strongly agree)	5.47 (0.63)	5.00 (0.63)	5.00 (0.00)
In my teaching of Calculus 1, I intend to show students how mathematics is relevant. (1=strongly disagree; 6=strongly agree)	4.23 (1.41)	4.50 (1.05)	4.00 (1.73)
How would you describe your teaching of Calculus 1? (1=Very innovative, 2=somewhat innovative, 3=somewhat traditional, 4=very traditional)	3.03 (0.53)	2.83 (0.75)	2.33 (0.58)

When asked to describe their teaching, GTAs from both institutions on average reported a somewhat traditional teaching style. At Institution 3, 24 GTAs reported “somewhat traditional”, 4 reported “somewhat innovative”, and 5 reported “very traditional”. When asked what they meant by their description of their teaching, the students who reported that their class was “very traditional” described this as including a combination of lecturing and answering student questions. One student reported that “Recitation is very formulaic: take questions on homework, present problems, ask for any questions at the end.” The students who reported that their class was “somewhat

traditional” some students reported it running as a “problem-solving session,” but students also reported occasionally implementing group-work, using “props and demonstrations,” and “spending less time on homework problems and instead had students work in small groups on a few ‘warm-up problems’ carefully chosen to facilitate greater insight and understanding.” Of the four students who reported a somewhat innovative teaching style, two provided descriptions of what they meant. These included “class participation” and “multiple learning methods.”

At Institution 4, 6 Mathematics graduate students and three Mathematics Education graduate students responded to this question. Among the Math GTAs, 2 described their class as “somewhat innovative,” 3 as “somewhat traditional,” and 1 as “very traditional.” The “very traditional” class was described as “Nearly pure lecture with Q&A.” The “somewhat traditional” classes were described as a combination of lecture with having students “answer questions from the text on the board and give feedback about their solutions.” The “somewhat innovative” classes were described as including group-work, the instructor answering student questions, and being “very open and play[ing] around a lot.”

Two of the Mathematics Education GTAs described their classes as “somewhat innovative,” which included group-work, technology, and open-ended tasks. The third Mathematics Education graduate student described his/her class as “somewhat traditional” and did not provide a description of what this meant.

Peer Mentor Model Summary

The findings from the GTA follow up survey further support the findings from the case study data reported above. The graduate students from Institution 3 and the Mathematics graduate students from Institution 4 indicated interests aligned with the research mathematics community, and they report to run their recitation sections as interactive, question and answer sessions and view their role as instructor to help students learn to solve problems. However, some of the descriptions of classes from Mathematics GTAs from Institution 4 also include group-work and expressed positive beliefs surrounding mathematics education. These included viewing their students as capable, their role as helping students reason through problems on their own, and that incorrect solutions are a natural part of mathematics.

The Peer-Mentor Model is primarily designed to support mathematics graduate students to lead recitation section, which is typically run as an interactive question and answer session at both institutions. Graduate students coming from both institutions report that this model prepared them for their roles, and report running the recitation section as intended. At Institution 4, there are also Mathematics Education graduate students that are involved in the teaching of Calculus 1, but do not participate in the Peer-Mentor Model professional development. Instead, they receive minimal formal professional development and report drawing on their experiences in the Mathematics Education program and informal discussions about teaching with other graduate students and faculty. While one of these students remarked that it would have been beneficial to have participated in some sort of mentoring and apprenticeship for Calculus 1 like she had for a Mathematics education course, overall they report feeling prepared for their role

as Calculus 1 recitation leaders. It is possible that although the Mathematics Education graduate student are not directly involved in the Peer-Mentor Model that these students have a positive, indirect influence on the community of Mathematics GTAs at Institution 4. While the Mathematics Education GTAs and the Mathematics GTAs are in different communities in some ways, there are together in the local community surrounding undergraduate instruction. From a situated perspective, the other members of a community are as integral to one's participation in that community as the formal preparation to become a part of that community.

Influence of Programs on GTA Beliefs and Practices

In this chapter I have provided rich accounts of the mathematical beliefs and instructional practices of GTAs coming from each of the three professional development models, drawing on qualitative and quantitative data. A primary goal of these accounts was to connect the beliefs and practices to the professional development. From a situated perspective their beliefs and practices are necessarily related to their experiences in the professional development programs. Our participation in a community is influenced by the nature of our interactions within that community, as well as our own individual social history, the other members of the community, the context of the community, and many other factors. Each of the professional development programs have different goals and needs, and so provided graduate students a variety of ways to participate in the community during their training. These different ways of engaging GTAs in the different communities resulted in graduate students with different beliefs and practices.

One way to determine the efficacy of a professional development is to consider how well the program achieved its goals. Often, a program's goals are related to the development and enactment of the desired beliefs and practices. The goals of the Apprenticeship Model are both immediate (to be successful when they are in the classroom) and long-term (to transition from the role of student to the role of instructor), and are related to their beliefs and practices. The findings in this chapter show that graduate students at Institution 1 have internalized the role of instructor, and thus the Apprenticeship Model PD program appears to be successful in achieving this goal. One goal of the Coordinated Innovation Model is to prepare graduate students to enact a specific instructional practice. The results in this chapter show that this professional development program was successful in preparing GTAs to enact these instructional practices, though less successful in gaining widespread "buy-in" to this approach.

CHAPTER 7: Framework for GTA-PD

In *Chapter 5*, I developed four guiding questions that I used to characterize graduate student professional development programs, and two questions to evaluate and/or implement these programs. As a reminder, these questions are:

1. What is the institutional and departmental context that the model is embedded in and supported by?
2. What is the (implicit or explicit) guiding philosophy of the model?
3. What are the structural components of the model?
4. What knowledge and practices are emphasized through this model, and how?
5. What aspects are necessary to institute this model?
6. What are the affordances of this model?

In this section, I take the four guiding questions a step further and (1) articulate what aspect(s) of a professional develop program each question targets, and (2) identify how these aspects are related to one another. Together, these two actions transform the characterization of GTA-PD programs into a framework. This framework provides a model of the aspects of a GTA-PD and the relationships between these aspects, and is a major contribution stemming from this study. This enables one to consider the implementation and evaluation of a professional development program more directly, addressing the fifth and sixth questions from *Chapter 5*.

Aspects of a GTA-PD Program

Each question above addresses a different aspect of graduate student professional development programs. In *Chapter 5*, I discussed each question in depth and considered variations of answers for each question. Here, I provide focused descriptions of each aspect of the programs.

- 1. Institutional and Departmental Context:** Objective information about the institution and department that is relevant to Calculus 1 instruction and the graduate student professional development program. This includes details about the current state of the institution, department, calculus program, and GTA professional development program, and the history of each of these elements.
- 2. Institutional and Departmental Culture:** Objective and/or subjective information about the views, beliefs, objectives, goals, and aspirations of the institution and department that are relevant to Calculus 1 instruction and the graduate student professional development program. This includes the views, beliefs, objectives, goals, and aspirations of (a) the institution regarding undergraduate education, (b) the department regarding Calculus 1 instruction, (c) the department regarding graduate students' roles in Calculus 1 instruction, and (d) the department regarding graduate student preparation for their role in Calculus 1 instruction. These views, beliefs, objectives, goals, and aspirations may or may not be explicitly stated.
- 3. Structure:** Objective information about the formal and informal structural components of the GTA-PD program. This includes the five components

identified by Belnap and Allred (2009): (a) timing, (b) frequency, (c) duration, (d) topics covered, and (e) overall design.

- 4. a) Development of knowledge:** Objective and subjective information about the types of knowledge emphasized through the structure of the program. This includes the three main types of knowledge identified by Schulman (1986): (a) pedagogical knowledge (PK), (b) content knowledge (CK), and (c) pedagogical content knowledge (PCK). These types of knowledge can be further specified using Mathematical Knowledge for Teaching (MKT) and the subdomains of knowledge in MKT, such as Knowledge of Content and Students (KCS) and Knowledge of Content and Teaching (KCT) (Ball et al., 2008).

b) Development of practices: Objective and subjective information about the ways practices are engaged in the three pedagogies of practice identified by Grossman et al. (2009): (a) representations of practice, (b) decompositions of practice, and (c) approximations of practice.

- 5. Implementation:** Objective and subjective information about what is needed to adapt, implement, and/or sustain a GTA-PD program.
- 6. Evaluation:** Objective and subjective information about the assessment of the efficacy of the GTA-PD program.

Relationships Between Aspects of the Framework

The central dimension of the framework is the *structure* of a program. The structure of a GTA-PD program is the aspect that is typically used to characterize a program, much like the specifications of a house (number of bedrooms and bathrooms,

square footage, architectural design, etc.) are typically used to characterize it. However, like these specifications are shaped and constrained by the environment in which one builds a house (including the lot size, zoning laws, and builder and/or designers' preferences), a professional development program is shaped and constrained by the environment within which it exists. The structure of the program is constrained, determined, and enabled by the surrounding environment. The *institutional and departmental context* and *culture* together comprise the environment within which the GTA-PD program exists. The institutional and departmental context guides the needs and capabilities of a graduate student professional development program. For instance, the responsibilities of graduate students are determined by (a) the number of graduate students in the department in relation to the number of other faculty and in relation to the number of undergraduates served by the department, (b) the types of classrooms available (large lecture halls versus small classrooms), and other components of the context of the institution and department. The institutional and departmental culture shapes how the department responds to these needs and capabilities. For instance, whether graduate students serve as recitation leaders or course instructors will be shaped by (a) the institution and departments' views on class size, (b) their orientation toward optimal learning environments, (c) their aspirations for undergraduate instruction, and other components of the culture of the institution and department.

Within the structure of the program, different *knowledge* and *practices* are emphasized and in different ways. Once a structure has been developed, various knowledge and practices can be emphasized and fostered in different ways. For instance, a GTA-PD program designer may decide to include an opportunity for graduate students

to prepare and present a short lecture, and be given feedback on this presentation. This activity could be enacted in a way to emphasize different types of knowledge (pedagogical, content, and/or pedagogical content) and serve as a representation of practice, decomposition of practice, and/or approximation of practice. If the goal of this activity is to prepare novice GTAs to implement a specific instructional strategy, the practice lecture may serve to give graduate students an opportunity to approximate the practices of that instructional strategy and develop the specific pedagogical knowledge associated with that approach. For other graduate students watching this practice lecture, the activity may serve as a representation of the practice. If, instead, the goal of this activity is to prepare novice GTAs to prepare and deliver a lesson, this practice lecture may serve to give graduate students an opportunity to approximate the practices of preparing and implementing a lesson, and emphasizes developing the pedagogical content knowledge associated with choosing correct examples, motivating, structuring, and concluding a lesson.

These two potential variations illustrate the different ways knowledge and practices can be emphasized and fostered within different enactments of the same professional development activity. Within a professional development program, many types of knowledge are emphasized (to varying degrees of depth) and GTAs engage in pedagogies of practice (to varying degree of authenticity). These varying degrees of depth and authenticity are represented in the framework by darker or lighter shading, where darker represents knowledge emphasized more deeply or more authentic pedagogies of practice. Figure 7.1 shows how these five aspects of the program are related to one another.

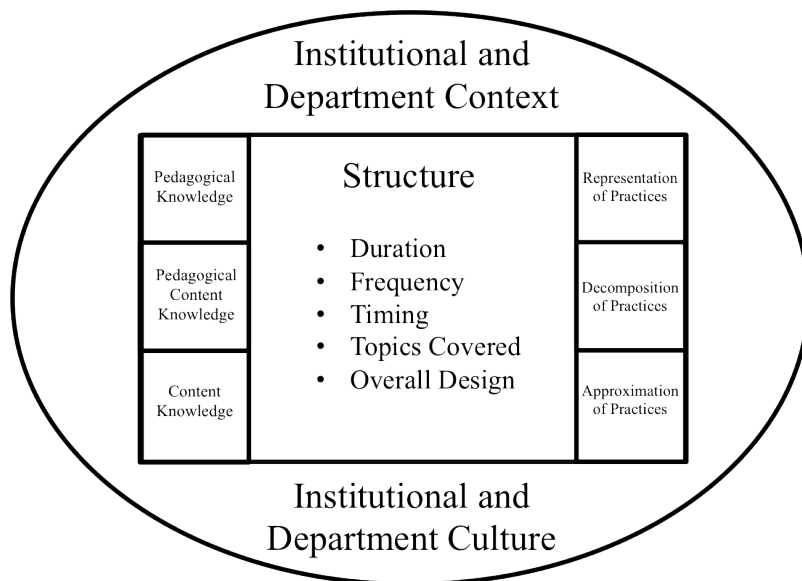


Figure 7.1 Framework of GTA-PD programs

Three Examples

In *Chapter 5*, I characterized three graduate student professional development program models by providing thick descriptions of each program, structured by answering the four guiding questions. Here, I use the framework to visually represent each model. As shown in Figures 7.2, 7.3, and 7.4, these representations give a clear overview of the structure and encompassing environment of GTA-PD programs. The shading provides a visual representation for the level of emphasis of the knowledge and the level of authenticity of the practices involved in the programs. These representations afford practitioners and researchers the ability to easily compare across models, and aid in the implementation (or adaption) of models and the evaluation of individual models and.

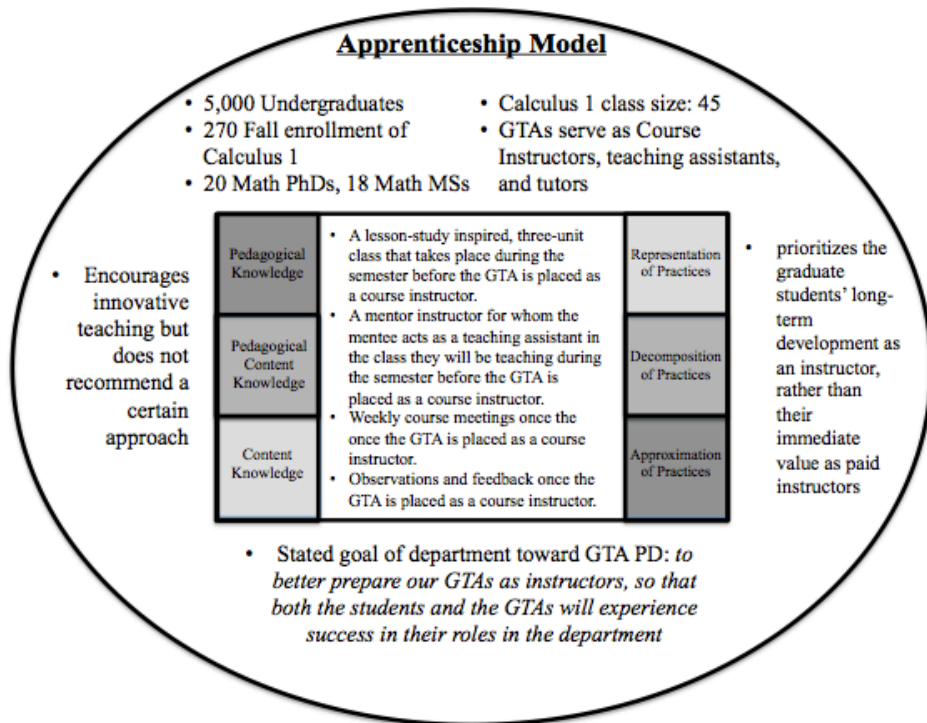


Figure 7.2 Apprenticeship model

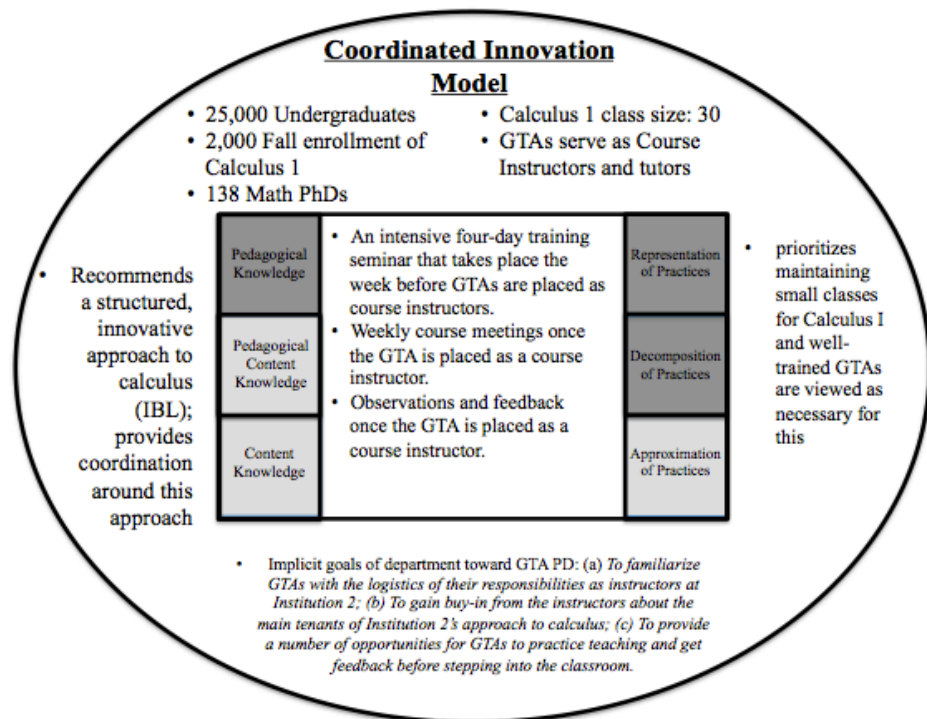


Figure 7.3 Coordinated Innovation Model

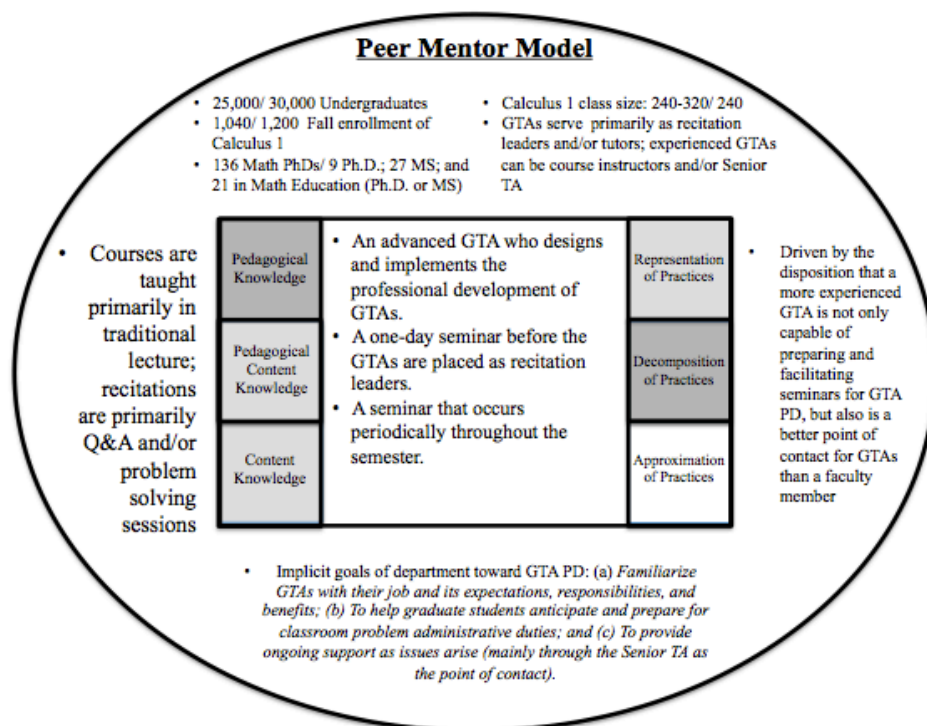


Figure 7.4 Peer Mentor model

Using the Framework

While these representations do not give the rich detail provided in *Chapter 5*, they provide enough information to compare across models, and can be used to ask and answer questions regarding the evaluation or implementation of an individual model. Both the implementation and evaluation of GTA-PD programs consider the relationship between the institutional and departmental environment and the program structure. The implementation of a program attends to what aspects of the institutional and departmental environment are necessary to support and sustain a specific program structure. The evaluation of programs attends to how well a specific program structure is meeting the needs of the institutional and departmental environment.

Implementation

The fifth question that emerged in the characterization of GTA-PD programs focused on what aspects of the institutional and departmental environment would be needed to implement a specific program. This includes considering what elements in the environment must be present for the GTA-PD program to be enacted, and what elements in the environment can vary, which may or may not lead to adaptations in the PD program. Thus, the implementation of a PD program attends to what is sufficient and what is necessary in the environment to support a specific program structure.

The framework representation aids the consideration of implementation of the programs. For example, Figure 7.3 illustrates that Institution 2 is responsible for teaching a large number of undergraduate students Calculus 1 in an innovative way, involving small class and coordination of the instruction across sections. To accomplish this, Institution 2 employs a large number of graduate students as Calculus 1 instructors, and so the Coordinated Innovation PD program is designed to prepare and support these instructors in enacting the innovative approach. In considering the implementation of this model, one should consider the demand of Calculus 1 students, the relative supply of graduate students as Calculus 1 instructors, and the desired instructional approach. Then one can attend to the components of the structure and the emphasis on different types of knowledge and engagement in different practices that support the goals of this structure.

Evaluation

The final question that emerged in the characterization of GTA-PD programs focused on the affordances of a program, and implicitly attends to a program's success. However, the success or failure of a program may be measured in a number of ways and

from a number of perspectives. The institutional and departmental environment includes a number of constituents that have a stake in the graduate student professional development program. These are the institution-level administration (such as Dean, Provost, or University-wide GTA Trainer), department-level administration (such as Department Chair, Course Coordinator, or mathematics GTA Trainer), mathematics instructors, graduate students, and the undergraduate students taught by graduate students. Thus, one way to evaluate a GTA-PD program is to measure how well the structure of the program served the needs of each of the above constituents within the environment.

The framework representation facilitates such a comparison. For example, Figure 7.2 illustrates that Institution 1 primarily employs graduate students as course instructors and values their immediate preparation as GTAs and their long-term development as instructors. To accomplish this, they emphasize pedagogical knowledge and pedagogical content knowledge, and provide graduate students many opportunities to engage in authentic approximations of practice. To evaluate the effectiveness of this program, one may investigate the beliefs and practices of the graduate students (as done in *Chapter 6*) and compare these to the beliefs and practices of the other Calculus 1 instructors at that institution (similar to as done in *Chapter 4*).

One of the primary motivations for examining GTA-PD programs in depth comes from the large role graduate student play in the teaching of Calculus I, and the large role Calculus I has been shown to have on students' decisions to leave the STEM pipeline. Stemming from this motivation, one may also relate the success of a GTA-PD program to students' persistence through the courses the GTA's are involved in. Three of the four

institutions involved in this study had lower than average student attrition in the calculus sequence, and one factor that may contribute to this is that the graduate students involved in calculus instruction at these institutions were well prepared. There was a higher than average student attrition rate at Institution 2. This is very likely attributable to the large number of students who are required to enroll in Calculus II as a general education course but not for their major studies. If they choose to not take the mainstream Calculus II course there are other ways they can fill this GE requirement. Further, because the approach to calculus at this institution is likely so different from students' experiences in high school, it is possible that students disliked Calculus I not because of their graduate student instructors, but because of the approach to calculus.

These two confounding factors lead to a word of caution in relating student persistence to GTA-PD. Such a comparison draws strongly on the process-product paradigm, where student success is directly linked to instructor quality. Certainly instructor quality plays a role on students' decisions to stay or leave a field of study, but there are many elements tied to this decision. However, it certainly cannot hurt to better prepare the instructors who are teaching the instructor courses of a large number of students who may go onto STEM careers.

An alternate way to evaluate GTA-PD programs would be to revisit the traits of successful K-12 professional development programs. Multiple researchers consistently find that successful professional development programs:

1. Are sustained over a long period of time;

2. Focus on subject matter, both helping teachers understand the mathematics of specific content domains and students' mathematical thinking in those domains;
3. Provide opportunities for "hands on" learning by modeling the type of instruction expected;
4. Are integrated into daily lives of teachers;
5. Provides teachers with feedback and assessment that they need to grow as teachers; and
6. Have support from other constituents, such as administrators and the school district.

As previously mentioned, there are many ways that graduate student professional development is related to K-12 teacher training (both in-service and pre-service). There are also many differences in the needs of the novice teachers, the nature of the roles they are being trained for, the environments these jobs exist within, and the goals of the stakeholders. As such, it is necessary to carefully reflect on the applicability of each of these six qualities to GTA-PD programs, consider alternate but related qualities of GTA-PD programs, and begin to conjecture qualities of GTA-PD programs that may not appear in or be relevant to K-12 PD programs. In doing so, I begin to articulate the qualities of a successful GTA-PD program.

Qualities of a successful GTA-PD program

In this section, I examine each of the six qualities that researchers have identified as components of successful professional development programs at the K-12 level. I then

pose alternate qualities of successful professional development programs at the undergraduate level.

Sustained over a long period of time

The continuity of professional development into the instructional period is an important component of professional development programs, at both the K-12 level and the undergraduate level. The difference between these two contexts is the relative length of the instructional period. At the K-12 level, teachers stay in their positions for many years, and thus professional development programs at this level can be sustained over years. At the undergraduate level, GTAs are in their appointments for one to multiple terms. Relative to this appointment, professional development that extends into the term may be considered a “long period of time.” The main components of the Apprenticeship Model are sustained over a relatively long period of time, with both the lesson-study style course and the mentoring appointment lasting one semester. The week-long seminar component of the Coordinated Innovation model is not sustained over a long period of time, but the ongoing weekly meetings are, and serve as sustained professional development.

Focus on subject matter

At the K-12 level, a focus on subject matter is an important component of successful professional development programs for two reasons. First, the professional development programs need to be situated within the contexts of mathematics, rather than

be general pedagogical trainings. Second, teachers at the K-12 level may need to develop or reinforce their content knowledge surrounding their mathematical contexts.

At the undergraduate level, professional development programs should be situated within the context of mathematics, though should emphasize the development of knowledge beyond subject matter knowledge. Studies into graduate student preparation consistently find that graduate students do not find the campus-wide professional development programs to be worthwhile nor beneficial. This was also true among the graduate students involved in my study. For instance, one GTA from Institution 4 said:

GTA 4.4: There was a very broad TA training thing, but it wasn't math-specific, it was just for the whole campus. TAs all over, and it was just one day. I don't really remember what we talked about. It was more like, 'Be nice to your students, don't tell them what each other's grades are' and things like that.

This quotation indicates that this training is not necessarily irrelevant, but that it is not complete (nor memorable). Thus, at the undergraduate level the professional development should be situated within the context of mathematical subject matter. It should also be focused on developing knowledge beyond the subject matter. There is a widespread misconception that because undergraduate instructors have robust mathematical content knowledge, they do not need professional development surrounding subject matter. However, this belief has been shown to be incorrect from both a theoretical and an empirical perspective.

From a theoretical perspective, content knowledge combined with pedagogical knowledge is not sufficient in teaching mathematics; instead, there is knowledge specific

to teaching the content that is also needed (Shulman, 1987). This perspective has also been validated through research into teacher knowledge. For instance, Speer, Wagner, and Rossa (2004) reported on the difficulties one research mathematician had while teaching a differential equation curriculum that encouraged group discussions motivated by student thinking. They attributed these difficulties to a deficit in the professor's mathematical knowledge specific to student thinking about this content. It is especially important for graduate student professional development to emphasize the development of such knowledge, as one primary source for developing it comes through experience, and graduate students typically lack teaching experience. Thus, at the undergraduate level the focus should be on developing pedagogical content knowledge, rather than a focus on developing content (subject matter) knowledge.

Provide opportunities for “hands on” learning

Among the four programs that I studied, the most commonly identified “helpful” component was the opportunity to practice teaching (and the related component of receiving feedback for this teaching). Many graduate students come into their roles as recitation leaders or course instructors with no experience standing in front of a class as an authority. Thus, even presenting and getting feedback on a seven-minute lesson can be wildly important in removing the mystery (and fear) of stepping into the classroom for the first time. More extensive experiences in practice teaching can go much further, approximating the practices of teaching rather than simply removing the fear of a new experience.

Integrated into daily lives

One primary difference between teachers at the K-12 level and graduate student teaching assistants is the nature of their appointment as a teacher/instructor. For teachers at the K-12 level, their primary responsibility is teaching. This responsibility includes preparing for class, grading, and time spent in the classroom. Because of this multifaceted but unified responsibility, it is very reasonable to incorporate professional development into teachers' daily lives. For graduate students, being a GTA is often one of three responsibilities. In addition to their role as course instructor or recitation leader, graduate students are students, and often are also conducting research in their field of study. Thus, it is not reasonable to integrate professional development into their daily lives. Instead, having a weekly meeting with other instructors and/or recitation leaders would be a beneficial and reasonable way to maintain ongoing professional development, while balancing the multiple time demands a graduate student faces.

Provide feedback and assessment

As previously mentioned, many graduate students involved in my study appreciated the opportunities to practice teaching and receive feedback on this teaching. Additionally, whenever GTA's were observed in the classroom they appreciated getting feedback and concrete ways to improve their teaching. Thus, receiving feedback is also a highly important component of GTA-PD.

At the K-12 level, reports have identified the assessment of the relationship between the PD and student learning as an important element of professional development programs. For instance, Hawley and Valli (1999) found that successful

professional development programs “incorporate evaluation of multiple sources of information on outcomes for students and processes involved in implementing the lessons learned through professional development” (p. 138). Certainly it is important for institutions and/or departments to evaluate the effectiveness of the professional development programs. The GTA-PD framework presented in this study can aid in this evaluation, by helping stakeholders connect the goals of the programs with the achievement of those goals. However, I caution here in evaluating the programs by connecting them to student learning. While this can be one way to assess the success of a program, it should not be used to “assess” graduate students, but rather as one data point in a complicated network of inputs into student learning.

Across the successful doctoral granting institutions, we did see attention to local data as a common thread (Rasmussen, Ellis, Zazkis, & Bressoud, 2014). Being aware of student success in the calculus sequence, and how this may or may not relate to various inputs (including placement into Calculus I, instructor professional development, curriculum changes, student supports, etc.) emerged as an actionable trait among more successful programs. Thus, attendance to the relationship between student success and professional development is important, but should not be solely relied on as a way to assess the success of the program.

Support from other constituents

The final element of successful professional development programs at the K-12 level may be the most important to translate to the undergraduate level: support from other constituents. At each of the four institutions involved in my study, support from key

stakeholders was integral to the success and longevity of the professional development programs. It appeared necessary to have (at least) department level support of the professional development program, rather than having them run by one motivated faculty member.

Summary of GTA-PD program success

When comparing elements of successful PD programs identified as successful at the K-12 level to the three models of GTA-PD programs discussed in this study, a number of commonalities emerge. Of the six elements identified at the K-12 level, five of these appear to remain related to success of a GTA-PD program, some with minor adjustments. Some of these elements are related, and thus can be condensed into the following four elements:

1. Extend into the instructional term and occur periodically during the term;
2. Situated in the context of mathematics, and focus on students' mathematical thinking in those domains;
3. Provide opportunities for "hands on" learning through approximations of practice and give feedback on these experiences;
4. Have support from other constituents in the department and institution.

In addition to these four elements, two of the four programs I observed supported GTAs in implementing innovative practices. One model for doing so did not recommend (or require) any specific instructional model, but rather provided multiple examples of innovative practices and gave the instructors the freedom to incorporate them into their practices as they wished. The other model strongly recommended a specific instructional

approach, and trained instructors how to implement this approach. Both models were successful in supporting GTAs in implementing instructional approaches that have been shown to be related to student success. Based off of these two models, I conjecture that one element of successful undergraduate professional development programs is supporting instructors in implementing innovative instructional approaches. However, more data is needed in order to determine if this is a more widespread trait.

There is one other common trait across the GTA-PD programs that I observed that is not addressed in the above list. This is their existence. Among mathematics departments that employ graduate students in the teaching of undergraduate courses, robust professional development of the graduate students is relatively uncommon (Bellnap & Allred, 2009). Thus, the trait of existence is implied in this list as a novel and necessary component of a successful GTA-PD program.

Connection to Theoretical Perspectives

With an eye-toward instructor quality and the process-product perspective, the framework presented in this chapter may be used to help direct a study focused on the process of GTA professional development and the product of graduate student instructor quality. A future study aligned with this perspective may resemble *Chapter 4*, and compare GTAs coming from one program to another program along the dimensions addressed in *Chapter 4*. From the situated learning perspective, this framework highlights the influence the surrounding environment has on a graduate student professional development program, and attends to the process of bringing a graduate student into the community of instructors by engaging them in certain practices (to varying degrees of

authenticity) and helping them develop certain knowledge (to varying to degrees of emphasis). A future study aligned with this perspective may more closely resemble *Chapter 6*, and compare the beliefs and practices of graduate students to other instructors in the community throughout their time in the program.

Limitations and Future Directions

The framework articulated in this chapter emerged out of the mixed method analysis involving four doctoral granting institutions that employ graduate students in the teaching of Calculus 1, and who have been shown to have successful Calculus 1 programs. The framework is designed to characterize existing graduate student professional development programs, and aid in the evaluation of existing programs and the implementation of new programs. There are a number of limitations of the framework itself and the overarching study presented in this dissertation.

A number of limitations of this work arise from the design of the study, which itself was embedded within the larger CSPCC study. The CSPCC study identified institutions with calculus programs that were more successful than others. In this study, success was defined to be a combination of pass rate in Calculus 1, increased (or maintained) confidence, interest, and enjoyment of mathematics, and maintained intention to take Calculus 2. For my dissertation work, I focused on the selected institutions that employ graduate students in the teaching of Calculus 1, which were all doctoral granting institutions although graduate students may have been involved in the teaching of Calculus 1 at Masters granting institutions that were either not involved in the study or not selected as successful. Thus, the institutional and departmental environment

that I considered in my work is limited by what I saw at doctoral granting institutions. While there are many commonalities between Masters granting and Doctoral granting institutions, there are likely also important distinctions. For instance, graduate students at Masters granting institutions may have different career ambitions than those at Doctoral granting institutions, and thus GTA-PD programs may take this under consideration as they enculturate graduate students as instructors or recitation leaders. Further, this study focused on graduate students employed in the teaching of Calculus 1 exclusively, while graduate students are often involved in the teaching of both lower level and high level classes (such as precalculus and linear algebra). Thus, future work will examine the generalizability of the findings in this dissertation to different institution types and to other content domains.

An additional limitation stemming from the design of the study is the lack of data measuring instructor knowledge. This was explicitly not an area of attention for the CSPCC study, and it was outside the scope of this study to introduce it as one for the targeted dissertation work. In this study, I have addressed the role knowledge plays in the literature on instructor quality and professional development. Additionally, in my theoretical perspective I emphasized the role knowledge acquisition plays in becoming part of a community. During the characterization of GTA-PD programs (in *Chapter 5*), I attended to the opportunities provided to graduate students to develop different types of knowledge, but did not collect data to directly assess the extent to which they actually developed the knowledge. I similarly did not compare instructor knowledge in the comparison of GTA instructor quality to non-GTAs (in *Chapter 4*), and did not investigate instructor knowledge among graduate students from each of the three models

(in *Chapter 6*). This limitation provides multiple areas for future work, comparing existing instructor knowledge and examining the development of instructor knowledge among graduate students.

Two further avenues that are not deeply investigated in this study, but that are enabled by this work, are the implementation and evaluation of GTA-PD programs. As mentioned above, the framework takes steps to facilitate both activities, but this study did not investigate these areas in depth. Future work will test what the framework affords the evaluation of existing programs for researchers and practitioners, and explore ways to expand or adjust the framework for the purpose of evaluation. To explore the implementation of GTA-PD programs, future work will explore how practitioners may use the framework to consider the implementation of existing programs, and what additional information they draw on during these considerations. The work presented in this dissertation, especially in *Chapter 7*, is the beginning of an important line of research that will contribute to a larger research program investigating GTA-PD programs.

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APPENDECES

Appendix A: CSPCC Surveys

In lieu of reproducing each of the six surveys, I direct you to the online resources for each:

- **Student surveys, instructor surveys, and course coordinator survey** may be found online at the website for the Characteristics of Successful Programs in College Calculus (CSPCC): <http://www.maa.org/cspcc/>

Appendix B: GTA Survey

The GTA survey may be found at the survey monkey website (please feel free to “answer” the questions using “X” as a response so I know to disregard these responses): <http://www.surveymonkey.com/s/LMKWLMT>

I also reproduce the questions here.

MAA Calculus Survey for Graduate Students

***1. University:**

***2. Degree currently seeking:**

- PhD in mathematics
- PhD in mathematics education
- Masters in mathematics
- Masters in mathematics education
- Other (please specify)

***3. How many times have you taught Calculus or lead a recitation for Calculus?**

- 0 (I have not taught a class/recitation yet, but will soon)
- 0 (I am currently teaching my first class/recitation)
- 1
- 2
- 3
- 4
- 5 or more

***4. How would you describe your teaching of Calculus I?**

- Very innovative
- Somewhat innovative
- Somewhat traditional
- Very traditional

Please describe what you mean by innovative or traditional.

***5. How strong is your interest in:**

teaching Calculus I?

teaching more advanced math classes (e.g. Linear Algebra, Real Analysis, Abstract Algebra, etc.)?

participating in activities that raise your awareness of how students learn key ideas in calculus?

improving your own teaching?

conducting research in mathematics?

conducting research in mathematics education?

working in industry (i.e. a non-academic position)?

*** 6. Please select the most appropriate responses below.**

Strongly

When studying Calculus I from a textbook or in course materials, students tend to make sense of the material so that they understand it. (

When studying Calculus I from a textbook or in course materials, students tend to memorize it the way it was presented. (

When students make unsuccessful attempts while solving a Calculus I problem, it is an indication of their weakness in mathematics. (

When students make unsuccessful attempts while solving a Calculus I problem, it is a natural part of solving the problem. (

My role as a Calculus instructor is PRIMARILY to help students learn to reason through problems on their own. (

My role as a Calculus instructor is PRIMARILY to work problems so students know how to do them. (

A student's success in Calculus I PRIMARILY relies on his or her ability to solve specific kinds of problems. (

A student's success in Calculus I PRIMARILY relies on his or her ability to make connections and form logical arguments. (

In my teaching of Calculus I, I intend to show students how mathematics is relevant. (

All students in Calculus I at my university are capable of understanding the ideas in Calculus. (

Calculus is about getting specific answers to specific problems. (

*** 7. I feel prepared to teach Calculus I.**

- Strongly disagree
- Disagree
- Slightly disagree
- Slightly agree
- Agree
- Strongly agree

*** 8. How useful were each of the following in preparing you to teach Calculus I?**

Not applicable - this was not offered to me

One-to-five day training before you began teaching	<input type="radio"/>
Seminar or class during the academic year about teaching	<input type="radio"/>
Regularly scheduled meeting with other Calculus instructors	<input type="radio"/>
Informal discussions with other instructors	<input type="radio"/>
Faculty mentor	<input type="radio"/>
Faculty observation of your teaching	<input type="radio"/>
Peer observation of your teaching	<input type="radio"/>
Your observation of peers' teaching	<input type="radio"/>

Please describe any other training programs you participated in and their usefulness

*** 9. Please describe any other experiences that have contributed to your level of preparation to teach.**

Appendix C: Case Study Protocol

TA Trainer Interview Protocol

Thank you again for meeting with us to talk about your Calculus program. As you may know, the Mathematical Association of America is conducting a large-scale study of Calculus 1, sponsored by NSF. The first phase involved a national survey of instructors and students in mainstream Calculus 1 classes, collected during the fall term of 2010. In the second phase of the study we are conducting follow-up case studies at institutions chosen because they were identified as doing something that is interesting and successful. Your institution was selected as one of the case studies. Our goal is to better understand how and why things work here, which can then lead to recommendations for similar institutions. This interview should last around 45 minutes, and will focus on the training and professional development of GTAs. So let's get started.

Question
<p>Q1. What are graduate TA responsibilities?</p> <ul style="list-style-type: none"> ○ Grading homework ○ Grading exams ○ Running recitations ○ Designing exams ○ Teaching their own class ○ holding office hours ○ working in a tutoring center ○ Other _____ <p>A. How does the department determine which graduate students are selected to be TAs in each of the roles mentioned?</p> <ul style="list-style-type: none"> ○ Through an interview ○ Other sort of screening ○ Asked ○ Assigned ○ Other
<p>Q2. Please describe the training TA's receive <i>before</i> they began their duties.</p> <p style="text-align: center;"><i>(For A-E, ask ahead of time if possible and fill in)</i></p> <p>A. Is the training program optional or required?</p> <p>B. Who participates in the program?</p> <p>C. Is this program department specific or university wide?</p>

- D. Who facilitates the program?
- E. How long is this program?
- F. What is done in this program?
 - Practice writing on board?
 - Discuss how to develop a lesson?
 - Practice writing syllabus/ homework/ exam?
 - Watch videos of students solving problems?
 - Discuss multiple ways that students may solve a problem?
 - Discuss student difficulties in Calculus?
 - Discuss course policies and logistics?
 - Discuss ethics of teaching?
 - Practice facilitating groupwork?
 - Watch videos of yourself teaching?
 - Other _____
- G. What do you hope that the TA's learn from this program?
- H. Do you think that this program was effective? How do you know?

Q3. What types of ongoing support or training do TA's continue to receive during the school year? (*Probe for multiple*).

- A course
- Peer observation
- Faculty Observation
- Faculty mentor
- Other _____

(Ask A for each training and then ask question B for each training, etc.)

(For A-D, ask ahead of time if possible and fill in)

- A. Is the _____ (*course, observation, mentoring, other*) optional or required?
- B. Who participates in the _____ (*course, observation, mentoring, other*)?
- C. Who facilitates the _____ (*course, observation, mentoring, other*)?
- D. How long/frequent is this _____ (*course, observation, mentoring, other*)?
- E. What is done during _____ (*course, observation, mentoring, other*)?
 - a. Practice writing on board?
 - b. Discuss how to develop a lesson?
 - c. Practice writing syllabus/ homework/ exam?
 - d. Watch videos of students solving problems?
 - e. Discuss multiple ways that students may solve a problem?
 - f. Discuss student difficulties in Calculus?
 - g. Other _____
- F. What did you hope that the TA's learn from this _____ (*course, observation, mentoring, other*)?
- G. Do you think that _____ (*course, observation, mentoring, other*)

was effective? How do you know?

Q4. What about your TA training program is especially effective?

- A. *(If applicable)* How do you know it is effective?
- B. *(If applicable)* How did you get to this point?
- C. What could make it even more effective?
- D. Please describe some of the challenges that the TA training program faces.

Q5. What is your role as a TA trainer?

- A. How did you come to be in this position?
- B. How effective do you think you are in this role?

Q6. Who do TA's talk to about teaching and student learning of calculus?

- Past teachers who they have taught for
- Past teachers they have worked for/with
- Current teachers who teach them
- Current teacher they work for/ with
- Peers
- TA resource center
- Teaching center
- Mentor
- Peers (informal discussions)
- Tutoring center
- Regularly scheduled meetings
- Professional organizations (MAA meetings)
- Special programs for TAs
- Other _____

A. What do you think they talk about?

Q7. How are TAs evaluated on their teaching?

Q8. How are TAs rewarded for good teaching?

- A. Please give us an example of this.
 - Monetary award
 - Public recognition
 - Given preferred classes to teach
 - Other _____

Q12. We are interested in how uniform the different Calculus 1 sections taught by

TAs are regarding various aspects of the course. Let's start with pedagogy.

- A. How uniform is the teaching of Calculus 1 across TAs? (*probe for whether this is new and what precipitated a change*)
- B. What about textbook? (*same probe*)
- C. How about exams? (*same probe*)
- D. And technology use? (*same probe*)
- E. How about the homework system? (*same probe*)

Q10. Please tell me about how much time and effort you encourage TAs to spend on teaching compared to studying for their classes or doing research.

- A. How have you conveyed these attitudes towards the TAs?
 - official policy
 - casual conversations
 - formal conversations

Q11. As a whole, what makes the Calculus program at your institution effective?

- A. Is there anything else about the Calculus program you want to tell me about?

TA Interview Protocol

Thank you again for meeting with us to talk about your Calculus program. As you may know, the Mathematical Association of America is conducting a large-scale study of Calculus 1, sponsored by NSF. The first phase involved a national survey of instructors and students in mainstream Calculus 1 classes, collected during the fall term of 2010. In the second phase of the study we are conducting follow-up case studies at institutions chosen because they were identified as doing something that is interesting and successful. Your institution was selected as one of the case studies. Our goal is to better understand how and why things work here, which can then lead to recommendations for similar institutions. This interview has two parts and should last around an hour: the first set of questions is about your teaching practices, and the second set is about various influences on your teaching, including your training. So let's get started.

Question
<p>A. Teaching practices: (<i>Suggested opener</i>) I am familiar with the general structure of calculus classes at your school would like to focus on your teaching practices and style.</p>
<p>Q1. What is your role as a TA in teaching calculus? (<i>Probe for all roles</i>).</p> <ul style="list-style-type: none"> ○ Grading homework ○ Grading exams ○ Running recitations ○ Designing exams ○ Teaching class ○ holding office hours ○ working in a tutoring center ○ Other _____
<p>Q2. How were you assigned/ chosen to _____ (<i>fill in role from above: teach, run a dissertation, etc</i>)?</p> <ul style="list-style-type: none"> ○ Through an interview ○ Other sort of screening ○ Asked ○ Assigned ○ Other
<p>Q3. What do you like best about _____ (<i>fill in role from above</i>)?</p>

A. What do you like least?

Q4. Describe a typical class session, what you do, what the students do.

- lecture?
- small groups?
- worksheets?
- technology?
- give quizzes?
- review homework?
- review for exams
- have students present?
- address student questions?
- other?

Q5. Tell me about the assignments that you give your students.

- Homework
- Web Homework
- Labs
- Projects
- Group assignments
- Writing projects
- in-class assignments

A. For _____ (each of the above that were mentioned) what mathematically do you want your students to get out of the assignment? For example, does the assignment focus on computational proficiency, connections between representations, modeling, explanation and justification, etc.

- computational proficiency
- connections between different representations
- modeling
- explanation and justification
- other _____

A. What is the source of your exam problems?

B. What kinds of exposure do students have to those problems or problem styles before seeing them on an exam? (Have they been modeled in class or on homework? Are they novel?)

Q6. Tell me about your office hours.

- A. How many are you required to hold?
- B. How do you encourage your students to visit you during your office hours?
- C. What types of students visit you during office hours?
- D. What do you think they students need from you during office hours?
- E. What is it that you hope to learn about your students during office hours?

Q7. We are interested in how uniform the different Calculus 1 sections are regarding various aspects of the course. Let's start with pedagogy.

- A. How does the way you teach Calculus compare to other TA's or instructors?
- B. What about the textbook/ class materials?
- C. How about exams and quizzes?
- D. And technology use?
- E. How about the homework system?

Q8. What control do you have over your calculus course?

- syllabus?
- quizzes
- exams?
- lesson plans?
- grading?
- use of online homework?
- common final?
- use (or nonuse) of technology?
- use (or nonuse) or teaching practices, such as groupwork?

Q9. To what extent do your students work together outside of class?

- A. What do they do?
- B. Do you specifically encourage or structure their work outside of class?

Q10. What do you want your A students to get out of your class?

- A. What do you want your C students to get out of your class?

B. Influences on teaching: Now I'm going ask you some questions about your influences for the way you teach Calculus.

Q11. Please describe the training you received *before* you began your role(s) as a TA.

- A. Was the program optional or required?
- B. Who participated in the program?
- C. Who facilitated the program?
- D. How long was this program?
- E. What did you do in this program?
 - Practice writing on board?
 - Discuss how to develop a lesson?
 - Practice writing syllabus/ homework/ exam?
 - Watch videos of students solving problems?
 - Discuss multiple ways that students may solve a problem?
 - Discuss student difficulties in Calculus?

- discuss course policies and logistics?
 - discuss ethics of teaching?
 - practice facilitating groupwork?
 - watch videos of yourself teaching?
 - Other _____
- F. What did you learn from this program?

Q12. What types of ongoing support or training do you continue to receive during the school year? (*Probe for multiple*).

- A course (for credit)
 - A meeting (not for credit)
 - Peer observation
 - Faculty Observation
 - Faculty mentor
 - Observe other instructors
 - Other _____
- A. Was the _____ (*course, observation, mentoring, other*) optional or required?
- B. Who participated in the _____ (*course, observation, mentoring, other*)?
- C. Who facilitated the _____ (*course, observation, mentoring, other*)?
- D. How long/frequent was this _____ (*course, observation, mentoring, other*)?
- E. What did you do during _____ (*course, observation, mentoring, other*)?
- Practice writing on board?
 - Discuss how to develop a lesson?
 - Practice writing syllabus/ homework/ exam?
 - Watch videos of students solving problems?
 - Discuss multiple ways that students may solve a problem?
 - Discuss student difficulties in Calculus?
 - discuss course policies and logistics?
 - discuss ethics of teaching?
 - practice facilitating groupwork?
 - watch videos of yourself teaching?
 - Other _____
- F. What did you learn from this _____ (*course, observation, mentoring, other*)?

Q13. What/who else has influenced the way that you teach?

- Your past teachers
- Past teachers you have worked for/with
- Your current teachers
- Current teacher you work for/with
- Peers

- Course coordinator
- MAA monthly
- Other journals
- Reading online
- Conferences

Other _____

Q14. Who do you talk to about teaching and student learning of calculus?

- Past teachers
- Current teacher
- TA resource center?
- Teaching center?
- Mentor?
- Peers (informal discussions)?
- Tutoring center?
- Regularly scheduled meetings?
- Professional organizations (MAA meetings, Project NExT)
- Special programs for TAs
- Other _____

What do you talk about?

Q15. How are TAs evaluated on your teaching?

- observations?
- student evaluations?

Q16. How are TAs rewarded for good teaching?

- Monetary award
- Public recognition
- Awarded preferred classes to teach
- Awarded more sections
- Other _____

Q17. Please tell me about how much time and effort you spend on teaching compared to studying for your classes or doing research?

- B. What is your advisor's attitude about how much time/effort you should spend on teaching?
- C. What about your peer's opinions about how much time/effort you should spend on teaching?
- D. Your supervisor's (CC's)?

E. How have they conveyed these attitudes towards you?

- official policy
- casual conversations
- formal conversations

Description of Observation Protocol for CSPCC

Developed by: Nina White and Vilma Mesa, University of Michigan

Overview

This classroom observation protocol serves at least three purposes within the CSPCC study. First and second, it serves to corroborate interview and survey data. Third, it provides a snapshot of instruction. Although we can't make any conclusions from single observations, especially not about what is not observed, this snapshot provides an opportunity to see if a single observation resembles or does not resemble stereotypical calculus instruction, where we use the gross stereotype of calculus instruction is mostly focused on rehearsing procedures, with limited participation from students, with teachers delivering most of the information or presenting most of the solutions; group work use is limited, and technology, when used by the instructor is for demonstrations purposes, when used by the students is for computation purposes; in general the cognitive demands of the tasks is low and there is an overemphasis on symbolic manipulation with less emphasis on connections between representations; contextualization of problems is low.

This observation protocol is designed with calculus instruction in mind. Many calculus classes are taught in a lecture style and are not very "reformed." It is designed to be a low-inferential observation protocol that will capture important characteristics of calculus classes and will be useful in comparing all classroom formats (reformed or not). In addition to attending to some standards-based criteria (e.g., student engagement, student exploration), we document the *problems* that are worked by students or the instructor and some of their characteristics. We seek to capture what is it like for a student to be in any given calculus class.

The observation protocol comprises a cover sheet and three parts.

1. Activity Log (Paper): This log is recorded in real time during the class at 5-minute intervals. It keeps track of the basic activities in the class. These categories are not very detailed, but provide a framework for the richer observational description in the Problems Log. After the observation, there is a place for the observer to record impressions of the class activity, using the log as a record and evidence.
2. Problems Log (Paper): This log is also recorded in real time. Every problem in the class (whether presented by the instructor, presented by students, or worked in groups) is recorded in a detailed log. Note: To supplement this log it will be helpful to collect and label a lesson plan (if available) and any materials handed out in class. After the observation, there is a place for the observer to record impressions of the class activity, using the log as a record and evidence.
3. Post-Observation Survey (Online): This portion of the protocol is online. It is to be filled out as soon as possible after the observation. It comprises two parts; prompts to summarize the two Logs are followed by a more general Survey about the class. The two Log Summaries ask the observer to use the Logs recorded during class to answer specific questions about the classroom practices and problems. The questions in the Survey are designed to correspond to questions from the student and instructor surveys in Phase I and codes we seek to capture in the interview data. The Survey covers four areas: Atmosphere, Interaction, Connections, and Mathematical Quality. These questions can be answered from memory, so no other extra note taking is

necessary. We strongly recommend that you familiarize yourself with the questions before the observation.

This document provides detailed descriptions of all three parts of the protocol, including the code definitions for both Logs and a copy of the questions in the Post-Observation (online) portion.

Make sure to create pdfs of the logs you collected.

Tips for Using this Protocol

1. Spend time reading over the definitions of the codes to make sure you understand them. Ask for clarification if needed or take extra notes if in doubt.
2. Bring a stopwatch to your observation. The Activity Log is easiest to fill out with the assistance of a stop-watch.
3. Bring your own surface to write on. It will be helpful if it can hold two pages at once.
4. Collect any additional materials from the instructor before or after class. This includes quizzes, worksheets, lesson plans, etc. Label all collected materials with instructor name, observer name, observation date, institution name, and class name.
5. Print many copies of the Problem Log. We have needed about one page per 10 minutes of class. Bring even more, just in case. To save on hand-writing the header of each page, you have the option of electronically filling in the header before printing the copies—but this must be done separately for each observer and each observation.
6. Number the Problem Log pages as you use them.
7. Fill out the Post-Observation portion as soon as you can after the observation.

Code Changes Since Version 7.0

- More precise definition of P codes (Presentations) on both Logs
- More precise definitions of Technology Codes on Problem Log
- Minor changes and clarifications of E and D codes in Activity Log
- SA (Single Answer) no longer exists as a code in Features on Problem Log
- MS (Multiple Solutions) is now called MM (Multiple Methods)
- S/M now refers to both learning a procedure AND practicing a procedure
- More precise instructions for what to include in the Notes part of Problem Log

Activity Log Description⁵

This log looks like this:

Class:	Date:	Instructor:
Institution:		Observer:

Activity Log

(Adapted from IBL Observation Protocol and CETP Core Evaluation – Classroom Observation Protocol)

For each 5-minute interval, code all activities that occur. Don't put the same code more than once into the same 5-minute box.

Time	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	50-55	55-60
Activities:												
Time	60-65	65-70	70-75	75-80	80-85	85-90	90-95	95-100	100-105	105-110	110-115	115-120
Activities:												

L	Professor lecturing—presenting material not in response to student concerns/questions. Lecture includes setting up a problem to be solved. It also includes solving a problem at the board without student involvement.	D	Class discussion—this is characterized by significant public student generation of content, such as students describing a solution from their seats to the class and the class (or the instructor) responding. Note that I can arise within a session of D.
IRE	IRE-style lecture. “Fill-in-the-blank” kind of interaction with students. Does not require students to explain things. Class may answer in unison. Student contribution are general one word or short phrases which fit into instructor’s train of thought. Only use this code embedded inside of lecture, not, for example, to code a few exchanges within a class discussion.	G	Working on a problem or an example in groups of 3 or more.
LwQ	Lecture with Questions— Students ask questions and respond with full sentences to instructor questions (short of describing in-depth processes or solutions). However, content is still primarily created by the instructor.	2	Working on a problem or an example in pairs.
LwC	Lecture with Clicker. Lecture is driven by student responses on clickers. Feedback by clicker is consistently sought during the lecture.	I	Working on a problem or an example individually. This may last only a few minutes.
E	Extended explaining by instructor, in response to question or difficulty. An extended takeover of class—a mini-lecture. Different from L because is responsive to an issue that arises on the spot. It can be described as “reactive content delivery.” This is by definition responsive and includes <i>revoicing with elaboration</i> .	P	Students presenting a solution or proof (individuals or groups) in a publicly visible way. That is, a student may present at the board, on a document projector, or from a laptop screen. If a student orally describes a solution from his seat, then P is <i>not</i> the right code. In this case, use D instead.
		T	Students or instructor using technology, for example calculators, computer-based quizzes/worksheets, computer animations, or computer algebra systems.
		B	Addressing class business, procedural activity (e.g. returning papers)
		A	Assessment. For example, a quiz.
		O	Other (describe)

Activity Log

It is meant to record the general class activity and is divided into 5-minute intervals.

Classroom Activity:

A stopwatch is useful in using this part of the log. For every 5-minute interval, the observer records the general format/mode of instruction and/or class activity. The following codes are used. *More than one code can be used in each 5-minute block. However, there is no need to repeat the same code within one 5-minute block.* The definitions also appear in the recording sheet.

Instructor lecturing—presenting material not in response to student concerns/questions. Lecture includes setting up a problem to be solved. It also includes solving a problem at the board without student involvement.

IRE IRE-style lecture. “Fill-in-the-blank” kind of interaction with students. Does not require students to explain things. Class may answer in unison. Student contributions are general one word or short phrases which fit into instructor’s train of thought. Only use this code embedded inside of lecture, not, for example, to code a few exchanges within a class discussion.

wQ Lecture with Questions— Students ask questions and respond with full sentences to instructor questions (short of describing in-depth processes or solutions). However, content is still primarily created by the instructor.

⁵ Adapted from IBL Observation Protocol and CETP Core Evaluation – Classroom Observation Protocol.

wC Lecture with Clicker. Lecture is driven by student responses on clickers. Feedback by clicker is consistently sought during the lecture.

Extended explaining by instructor, *in response to* question or difficulty. An extended takeover of class—a mini-lecture. Different from L because is responsive to an issue that arises on the spot. E can be described as “reactive content delivery.” This is by definition responsive and includes *revoicing with elaboration*.

Class discussion—this is characterized by significant public student generation of content, such as students describing a solution from their seats to the class and the class (or the instructor) responding. Note that E can arise within a session of D.

Working on a problem or an example in groups of 3 or more.

Working on a problem or an example in pairs.

Working on a problem or an example individually. This may last only a few minutes.

Students presenting a solution or proof (individuals or groups) in a publically *visible* way. That is, a student may present at the board, on a document projector, or from a laptop screen. If a student orally describes a solution from his seat, then P is *not* the right code. In this case, use D instead.

Students or instructor using technology, for example calculators, computer-based quizzes/worksheets, computer animations, or computer algebra systems.

Addressing class business, procedural activity (e.g. returning papers)

Assessment. For example, a quiz.

Other (describe)

Problem Log Description

This log looks like this:

Class:	Date:	Instructor:
Institution:		Observer:

Problem Log – Make many copies of this page

Time	Notes	Codes			
		Actor	Tech	Rep	Feat.
---		Actor	L P	C G	I 2
		Tech	C	GC	CAS A
		Rep	G	T	S W
		Feat.	P/J D	S/M C	MM OE
---		Actor	L P	C G	I 2
		Tech	C	GC	CAS A
		Rep	G	T	S W
		Feat.	P/J D	S/M C	MM OE
---		Actor	L P	C G	I 2
		Tech	C	GC	CAS A
		Rep	G	T	S W
		Feat.	P/J D	S/M C	MM OE
---		Actor	L P	C G	I 2
		Tech	C	GC	CAS A
		Rep	G	T	S W
		Feat.	P/J D	S/M C	MM OE

CODES											
Actor				Tech		Rep		Features			
L	Within Lecture	P	Students Presenting	C	Calculator	G	Graph	P/J	Proof/Justif.	D	Diagrams used
C	Class	G	Group (3+)	GC	Graphing Calculator	T	Table	S/M	Skill/Method	C	Contextualized
I	Students Individual	2	Pairs	CAS	Computer Alg. System	S	Symbol	MM	Multiple Solu. Methods	OE	Open-ended
				A	Animation	W	Word				

This log records important characteristics of problems observed in a calculus class. It records who performed each problem, and, when ascertainable, how technology was used in the problem, what representations were used in the course of solving the problem, and other “complexity” features of the problem. There is space to record the content of the problem.

This record can shed light on several dimensions of the calculus class, for example:

1. The mathematical quality of instruction.
2. Evolution of concepts within the lesson.
3. Interactivity of the classroom.
4. Use of technology in the classroom.
5. Variety of representations used.
6. The nature of problems presented/worked.

Using this log

The log should be used in real time to record every instance of a problem observed class, *whether or not the students are involved in the problem-solving process.*

It is not always straightforward to decide what constitutes a “problem.” Teachers may announce: “let’s do an example” or “let’s to do a problem.” These are easy ways to signal that an example/problem is coming. However, a question posed casually to the class may evolve into a problem. One way to address this is to start recording content and later decide whether it is or is not a problem. Use your judgment in identifying what constitutes an example or problem. A definition or illustration should not count as an “example.”

To supplement this log it will be helpful to collect and label a lesson plan (if available) and any materials handed out in class. *Label collected materials with instructor name, observer name, observation date, institution name, and class name.*

What you record

Time:

As much as possible, record the **start** and **end** time of each example/problem. This is not always straight-forward; use your best judgment. Having a beginning and end time might be useful in learning how long on average teachers spent in their examples/problems.

Actor:

Who is working the problem? This may change over the course of a problem. This code gives evidence of student involvement and investment in the class (and what instructor practices encourage that). *Record a new instance of the problem each time the actor changes.*

A problem solution is presented by the “Lecturer” (this word being a proxy for Instructor). That is, the instructor presents the solutions without significant contribution from students.

Class. This is where a student or group of students presents or works a solution through the instructor. That is, students speak and the instructor writes or summarizes. It's qualitatively different than a student presenting, because the work is filtered through the instructor. This will often correspond to a code of D in the Activity Log.

Students working **Individually**

Students presenting a solution or proof (individuals or groups) in a publically visible way. That is, a student may present at the board, on a document projector, or from a laptop screen. If a student orally describes a solution from his seat, then P is *not* the right code. In this case, use C instead.

Students working in groups of 3 or more on a problem.

Students working in pairs

Notes:

Use this area to record the content of the problem and other mathematical or pedagogical features you observe. At a minimum record/summarize the statement of the problem; information collected here might allow a comparison with exam and homework problems. If possible, record/summarize various solutions presented. This will give information on standard or non-standard solution methods, if multiple solution methods are presented or encouraged, and how various representations are used in the solution. You can use more than one line, but make sure to only mark the codes in the row

corresponding to the first “Notes” box you use for a problem. Lastly, consider including notes on mistakes in the presentation, connections made to other problems or concepts, sketches of diagrams used, students involvement in a whole-class solution, their apparent previous exposure to a given problem or problem type, or anything else you find important or striking.

Technology:

This captures what technology was used in solving a problem. Technology can be an excellent illustrative tool because many examples can be explored at once. It can also allow the students to solve problems that are computationally intractable by hand (such as empirical evidence of limits). However, it can detract from the development of number sense and procedural fluency. This particular category serves to corroborate the responses in the End of Term Student and Instructor Surveys. Multiple codes may be used to describe technology used in a given problem.

Calculator. This refers to the functionality of a graphing calculator, rather than the instrument itself. The actual instrument used may be a graphing calculator, a smart phone, a CAS, or the internet. If an action is performed with technology that is within scientific calculator capabilities (e.g. arithmetic or trigonometric calculations), it should get this code.

C **Graphing Calculator.** This refers to the functionality of a graphing calculator, rather than the instrument itself. The actual instrument used may be a smart phone, a CAS, or the internet. If an action is performed with technology that is within TI-83 capabilities (so no symbolic differentiation or integration) but outside the capabilities of a scientific calculator, it should get this code. This will primarily come up when a problem requires graphing and/or creating tabular data from a function.

AS **Computer Algebra System.** If an action is performed with technology that is within outside of TI-83 capabilities (e.g. differentiation or integration, graphing implicit functions, creating animations, etc.), it should get this code.

A problem is solved or motivated using an animation.

Representations:

Many reformed calculus textbooks and programs (e.g., Harvard Calculus and Hughes-Hallet) emphasize the “Rule of Four” (previously called the “Rule of Three”), a term which refers to translating between four main kinds of representations of mathematical ideas—graphical, numeric (tabular), symbolic, and verbal. The assumption is that students will gain deeper conceptual understanding of calculus using all four representations instead of the more traditional emphasis on purely symbolic manipulation.

In this section, code *all* the representations used in the entire problem-solving process (not just the statement of the problem). This will be difficult (or sometimes impossible) during student group work or pair-sharing. Record anything you observe, but don’t worry about what you miss during these kinds of activities. If solutions are later shared with the whole class, you may have an opportunity to add more information.

Graph. A function, equation, or other relationship between two variables is depicted graphically.

Table (aka numeric or discrete data). A function, equation, or other relationship between two variables is depicted discretely. This will usually be in table form and the data will usually be numeric.

Symbolic. A function, equation, or other relationship between two variables is depicted symbolically, that is, using algebraic symbols.

Words. A function, equation, or other relationship between two variables is given in words. This may not be explicit—the words may describe a situation and the problem may require that variables be defined and the relationship between them extracted from the information given. This will be typical of harder word problems. Further, you should use your judgment as to the importance of the words in a given problem. If a problem gives a symbolic representation of a function and asks you to “find the y-intercept,” the words are of minimal importance and the code should not be applied.

Features:

This category seeks to capture an assortment of other defining features of the problems. There are codes for various features of the solution process and answer, as well as codes signifying use of diagrams and existence of problem context. Some of these codes were chosen because of their correspondence to questions in the Interview Protocols. These showed substantive agreement in the last calibration test.

/J Proof/Justification. This refers to a problem where the solution includes a proof or justification of the method, steps, or conclusions. This is different than a solution *describing* steps taken; a P/J problem will focus on “why?” rather than “how?”

/M Skills/Methods. The *main* cognitive activity in such a problem is either learning or applying a skill, method, or procedure. This does not refer to using routine methods within more complicated problems. A very straight-forward optimization problem should be considered S/M.

E Open-Ended. Answer to problem is open-ended. This may include a problem about coming up with new methods, making hypotheses, or formulating questions. In particular, there is more than one correct answer to such a problem.

Diagram. A diagram is used somewhere in the statement, solution process, or answer to a problem. This overlaps with graphical representations (G), but also includes diagrams for the geometric set-up of a problem that don’t come from functions.

Contextualized. A problem is contextualized if there is a real-world or pseudo-real world setting. A contextualized problem is not necessarily more difficult, nor does it necessarily require modeling. For example, “Find the maximum value of $f(t) = -t^2 - 4t + 6$ ” is not contextualized but “A baseball’s arc is given by $f(t) = -t^2 - 4t + 6$, where t is time in seconds after contact with

a bat. What is the height of the baseball's peak?" is contextualized, but not any requiring any more thought.

M **Multiple Methods.** Use this code if multiple methods for arriving at a solution are presented (either by students or instructor).

A note on the choice of the **Contextualized** code. This is a catch-all proxy for modeling and applications—the kinds of questions we ask about in the Interview Protocols. We realize that not all contextualized problems are actually prompting modeling and/or applications. However, it might be difficult to decide on real time whether a problem is modeling, applications, both, or neither, because modeling and applications might have similar or overlapping definitions. Students and instructors may assume that these terms mean the same thing; so this code allows us to capture any problem that might be considered as modeling and/or applications. Include as much detail as possible about the problem so you can make a note about it in the post-observation survey.

Post-Observation (Online) Portion Description

This portion of the protocol is online in a google form:

<https://docs.google.com/spreadsheets/viewform?formkey=dGs1dnQzQlJSRGVobEdNeGhiY183Q1E6MQ>

It has four parts:

1. Cover Sheet (CS)
2. Activity Log Summary (ALS)
3. Problem Log Summary (PLS)
4. Post-Observation Survey (POS)

Cover Sheet

This is an electronic version of the paper cover sheet.

Activity Log Summary

The codes collected in the Activity Log are not be considered the primary data; rather, they serve as a record to create a more descriptive summary of the activities observed in the lesson. That is, we want to consider the observers' impressions corresponding to the codes over the specific quantities of codes. In the online form the observer will create Activity Log Summary to capture these impressions. This will be coded using the same coding scheme as the interview data.

The following instructions are given for creating the Activity Log Summary:

For each activity code that show up in your Activity Log, describe its enactment.

For example, if your Log had L, I, 2, and D codes, the summary could read:

L: As can be seen in the Log, the predominant activity during the class was lecture. This lasted for about 45 minutes out of the 60 minute class. The lecture focused on solving example problems. The lecture was animated and the students seemed entertained.

I, 2: Halfway through the class, the professor asked the students to work for 5 minutes on a problem individually and then share their answer with a partner.

D: About 10 minutes was spent discussing various solutions pairs had come up with. No students came to the board, but they did express their solutions fully and some students critiqued others' solutions. The instructor did a lot of revoicing in the class discussion.

Problem Log Summary

The online form prompts the user to reference the Problem Log data as a record for creating a summary called the Problem Log Summary. This summary can be coded using the same coding scheme as the interview data.

The Problem Log Summary comprises nine questions about the Problem Log data, giving the observer a space to describe the nature of problems in more detail. The questions are the following:

1. In a few sentences, describe the mathematical content of the class and the trajectory of problems done.
2. If applicable, describe problems done in class that were open-ended.
3. If applicable, describe problems done in class that were contextualized. Were any of the problems examples of applications or modeling? Explain.
4. If applicable, describe problems done in class that required or elicited justification or mathematical argumentation.

5. If applicable, describe problems supporting or requiring conceptual understanding.
6. If applicable, describe problems supporting or requiring the use of mathematical definitions.
7. If applicable, describe problems supporting or requiring the use of representations other than symbolic representations.
8. If applicable, describe problems supporting or requiring the use of procedures. Were procedures learned for the first time? Justified? Practiced?
9. In general, what was your perception of the cognitive demand of problems done in class?

Survey

The questions in the Survey are designed to complement information captured by the two Logs. The questions were chosen for one of two reasons: (1) to correspond to questions asked in the Phase I surveys and (2) to correspond to the Codebook that emerged from the interview data, yielding explicitly designed opportunities for triangulation with the interview data.

The questions are organized into four areas: Atmosphere, Interaction, Connections, and Mathematical Quality.

Atmosphere:

Did the students seem to find the class interesting and engaging? What student behaviors lead you to this conclusion? (e.g. “Students asked a lot of questions and seemed excited to present at the board.”)

Did the pace of the class seem reasonable? What student behaviors lead you to this conclusion? (e.g. “Students seemed to be furiously writing down notes without understanding.”)

Was the instructor’s language understandable/audible? Describe:

Did the instructor refer to other resources available to students? (e.g., office hours, the book, a tutoring center, study groups). Describe.

Was this section lead by a graduate student? Adjunct? Describe the affect this had on the class.

If this was a non-standard section (such as a lab or recitation), describe its form and function.

Describe your perception of the diversity of the classroom. (For example, you may want to discuss ethnic, gender, academic or physical abilities diversity.)

What did you personally find interesting or engaging about the class?

How did the class size affect the class? For example, how did it affect student participation or rapport with the instructor?

Interaction:

Describe students’ interaction with the instructor. What were the main forms of interaction? (E.g. question-asking? Question-answering? IRE-responses?)

Describe uniformity or non-uniformity of student-instructor interaction. (E.g. two students asked and answered many questions. The rest of the classroom did not interact much with the instructor.)

Describe observed student to student interaction, if any. (E.g., did you observe pair sharing, students challenging each others' work, students helping each other, etc.)

Describe what you can remember about instructor questioning behaviors. (E.g. "Instructor asked mostly engaged in mostly IRE-style questioning. If answers were not forthcoming after a few seconds, he moved on without student response.")

1. Describe what you can remember about student questioning behaviors. If applicable, describe your perception of instructor's behaviors that encouraged or discouraged questioning. (E.g. "Students asked few questions, but when they did, they were "why?" questions.")
2. Describe student contribution to content delivery in class. (E.g. "Students discussed solutions with the class from their seats.")

Connections:

1. Were connections made to other disciplines? Describe.
2. Were connections made to material from other points in the semester or previous courses? Describe
3. Was the textbook or textbook resources (e.g. worksheets or slides) used in class? If so, how?
4. Was homework dealt with or referred to in some way during class? Describe.

Mathematical Quality:

1. Did the instructor display an understanding of the mathematical content? If not, describe
2. Were mathematical concepts presented clearly and accurately throughout the lesson? If not, describe.
3. Were errors present in the lecture? Describe the errors. Were they significant? Typographical? Mathematical? Omissions? How did the instructor handle his own errors?
4. Did the instructor use precise language and notation?
5. Did the instructor preemptively address student errors or misconceptions? Describe.
6. Did the instructor explicitly address student errors or misconceptions as they arose? Describe.
7. Did instructor make learning goals explicit? Describe.
8. Describe students' demonstration of mathematical language and mathematical questioning.

Appendix D: Survey Response Rate

Institution (MAA ID)	Tenure/Tenure track		TT Students		Other full/part time		part time Students		GTAs		GTAs Students		All instructors		All Students	
	STS	ETS	STS	ETS	STS	ETS	STS	ETS	STS	ETS	STS	ETS	STS	ETS	STS	ETS
11170	1	1	5	10	6	6	52	77	4	4	15	33	11	11	72	120
11171	0	0	0	0	1	0	4	0	5	3	16	21	6	3	20	21
11173	3	2	28	62	2	2	3	3	1	1	6	2	6	5	37	67
11174	1	1	0	4	0	0	0	0	0	0	0	0	1	1	0	4
11181	0	0	0	0	1	1	6	8	2	1	2	9	3	2	8	17
11183	1	1	18	44	0	0	0	0	0	0	0	0	1	1	18	44
11185	0	0	0	0	2	1	6	9	2	1	16	20	4	2	22	29
11186	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
11190	1	1	29	40	2	2	13	30	0	0	0	0	3	3	42	70
11192	1	1	0	0	2	2	13	18	0	0	0	0	3	3	13	18
11195	3	3	5	16	13	10	63	126	1	1	3	14	17	14	71	156
11198	0	0	0	0	2	1	4	5	1	1	21	38	3	2	25	43
11199	1	1	26	45	0	0	0	0	0	0	0	0	1	1	26	45
11204	2	2	19	15	1	0	2	3	1	1	1	4	4	3	22	22
11205	0	0	0	0	1	0	15	20	0	0	0	0	1	0	15	20
11209	0	0	0	0	7	6	172	160	1	0	13	17	8	6	185	177
11211	0	0	1	1	1	1	0	0	0	0	0	0	1	1	1	1
Large PhD Total	15	13	131	237	41	32	353	459	18	13	93	158	74	58	577	854
11019	0	0	0	0	0	0	2	3	0	0	0	0	0	0	2	3
11029	1	1	1	0	6	5	53	70	0	0	0	0	7	6	54	70
11035	0	0	0	0	1	1	57	72	0	0	0	0	1	1	57	72
11039	2	2	64	75	1	1	25	44	0	0	0	0	3	3	89	119
11040	1	1	2	8	0	0	0	0	0	0	0	0	1	1	2	8
11055	0	0	0	0	3	2	4	11	0	0	0	0	3	2	4	11
11056	1	1	0	0	0	0	0	0	2	1	1	3	3	2	1	3
11061	2	2	11	15	0	0	0	0	1	1	0	7	3	3	11	22
11062	0	0	0	0	3	3	17	35	0	0	0	0	3	3	17	35
11064	0	0	0	0	1	1	10	12	0	0	0	0	1	1	10	12
11072	1	0	0	0	1	1	0	4	0	0	0	0	2	1	0	4
11073	2	2	18	33	0	0	0	0	0	0	0	0	2	2	18	33
11076	1	1	15	24	0	0	0	0	0	0	0	0	1	1	15	24
11079	0	0	0	0	4	4	54	110	1	1	18	19	5	5	72	129
11080	0	0	0	0	1	1	13	47	0	0	0	0	1	1	13	47
11084	1	1	6	10	1	1	22	29	1	1	3	2	3	3	31	41
11098	3	4	6	18	2	1	2	4	0	0	0	0	5	5	8	22
11099	1	1	16	29	0	1	1	13	0	0	0	0	1	2	17	42
11101	1	1	2	4	1	1	2	19	3	2	9	16	5	4	13	39
11103	6	6	32	35	1	0	0	0	0	0	0	0	7	6	32	35
11105	0	0	0	0	0	0	0	0	1	1	12	24	1	1	12	24
11106	4	2	14	11	3	3	20	31	0	0	0	0	7	5	34	42
11112	1	1	11	14	0	0	0	0	2	2	0	7	3	3	11	21
11117	1	1	2	0	0	0	0	0	6	4	33	33	7	5	35	33
11120	2	2	19	24	2	2	10	14	1	0	1	0	5	4	30	38
11130	1	1	21	20	0	0	0	0	0	0	0	0	1	1	21	20
11133	2	1	9	19	3	2	13	44	0	0	0	0	5	3	22	63
11134	1	1	33	31	1	1	1	0	0	0	2	0	2	2	36	31
11138	1	1	2	4	2	1	12	23	0	0	0	0	3	2	14	27
11143	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
11144	0	0	0	0	0	0	0	0	2	1	0	3	2	1	0	3

11151	0	0	0	0	2	2	4	4	1	1	0	0	3	3	4	4
11153	4	3	57	99	0	0	0	0	0	0	0	0	4	3	57	99
11154	1	1	3	6	0	0	0	0	0	0	0	0	1	1	3	6
11161	1	1	1	28	0	0	0	0	0	0	0	0	1	1	1	28
11162	2	1	13	12	1	1	7	6	0	0	0	0	3	2	20	18
11164	0	0	0	0	0	0	0	0	2	2	1	2	2	2	1	2
11165	0	0	0	0	1	1	12	15	5	5	6	28	6	6	18	43
11168	1	1	0	0	2	1	5	11	1	2	5	10	4	4	10	21
Small PhD Total	46	40	358	519	43	37	346	621	29	24	91	154	118	101	795	1294
Instit. 1	1	0	12	13	6	5	64	132	3	1	27	22	10	6	103	167
Instit. 2	1	1	16	20	10	8	85	114	23	18	105	145	34	27	206	279
Instit. 3	0	0	0	0	3	4	56	108	0	0	0	0	3	4	56	108
Instit. 4	3	3	97	124	0	0	0	0	0	0	0	0	3	3	97	124
Grand Total	66	57	614	913	103	86	904	1434	73	56	316	479	242	199	1834	2826