Promoting equity in introductory physics: An identity perspective on learning physics and learning to teach

by

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Abstract

If the goal of teaching introductory physics is to help every student have successful learning experiences, then we need to answer at least two key questions to achieve this goal. First, what instructional strategies will promote equitable success for students? And second, how can we prepare instructors to use these teaching strategies effectively? Prior research demonstrates a persistent gender gap in introductory physics; however, we find that physics identity mediates the impact of gender on both conceptual understanding and retention in physics programs. Therefore, we apply Wenger's framework of identity development in communities of practice to hypothesize that collaborative, community-building instructional strategies can promote equity by enabling women's identification with physics. Through meta-analysis of results from 26 courses, we find trends in three different models of equity that support this hypothesis. To address our second question, we apply a similar community-based model to TA professional development. We find that teaching communities of practice can yield statistically significant improvements in TAs' identification as physics educators, and make qualitative changes to TAs' teaching approaches.

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Co-Authorship

The research behind this thesis was strongly supported through collaborations. While the research and writing of this thesis was performed by the author, others provided significant contributions as described here.

While the gender gap project was led by the author (with the author applying the literature to determine interesting research directions, creating surveys, collecting most data, performing statistical analyses, and interpreting these data), it was well supported by collaborations. Each step in the research process—from the literature review to the interpretation of results—benefited from continual discussion with James Fraser, who provided many helpful suggestions on research methods, potential new research directions, and data interpretations. Several course instructors—Anne Topper, Marsha Singh, Alastair McLean, and Tony Noble—provided feedback on survey items and gave procedural suggestions for implementing these surveys within their course contexts. Alastair McLean, Benedict Drevniok, Jennifer Campbell, David Northeast, and Tony Noble also provided support in data collection.

With many helpful contributions from coauthors, the author also took a principal role in the TA professional development project. The author designed and facilitated the professional development intervention based on her review of the literature and regular discussion with James Fraser. The author prepared surveys with sections of

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these surveys borrowed from previous work, as cited in those sections. The author collected and analysed all quantitative data, discussing interpretations of these results with James. The author performed and recorded TA interviews, which were then transcribed by typist Rebecca Geerlinks. Qualitative coding was done by both the author and coauthor for this section, Terry Bridges. Terry contributed interpretations of qualitative data; the themes highlighted in Chapter 4 were chosen through discussion between Terry and the author. As coauthors on this paper, both Terry and James provided edits and suggestions on the author's writing. It should also be noted that the TAs themselves were highly instrumental in this work. As intended in the experiment design, the TAs had autonomy to contribute to and shape the intervention, so that it could better suit their professional development goals. Furthermore, post-experiment discussions with TAs shed considerable light on quantitative findings and provided more thorough interpretations of qualitative data.

Coauthors on a paper currently in preparation for Reports on Progress in Physics——Laura Tucker, Kelly Miller, Jason Dowd, and James Fraser—provided ideas and helpful perspectives on barriers hindering the uptake of research-based pedagogy. Ideas and some excerpts from Section 1.1 come from the author's work in this coauthored paper. Written permission for the use of all coauthored work in this thesis was obtained.

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List of Abbreviations

CSEM	Conceptual Survey of Electricity and Magnetism
FCI	Force Concept Inventory
FMCE	Force and Motion Conceptual Evaluation
IE0	Interactive Engagement level 0
IE1	Interactive Engagement level 1
IE2	Interactive Engagement level 2
PER	Physics Education Research
SPSS	Statistical Package for the Social Sciences
STEM	Science, Technology, Engineering, and Mathematics
TA	Teaching Assistant

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Chapter 1

Introduction

1.1 Physics education research: An interdisciplinary frontier

The work behind this thesis represents a natural, yet easily overlooked, interdisciplinary pairing: doing physics and learning physics. Great technological innovations happen when physicists rigorously apply the scientific method in their research. Logically then, a scientific approach for evaluating physics teaching is essential to address the challenges and opportunities in our changing scientific landscape. Going beyond merely 'keeping up' with changing technologies, physics education research (PER) has the goal of driving new innovations in physics through significant advances in physics education.

Why not keep the processes of 'physics doing' and 'physics learning' separate

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in their designated departments? Following the leadership of physics education researchers situated in physics departments at Harvard, University of Colorado, University of Washington, and others, we argue that researching education directly in a physics context allows for the specificity and application essential to successful research. While general education researchers often provide highly beneficial frameworks and general teaching tools, physics education researchers can best understand the concepts and skills that students need to learn in physics along with the specific obstacles that prevent that learning. Through understanding the unique challenges and opportunities in learning physics, PER can design studies to meet the specific needs of physics students and physics instructors. Furthermore, since these studies occur in physics departments, practical applications of this research are much more straightforward to implement. The resulting relevant and tangible advances benefit both physics education and physics.

Unfamiliarity with PER methods, however, sometimes leads physicists to distrust this type of research. Unlike studies conducted within a physics laboratory, where parameters are carefully controlled, PER relies on data from diverse classrooms, yielding variable results. Therefore, a key element to the success of PER is meta-analysis [1]. While a single physics education study may point researchers and instructors in a helpful direction, replication and meta-analyses allow the education discovery to be generalized across classrooms. Effective meta-analysis naturally requires thorough citations, with results often published in journals such as Physical Review Special Topics - Physics Education Research, American Journal of Physics, and Science. When future research builds on past discoveries, consistently successful physics teaching trends can be identified. These trends do not guarantee outcomes,

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but they do provide instructors with likelihoods for the success of different instructional strategies. Just as a hockey fan would bet his/her money on the team with the best odds of winning, physics education research provides instructors with the information they need to choose teaching strategies most likely to yield the outcomes they want. Through novel individual studies, replication of previous work, and meta-analysis, physics education researchers identify trends to improve physics learning, and thereby advance physics.

The frontiers of physics are often interdisciplinary. For example, new discoveries in abstract theoretical physics often require blurred borders between physics, mathematics, and computing. The application of advanced physics tools to biological systems generates new understandings in biophysics. Similarly, physics education research draws from psychology, sociology, education, and physics to make advances for student learning in physics. The union of ‘doing physics’ and ‘learning physics’ is an exciting frontier for physics, and it has been a privilege to be a part of this interdisciplinary and growing field.

1.2 Thesis overview

I have chosen the manuscript style for this thesis [2] because this research addresses two related but distinct opportunities in physics: to improve gender equity in first year physics and to help teaching assistants (TAs) develop as effective instructors. I anticipate that packaging these lines of research in separate chapters should improve readability and hopefully the practical application of this thesis.

My research on the first opportunity—to improve gender equity in first year physics—includes both quantitative analyses of 790 introductory physics students

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at Queen's University and a meta-analysis of 26 courses across three continents. Acknowledging the different equity goals of different instructors, I took three different equity perspectives [3] to determine instructional strategies that may contribute to reducing the gender gap.

Engaging in the second opportunity—supporting TAs in their adoption of research-based instructional strategies—I developed a low-cost semester-long TA professional development program based on theoretical frameworks from psychology and sociology. I examined the effectiveness of this program both through quantitative statistical analyses and qualitative analyses of field notes and interview data.

What became the primary connection between these distinct lines of research——interventions built on an identity framework—was actually an unexpected turn for me in this research. This theme arose from a curious result: we were performing a pilot study to determine if our implementations of Just-in-Time-Teaching[1], Peer Instruction, and collaborative problem-solving[2] at Queen's could yield similar high learning gains to those observed in the literature [4]. As anticipated by decades of physics education literature, student learning gains were more than double those typically observed in traditional lecture courses. However, when I separated the data by gender and looked at predictors for a plan to continue in physics, I came across a rather surprising result. For men, conceptual understanding and academic success were strong predictors for a decision to continue in a physics program; however, neither of these variables predicted persistence for women. Instead, physics self-efficacy (measures of a student's belief in her competence and performance) and

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[1] Just-in-Time Teaching is a strategy supporting the 'flipped classroom' model in which the content delivery happens outside of class and synthesis and sense-making happens during class. Students read content and answer questions online prior to each class. These student responses then guide the lecture period.

[2] Peer Instruction and collaborative problem-solving are described in Appendix B.

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instructor rapport (a measure of recognition from the professor and TAs) were strong statistically significant predictors of female students' plans to continue in a physics program.

During the 2012 Canadian Association of Physicists conference, I had the opportunity to meet Dr. Shanahan, whose recent research proposed that the variables I happened upon—competence, performance, recognition, as well as a fourth variable, interest—were all components of a student's physics identity [5]. Further review of the literature showed potential for interventions, built on an identity framework, to reduce the gender gap in physics. I was sold, and dove into planning a master's project focused on promoting equity in introductory physics based on a physics identity framework.

It soon became apparent, however, that researching the gender gap on its own was not sufficiently satisfying. Discussions with colleagues, who were writing a paper on bridging the gap between education research and practice for Reports on Progress in Physics (to which I later joined authorship), inspired another direction for my research. As this group discussed, even the best research on equitable instructional strategies does little to support women in physics unless it is coupled with equally effective research on how to successfully disseminate these teaching strategies. A mental image of this thesis serving no practical purpose (except perhaps as a prop of the appropriate thickness to level projector units) motivated the second component of my research: teaching assistant (TA) professional development. How can we pass on research-based teaching strategies to the next generation of physics instructors?

As I explored the common challenges for TA professional development in the literature, TA buy-in to research-based pedagogies tended to top the charts. Prior

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research shows limited success for TAs who use prescribed active engagement strategies without truly buying into these pedagogies [6, 7]. How then can we go beyond prescribing active engagement strategies to helping our TAs *become* teaching professions? Very conveniently, I was concurrently learning about the impact of helping female students *become* members of a physics community through physics identity development in my gender gap research. It became clear that this identity framework had potential to be a solution (or part of a solution) in both of my research goals. We built a TA professional development intervention on a physics educator identity development framework, and we researched its effectiveness for addressing TA buy-in and helping TAs become physics teaching professionals.

In this thesis, my work on increasing equity in introductory physics is described in Chapter 3, and my research on TA professional development in Chapter 4. While these chapters are connected through a common identity framework, it is my intention in choosing a manuscript style thesis that both of these main chapters should also be able to stand alone. Therefore, I include the literature reviews pertaining to the gender gap in introductory physics (Chapter 3) and TA professional development (Chapter 4) directly in their respective chapters. To prevent excessive repetition, the Background chapter therefore provides a broad overview and motivation for this research, leaving the detailed critical review of relevant literature to the respective chapters.

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Chapter 2

Background

2.1 Motivation for gender gap research

Our histories are full of stories about exceptional women who defy cultural stereotypes and overcome barriers to make contributions in science. Just two years after her orphanage was mistakenly bombed during the Second World War—missing a full year of high school while taking up residence in a barn until it too was burned down by troops—Anna Timan (my grandmother) achieved a scholarship from Shell to study chemistry at the Vrije Universiteit in Amsterdam. We celebrate tenacious women, like Anna Timan, for their perseverance to learn and contribute to science, despite significant practical and sociocultural pressures to abandon such studies.

But why are these successful women the exception? The persistent and highly reproducible gender gap in physics—both in conceptual understanding and retention in physics programs [8, 9, 10, 11]—has concerned physics instructors and administrations for decades [12]. Just one in five graduates from a North American physics bachelor's degree is female [10, 13]. Gaps exist not only in representation, but also

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in conceptual understanding. Even the women who do enrol in introductory physics courses score approximately a letter grade lower than their male classmates on surveys of conceptual understanding in Newtonian mechanics [9, 14, 15].

The underrepresentation of women is a concern for physics as the scientific perspectives and potential contributions of women are severely underutilized. The President's Council of Advisors on Science and Technology projects that over the next decade, the United States will require 1 million more STEM (science, technology, engineering, and mathematics) professionals than expected from current trends—a shortage that could be largely remedied by increasing the retention of STEM majors [16]. However, the "why?" behind the gender gap leaves open even broader concerns of societal inequities and potential prejudices that could be causing these observed gaps.

2.1.1 Is the gender gap just a fact of life?

Some argue that women simply are not 'wired' for physics. This argument proposes that the gender gap in physics is mainly a reflection of biological differences between the brains of men and women. From this perspective, the gender gap in physics might simply be a fact of life, not a social justice issue [17]. In practice, it is very difficult to disentangle 'nature' and 'nurture'. Psychology literature finds that cognitive performance is determined both by innate neural efficiency and previous experience [18]. Men and women improve their abilities through the activities they do, and these activity choices are inherently influenced by both sociocultural contexts and students' prior abilities [19].

Yet, despite these blurred lines between sociocultural and biological explanations

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for the gender gap in physics, the literature provides strong support for a gender similarities hypothesis: that the effects of biological differences are too small to explain the large observed differences in men and women's participation in physics. In a synthesis of 46 meta-analyses comparing men and women on a wide variety of psychological variables, Hyde concluded that the average female brain is very similar to the average male brain [20]. Contrary to Gray's popular book [21], Hyde's findings remind us that men are not from Mars, and women are not from Venus: both genders are from Earth, a planet with many sociocultural influences.

The observed gender gaps in conceptual understanding and persistence in physics are too large to be explained by small biological differences alone [22, 23]. Therefore, researchers turn to sociocultural factors to understand the causes—and therefore potential solutions—for the gender gap. Longstanding concern with social barriers to women's participation in science is a common theme in the literature. Edward Clancy writes in his 1962 paper, "The emancipation of women—so far as her supposed freedom to pursue any intellectual activity she chooses is concerned—is... illusory" [12]. He paints a picture of strong social pressures that discourage women from studying the "unfeminine" subject of physics, cultural exaggerations of the differences between men and women, and stereotypes about women's abilities and roles in society [12].

More than fifty years later, that picture has changed much less than we might hope. Stereotypes about women's science interests and skills continue to hinder women's identification with physics [24, 25, 26, 27]. From the 1992 Barbie, who told young girls "Math class is tough" [28], to the sexist "jokes" that many women continue to experience in their physics and engineering classes [29], our culture remains littered

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with negative prejudices about women's abilities in physics. Furthermore, stereotypes about physics—narrow cultural definitions that associate the study of physics with masculine identities [30, 31]—lead to tensions between a woman's identification with physics and her gender identity [32, 33]. Prior work has found physics identity to be a strong predictor of academic success in physics [34] and students' career choice [5]. Might the gender gap be mediated by women's diminished identification with physics? We test this hypothesis through a statistical mediation analysis of students in four introductory physics courses at Queen's University.

2.1.2 What instructional strategies might promote equity?

If physics identity is mediating the gender gap, then a potential solution to the gender gap may include instructional strategies that reduce the disidentifying influences of stereotypes [35] and enable women to identify with physics. What sort of learning environment might achieve this goal? Etienne Wenger's communities of practice framework [36] suggests that previously disengaged students can identify with physics through participation in physics communities.

Wenger's framework points to community-building instructional strategies as a potential mechanism for reducing the gender gap by fostering an inclusive collaborative environment that enables women's (and potentially other stereotyped persons') identification with physics. Our aforementioned pilot study provides some support for this hypothesis: the gender gap on a conceptual survey of Newtonian mechanics was significantly reduced in this highly collaborative course. Yet with an uncountable number of variables influencing these results, we can hardly make strong generalizable

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claims about benefits of community-building instructional strategies. Was equity improved via teaching strategies that promoted engagement with physics communities? Or was it merely the result of a small class size and a uniquely talented professor?

These questions illustrate the need for meta-analysis. Fortunately, the gender gap in conceptual understanding has concerned many researchers across the globe, several of whom have measured the gender gap with similar standardized instruments (namely, Force Concept Inventory (FCI) [37] and the Force and Motion Concept Evaluation (FMCE) [38]). In our meta-analysis, we compare steps made towards equity in courses that make use of community-building instructional strategies to differing extents.

Defining equity, however, is a non-trivial task. For example, one instructor might consider equity to be achieved when women are equally represented and score as well as men on posttest measures of conceptual understanding. However, another instructor might consider this equity of parity framework to be unfair, since it inherently requires larger improvements for women than for men. Such an instructor might favour an equity of fairness framework in which men and women are equally served in one particular course, regardless of prior conceptual understanding gaps. Still others find that a focus on the gaps between men and women risks achieving ‘equity’ through inhibiting men’s learning. These proponents of an equity of individuality framework draw comparisons within genders, not between them, to find the most equitable instructional strategies. We apply each of these three equity models, postulated by Rodriguez et al. [3], to perform our meta-analysis in search for more equitable instructional strategies.

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2.2 Motivation for TA training research

In their 2011 paper, Henderson and Dancy write: “The biggest barrier to improving STEM education is not that we lack knowledge about effective teaching ... [It] is that we lack knowledge about how to effectively spread the use of ... research-based instructional ideas and strategies” [39]. Despite decades of physics education research developing high quality teaching materials, widespread adoption of these pedagogies remains surprisingly low. In a 2010 study by Dancy and Henderson, 70% of surveyed faculty responded that they were interested in applying researched-based pedagogies; however, in practice, the traditional lecture prevailed as the main instructional strategy used by these faculty [40]. As Dancy and Henderson illustrate, the molasses movement towards physics education reform demands research into better strategies for supporting instructors as they learn new strategies for teaching physics.

Learning to teach is a lifelong process for physics instructors as new pedagogies are developed, physics discoveries are made, and student dynamics and cultures change in our physics classrooms. Therefore, research into improved dissemination of PER is necessary at all levels—for graduate teaching assistants, new instructors, and tenured professors. However, graduate teaching assistants (TAs) are a natural focus for research in this project for several reasons. First, graduate TAs have an important role in creating equitable and helpful learning experiences for today’s students in introductory physics tutorials and recitations [41, 42]. Second, increased support for graduate TAs also benefits future students, as TAships often guide TAs’ approaches to teaching and future careers in education-related disciplines [43, 44]. Finally, graduate TAs are the focus of this research simply because I (the author) am a graduate TA. My role as a peer allowed me to facilitate non-hierarchical teaching assistant communities and

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provided me with a first-hand perspective of TAs specific needs.

In their 2010 paper, Henderson, Finkelstein, and Beach describe four prominent ‘change strategies’ for improving undergraduate physics education: disseminating curricula, developing reflective teachers, developing policy, and developing shared vision [45]. They propose that successful education reforms would tap into multiple change strategies [45]. Taking the goal of helping TAs *become* teaching professionals, we endeavour to develop reflective teachers and a shared vision among TAs by applying Wenger’s framework for identity development in communities of practice [46]. From Wenger’s communities of practice framework, we build a low-cost, time-efficient TA professional development intervention that targets physics educator identity. We explore Wenger’s three modes of belonging to a community of practice—engagement, imagination, and alignment—to determine the effectiveness of our intervention for enabling TAs to identify as physics educators and helping TAs change their approach to teaching.

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Chapter 3

Equity in Introductory Physics

Reducing the gender gap: Instructional strategies that target physics identity

Abstract: A persistent gender gap in physics—both in conceptual understanding and retention in physics programs—has concerned educators and policy makers for decades. In a study of 790 students from our institution, we found physics identity to play a significant role, distinct from prior knowledge, in mediating the gender gap in conceptual understanding and intention to continue in a physics program. These results led us to ask: Could instructional strategies that enable women to identify with physics through participation in communities of practice promote gender equity in introductory physics? Using three different models of equity, we performed a meta-analysis of results from 26 classes to answer this question, examining pretest and posttest measures of Newtonian mechanics conceptual understanding. We found that while collaborative, community-building instructional strategies did not eliminate the conceptual understanding gender gap on average, courses that applied community-building teaching strategies reduced the direct gender gap ($p = .025$, $d = 1.27$), normalized gender gap ($p < .001$, $d = 1.24$), and gender gap effect size ($p = .009$, d

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= .63). Contrary to a zero-sum perspective on the gender gap, we found that increased equity through community-building instructional strategies benefited both genders.

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3.1 Introduction

Despite growing success in scientific fields such as biology, chemistry, and life sciences [47], women continue to trail behind their male colleagues in both physics conceptual understanding and persistence in physics programs [48, 49, 8]. In surveys of physics conceptual understanding in introductory physics, women consistently score lower than men [14, 9, 15]. Furthermore, women earn just 21% of physics bachelor's degrees in the United States [10] and 20% of physics bachelor's degrees in Canada [13], despite making up a majority of the undergraduate population in both countries [8, 13]. These two gender gaps—in conceptual understanding and persistence—spiral into each other. Women who struggle in their conceptual understanding are less likely to continue in physics programs [50], and women in groups where they are a stark minority are more likely to conform to negative gender stereotypes than women in groups where they are well represented [51]. The stubborn persistence of the gender gap continues to cost society, as talented women—with the potential to make important scientific contributions—leave the field [48, 11, 52].

The persistent gender gap in physics has motivated a great deal of research into education strategies that could address women's lower conceptual understanding and retention in physics programs. Though prior research has strongly demonstrated the success of active engagement strategies over passive lectures for all students [4, 53, 54, 55], the jury remains out on the impact of active engagement for reducing the

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gender gap. While some studies have shown active engagement strategies to create a gender inclusive environment [56] that can reduce the gender gap [15, 57, 58], others have found the gender gap remained regardless of instructional strategy [59, 60, 61].

For example, one study from Harvard [15] found that the gender gap in conceptual understanding was reduced to a statistically non-significant level after a semester of Peer Instruction [62], the *Tutorials in Introductory Physics* [63], and cooperative quantitative problem solving activities. However, when a study from the University of Colorado [59] attempted to replicate these results, the gender gap in conceptual understanding stubbornly remained with no statistically significant improvements after a semester of Peer Instruction, the *Tutorials in Introductory Physics*, online homework, and help-room sessions. In a Clemson University study [64], three instructors used Peer Instruction, *Tutorials in Introductory Physics*, and collaborative group problem solving, but only one of these three instructors saw the gender gap reduced to a statistically non-significant level. Looking at these inconclusive results without a theoretical framework or quantitative meta-analysis, we can say little about the role of instructional strategies for reducing the gender gap [65].

Therefore, we explore the gender gap through a framework for physics identity development in communities of practice, drawing on literature from psychology, sociology, and physics education. We test a regression-based statistical model for mediation, and find that physics identity plays a mediating role in the conceptual understanding and retention gender gaps at our institution. We then apply this physics identity framework to perform a quantitative meta-analysis of research on over 5000 students

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in 26 introductory Newtonian mechanics courses, including five courses from our institution. Courses are grouped according to the number of collaborative community-building opportunities (e.g., Peer Instruction, collaborative problem-solving recitations, etc.), following the classifications of the Harvard and University of Colorado studies [15, 59]. Through meta-analysis, we go beyond apparent study-to-study contradictions to find overarching trends in the application of community-building teaching strategies for improving equity.

3.2 Background: An identity framework for promoting equity

Why take an identity perspective to explore instructional strategies that might reduce the gender gap in physics? In his communities of practice framework, Wenger claims that learning is inherently a process of identity formation as the learner gains new abilities and roles [46]. The meanings that the learner attaches to these roles define his/her identity [66], which in turn influences his/her behaviour [67]. Measures of college students' physics identities strongly predict students' career choice [5] and academic success in physics [34]. Positive physics identity formation is important for all students to engage in science [68], but has been found to be particularly important for female or minority students' participation in and engagement with physics [69].

When we explore sociocultural explanations for both academic success and retention in physics programs, identity is a recurring theme—even when it is not formally mentioned. Hazari et al. summarize physics identity in four components: performance, competence, interest, and recognition [5]. Though research into the role of

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physics identity in academic success and persistence in physics is relatively new, when we consider these four components of physics identity, we find themes of identity threaded throughout the literature of the last several decades.

Performance and competence—belief in one's ability to perform required tasks and understand specific content [5]—have clear ties to personal self-efficacy, a situation-specific self-confidence in one's own abilities [70]. Self-efficacy has been found to both shape students' engagement and performance, and to be shaped by students' engagement and performance [71, 72, 73, 74, 75]. Prior work has found self-efficacy to be a strong predictor of academic success [76, 77] and persistence in science [48, 78, 79, 80, 14]. Differences in male and female students' physics self-efficacy, which tends to be lower for female students than for male students [81], have been found to be a significant contributing factor in the gender gap [48, 49, 80].

Interest also plays a significant role in a student's choice of a college major, with one study citing interest as an even larger factor than self-efficacy [82]. Another study found that students' science interest in Grade 8 was a stronger predictor of obtaining a degree in science than even science ability [83]. During their pre-university school career, boys' interest in physics tends to increase, while girls' interest in physics tends not to develop to the same extent [84], and can even decline [85]. Some literature suggests this divergence in physics interest might be due to contexts presented in physics problems, which often more closely reflect the interests and activities of boys, rather than the activities of girls [85, 86]. However, other literature cautions against attempts to increase girls' interest in physics through the use of stereotypically feminine contexts, as such endeavours could merely perpetuate gender stereotypes [26].

Recognition may play a particularly important role in the gender gap through

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its connection to the performance and competence components of identity. Respect and recognition from course instructors can improve self-efficacy [48], with some research showing that recognition may be especially important for the development of women's physics self-efficacy [87, 88]. Prior work in mathematics identity has found that while all components of math identity (performance, competence, recognition, and interest) were significant predictors of career choice, recognition was particularly important for female students [89]. Unfortunately, a recent study of more than 5000 high-school aged students found that girls were less likely to receive recognition and encouragement in their physics studies from teachers, family, and friends [90].

Performance, competence, interest, and recognition are all bound together in the concept of physics identity. Identity plays a powerful role in student learning [5, 34]. However, men and women do not experience physics identity development equally [32, 91, 33]—not a surprising result given that men and women have very different self-efficacy [81], interest [85], and recognition experiences in physics [90]. In the following section, we explore the mechanics of how physics identity might impact the gender gap in conceptual understanding and persistence in physics programs.

3.2.1 The role of identity in the gender gap

Essential to the understanding of the gender gap in physics is the impact of sociocultural factors that discourage women's contributions to physics [19, 92]. These sociocultural factors have been found to far outweigh the influence of student ability [22, 23]. One such factor is stereotype threat, a well known cause of depressed performance among negatively stereotyped groups [35].

To illustrate the potential impact of stereotype threat on the gender gap in physics,

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we describe one recent study measuring men and women's performance on a short physics test that was administered with three different sets of instructions containing explicit, implicit, or nullified gender stereotyping [93]. In the explicit stereotype condition, participants were told that "this test has shown gender differences with males outperforming females" whereas in the nullified condition, participants were told that "no gender differences in performance have been found on this test". In the implicit stereotype condition, there was no mention of gender; participants were simply told that "these problems are based on physics material that you have already covered". The researchers found that women in the nullified stereotype condition scored significantly higher than women in the explicit and implicit stereotyping conditions. Furthermore, while statistically significant gender differences in performance were observed in the explicit and implicit stereotyping conditions, no statistically significant gender differences were observed in the nullified stereotyping condition [93].

Steele asserts that stereotype threat decreases student performance through a process of disindentification [35]. In the case of physics, stereotypes of women's science abilities and interests have been found to inhibit women's identification with physics [24, 26, 27, 25]. These stereotypes and prejudices lead to a decreased sense of belonging for women in physics [94]. A study of more than 2000 students from the University of Colorado found that female students who endorsed gender stereotypes had lower experiences of belonging in physics, which in turn predicted lower academic success [95].

Women's disidentification with physics is not only caused by stereotypes about women, however. It is also caused by stereotypes about physics. Our culture and

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teaching shape a narrow definition of a physicist [32, 96]. These stereotyped definitions often do not accurately reflect who physicists are in practice, nor do they resemble identities that many women to aspire to hold for themselves [32]. For example, in a study by Miller et al., female high school students reported a belief that science is an uncaring discipline with a violent focus on "blowing things up", having little relevance for improving the human condition [97]. These cultural stereotypes and historical definitions of who a scientist is shape students' identification or disidentification with science [98].

Prior work has considered gender identity as a community of practice [33, 30, 99]. In this context, students' physics identity can develop when students feel that their gender and physics identities are compatible [36]. However, the study of physics is often associated with masculine identities [30, 31]. Perform an internet image search on 'physicist', and images of white men will dominate the search. Even women who successfully complete their bachelor's degrees in STEM tend to adopt science identities that affirm male dominance. A qualitative engineering education study [29] found that some female engineering students attempted to accommodate the tension between their feminine and engineering identities by identifying as 'almost one of the guys'—a perspective that still affirmed the dominance of masculinity in engineering [29].

Not surprisingly, given these cultural definitions of women and of physicists, female students' self-concepts tend to differ greatly from their perception of scientists, while male students' self-concepts are more likely to align with their perception of scientists [100]. Similar to ethnic minorities, who may experience tensions between their ethnic and academic identities [101], some female students feel that they are

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departing from their ‘normal’ female identity when they engage with physics [33]. Further complicating the question of identity, students have been found to separate their identity as a science student from their identity as a potential scientist. In one study, female students built an identity as ‘good students’ while maintaining the belief that they could not become ‘good scientists’ [91].

In summary, stereotype threat about women’s science abilities and interests hampers women’s identification with physics. Additionally, dominant masculine stereotypes about physics leave little room for overlap between women’s gender and physics identities. With this sociocultural perspective, it should be no surprise that women have significantly lower physics identities than men [102]. Our analysis of the literature then leads us to our first research question:

1. *To what extent does physics identity account for the gender gap in conceptual understanding and persistence in a physics program among students at our mid-sized Canadian institution?*

Fortunately, a student’s identity is adaptable; students hold different identities in different contexts, and these identities can continually change [103]. The development of a physics identity is important for all students who want to learn physics, but this process requires particular attention for students whose physics identities are culturally in question—a significant concern for female physics students [96, 97, 32]. We turn next to Etienne Wenger’s communities of practice framework to predict instructional strategies that could promote the development of women’s physics identities.

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3.2.2 Fostering physics identity in a community of practice

Longstanding cultural and historical stereotypes about who women are and who can be a physicist have significant influences on women's physics identity development [93, 24, 26, 27, 33, 32, 97, 98], which in turn impacts female students' academic performance and persistence in physics [5, 34]. Facing such deeply entrenched cultural identities, one might question the feasibility of any introductory physics course intervention that could work against these cultural norms to reduce the persistent gender gap in physics.

Nonetheless, literature suggests potential solutions to promote women's physics identity development. While competitive environments tend to exacerbate stereotype threat and negative comparisons between students [104, 35], teaching strategies that decrease zero-sum competition (in which for every winner there are one or more losers) can contribute to reducing the gender gap [105]. Furthermore, values affirmation[1] has been shown to have long-lasting impacts for minority students' academic success [106], and specifically for improving the academic performance of women in physics [107]. Prior work has also found that collaborative learning opportunities, which build encouraging teacher-student relationships and peer relationships, improve students' science identity [103] and physics self-efficacy [108]. One study found that the physics identity of college students was predicted by high school experiences in which students taught each other (performance), the teacher encouraged students (recognition), connections were made to real-life (interest), conceptual understanding was emphasized (competence), and students engaged themselves in their learning [5].

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[1] Values affirmation is a stereotype threat reduction technique borrowed from psychology in which students write about values that are personally important to them.

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From this literature, we hypothesize that instructional strategies that build community—a collaborative and non-competitive environment in which students affirm each other and support others' success to everyone's benefit—could reduce the gender gap in physics.

How might community-building instructional strategies promote equity? According to Vygotsky, authentic learning occurs both on a personal level and at a social level through interactions and cooperation with peers [109, 110]. Etienne Wenger proposed a communities of practice framework for understanding how identity can be developed [46, 36]. He described these communities as the context for identity formation, writing, "Viewed as an experience of identity, learning entails both a process and a place. It entails a process of transforming knowledge as well as a context in which to define an identity of participation" [46]. The connectedness that a student can experience in community increases the importance and salience of the identity associated with that community [66].

In the context of learning physics, a student's physics identity can be fostered through a physics classroom community of practice in which the student is an engaged and valued member [111]. This framework is supported by research into the importance of a sense of belonging for academic success [112]. Wenger describes three modes of belonging to a community of practice: engagement, imagination, and alignment [36]. As students engage, imagine, and align with a physics community of practice, they strengthen their identification with physics [46].

- **Engagement** occurs when students participate in meaningful activities together. These activities require continual mutual engagement so that students develop a commitment to their learning and to each other, challenging students

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to both use their pre-existing knowledge and explore new concepts [46].

- **Imagination** involves the student creating an image of himself/herself as a member of the community [46]. Through imagination, students picture themselves as apprentice physicists.

- **Alignment** occurs when students choose activities in line with the community, both changing themselves to become members of the community and in turn changing the community [46]. Alignment does not imply a passive absorption of material (as in a traditional lecture), but an opportunity for students to contribute to the community in a genuine way.

Our second research question served to test the effectiveness of these communities of practice in building students' physics identities. We asked:

2. *Is a student's degree of participation in a physics community of practice connected to his/her physics identity?*

Finally, we brought our first and second research questions together to form a hypothesis for reducing the gender gap. If physics identity plays a significant role in the gender gap, and if community participation can support students—particularly those who experience conflict between their gender identity and a physics identity—to develop their identity as apprentice physicists, then we hypothesize that community-building instructional strategies could reduce the gender gap in physics. As students construct an identity in a physics community—attaching meaning to who they are as apprentice physicists and who they want to become [113][66]—we expect they will engage more deeply with the material and gain a higher level of conceptual understanding. This hypothesis led to our final research question:

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3. *Do collaborative, community-building instructional strategies reduce the conceptual understanding gender gap in Newtonian mechanics?*

We note, however, that similar hypotheses involving the role of interactive engagement in reducing the gender gap have been tested only to find conflicting results [15, 59, 64, 57, 58, 60, 61]. Therefore, we performed a quantitative meta-analysis of 26 classes, including data from five courses at our institution, to go beyond study-to-study conflicts and find overarching patterns for fostering equity.

3.3 Methods

Ethics approval was obtained from the General Research Ethics Board at Queen's University for this study. All participating students received a letter of information detailing the process and time involved in the study, its risks and benefits, measures taken to protect their confidentiality, the option to not participate or withdraw at any time, and contact information for the primary researcher and the General Research Ethics Board. Only results from students who gave consent to participate in the study were included in this work.

3.3.1 Measuring physics identity in communities of practice

In order to address our first and second research questions, we surveyed students in four introductory physics courses at the start and end of the Newtonian mechanics semester to determine students' i) physics identity, ii) engagement with a physics community of practice, iii) conceptual understanding of Newtonian mechanics, iv) intention to continue in a physics program, and v) gender.

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Physics identity survey

In order to build a physics identity scale to address the four components of physics identity outlined by Hazari et al. [5]—competence, interest, performance, and recognition—we created four subscales to measure each of these components. In each subscale, students responded to questions such as "My friends say that I'm good at physics" (recognition subscale) on a 7-point Likert-type scale from "strongly agree" to "strongly disagree". A student's physics identity score was calculated by taking the mean of a student's competence, interest, performance, and recognition scores.

Several items on the performance and competence subscales were adapted from the New General Self-Efficacy scale [114]. For example, the New General Self-Efficacy scale item, "When facing difficult tasks, I am certain that I will accomplish them" was adjusted for the performance subscale to state, "When solving challenging physics problems, I am certain that I will succeed." Other items were taken from Hazari's work on a longer physics identity scale [5]. Items were adjusted to ensure a concise scale that covered all four components of physics identity.

Table 3.1 shows the internal reliability measure, Cronbach's α, for each subscale. The α values in Table 3.1 indicate a good to excellent level of internal consistency for each subscale [115, 116].

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Table 3.1: Scale reliability

		Pre-term survey		**Post-term survey**	
Scale	N_{items}	$N_{students}$	α	$N_{students}$	α
Competence	4	468	.86	472	.90
Interest	4	466	.80	471	.85
Performance	3	287	.73	472	.85
Recognition	3	470	.90	472	.90
Physics community engagement	8	466	.75	472	.83

To explore the convergent validity of the physics identity survey with its four subscales combined, we compared students' total physics identity score to their responses (measured on a 7-point Likert-type scale) to the question "I consider myself to be a physics person"—a question that should directly target physics identity. We found strong correlations of $r = .794$ ($p < .001$, $N = 469$) on the pre-term survey, and $r = .803$ ($p < .001$, $N = 472$) on the post-term survey. These correlations suggest strong convergent validity for our physics identity scale.

Physics community engagement measurement

In order to measure students' engagement with a physics community of practice we built an 8-item survey measured on a 7-point Likert-type scale from "strongly agree" to "strongly disagree". Three questions for this scale were borrowed with permission from Li and Demaree's survey [117]. Cronbach's α for the pre-term and post-term community engagement scale indicates a good level of internal consistency, as shown in Table 3.1.

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Conceptual understanding measurement

We measured students' pre- and post-term conceptual understanding of Newtonian mechanics. To make direct comparisons possible in our meta-analysis, we used a standardized measure of mechanics conceptual understanding—the Force Concept Inventory (FCI) [37], which we administered in the first and last weeks of the semester. Academic performance was also measured through student scores on quizzes, assignments, midterms, and exams.

Intention to continue in physics and gender measurement

We asked students to rate the likelihood that they would major in physics (from "strongly agree" to "strongly disagree") on a 7-point Likert-type scale in our pre- and post- surveys. Finally, we asked students to report their gender as 'male', 'female', or 'prefer not to specify', and included results from students who reported a consistent gender in our study.

3.3.2 Testing mediation models

Physics education literature demonstrates that gender predicts both FCI scores and persistence in physics programs [15, 59, 9]. But is this result mediated by physics identity?

The hypothesized mediation model is illustrated in Figure 3.1: Gender (the independent variable) predicts FCI scores or persistence (the dependent variable) at least partially through physics identity (the mediator variable). Each arrow in this figure denotes a prediction used in one of the several regression expressions.

Classic tests for mediation (such as those by Baron and Kenny [118] or by Sobel

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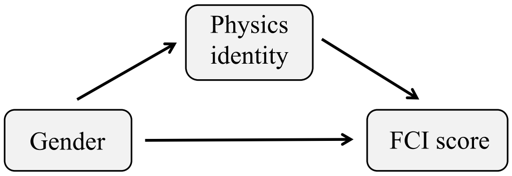

Figure 3.1: Simple mediation model: we hypothesize that the influence of gender on FCI scores is mediated by physics identity.

[119]) build regression models first to predict the dependent variable from the independent variable and then to predict the dependent variable from the independent variable *and* the mediator variable (in our case, physics identity). These tests then compare regression expressions to determine if the inclusion of the mediator variable (physics identity) significantly reduces the prediction of the dependent variable (FCI scores or persistence) from the independent variable (gender).

These classic tests, however, have low statistical power [120]. Therefore, their use increases the likelihood of making a Type II error, in which an effect that exists in the population is not detected by the test [121]. To overcome this concern, we apply a bootstrapping method, PROCESS, written for SPSS by Hayes [122]. This method increases statistical power by randomly selecting 1000 samples from the data set, building the same regression models described above with each of these samples, and testing for a statistically significant reduction in the gender coefficient for predicting FCI scores or persistence when physics identity is included in the regression expressions. This method provides a 95% confidence interval for the size of the mediation

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effect. Therefore, if this confidence interval does not contain zero, then the effect size for the mediation is non-zero ($p < .05$) [122]. In other words, the mediation effect is statistically significant when the effect size confidence interval does not include zero.

3.3.3 Examining the gender gap through meta-analysis

In our meta-analysis, we include seven studies [49, 15, 59, 123, 124, 125, 126], chosen based on their context (introductory Newtonian mechanics), the availability of complete quantitative results and instructional strategy descriptions in published papers or directly from authors, and consistent gender gap measurement tools. We selected studies that measured students' conceptual understanding of Newtonian mechanics using standard tests such as the Force Concept Inventory (FCI) [37] or the Force and Motion Concept Evaluation (FMCE) [38], a test that positively correlates with the FCI [127]. Our meta-analysis also contains the results from four different introductory physics classes at our university in this analysis, including two years of data from one of these classes, for a total of 1798 women and 3725 men spread across 26 courses in three continents.

We classify the 26 courses in our study as IE0, IE1, or IE2 following the same categories as the Harvard and University of Colorado studies to define IE1 and IE2 [15, 59]. IE0 (interactive engagement level zero) indicates a course dominated by traditional lectures with few collaborative learning opportunities; this was the case for three classes in our meta-analysis. Twelve courses in our analysis are designated as IE1, adopting some collaborative learning components without completely transforming the course (e.g., Peer Instruction in lecture periods with traditional or no recitations). Finally, eleven courses are defined as IE2: fully-transformed courses

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containing many collaborative learning opportunities (e.g., Peer Instruction in lecture periods, Just in Time Teaching to support Peer Instruction, and collaborative team problem solving in recitation sessions).

While it is easy to claim 'equity' as the goal of our meta-analysis, it is not so straightforward to define what equity means. For some readers, equity implies equal outcomes: these readers might feel that equity is achieved when women perform at the same level as men by the end of the semester. However, this equity of parity model inherently suggests that women need to learn more than men in order to achieve an equal level of conceptual understanding by the end of the course [3]. Therefore other readers may consider equity to imply equal learning gains (therefore largely maintaining the gender gap) because a course that helps women more than it helps men could be considered unfair [3]. Still other readers may find this focus on comparisons between men and women to be problematic; these readers may take an equity of individuality perspective that focuses on finding instructional strategies that offer the best learning environments for women [3].

Each of these equity models [3]—equity of individuality, of parity, and of fairness—offers unique insights. We do not argue that one model should trump another. Rather, we perform our meta-analysis from each of these perspectives.

Equity of individuality

An equity of individuality model focuses on improvements within a single gender, instead of looking for differences and similarities between men and women [3]. For example, an equity of individuality model asks questions such as, "Are women more

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successful in collaborative courses or traditional courses?" This model has the benefit of avoiding prejudices that can arise through comparisons between groups. However, an equity of individuality model risks perpetuating the under-representation of women, since it does not directly attend to this gap [3].

We investigate equity of individuality by comparing women's gains in different course types. Conceptual understanding normalized gain is typically calculated on a student-by-student basis and averaged across the class. This gain is the fraction of the possible improvement from the student's pretest score (S_i, the percentage grade on pre-term FCI) to his or her posttest score (S_f, the percentage grade on the post-term FCI) [128]. Using pretest and posttest scores out of 100, a student's normalized gain is given by Equation 3.1.

$$g = \frac{S_f - S_i}{100 - S_i} \tag{3.1}$$

In our meta-analysis, we did not have access to individual student data for most classes. Therefore, we calculate estimates of the average normalized gains, $\bar{g}$, for each gender using men and women's average pretest and posttest scores, $<S_f>$ and $<S_i>$, for each course as shown in Equation 3.2.

$$\bar{g} = \frac{<S_f> - <S_i>}{100 - <S_i>} \tag{3.2}$$

We contrast women's normalized gains in each of the three course-types using ANOVA contrasts[2].

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[2] To determine whether we could use parametric tests in our analysis, we investigate measures of skewness and kurtosis among these average normalized gains. For women's normalized gains, $Z_{skewness}$ = -.73 and $Z_{kurtosis}$ = .63, indicating that our data fit a normal distribution to a 95% confidence interval. Therefore, we cannot reject the null hypothesis that our data significantly deviates from a normal distribution.

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Equity of parity

An equity of parity model focuses on the goal of obtaining equal post-term conceptual knowledge for both men and women [3]. For example, an equity of parity model asks questions such as, "At the end of a collaborative Newtonian mechanics course, are men and women equally prepared to tackle a second-year mechanics course?" Rodriguez et al. state that equity of parity can be observed through i) a direct reduction in the gap between men and women's scores and ii) a reduction in the effect size of this gap [3].

The direct reduction in the gender gap compares the posttest gap $S_{Mf} - S_{Ff}$ to the pretest gap $S_{Mi} - S_{Fi}$. This commonly used measure of the gender gap is often examined by comparing statistical significance in pretest and posttest results. For example, some studies show a statistically significant gender gap becoming statistically non-significant in fully interactive (IE2) courses [15]. Statistical significance alone, however, does not tell the whole story. This binary measure of the gender gap is highly dependent on class size: a larger number of students (and therefore a large class) is needed to pick up smaller differences. Therefore, the p-value testing of previous studies can point researchers in a helpful direction, but as Rodriguez et al. suggest, comparisons of the direct gender gap are not sufficient on their own; we also require a comparison of effect sizes [3].

As the name implies, the gender gap effect size quantifies the magnitude of the gender gap effect. Effect size is promoted by researchers to provide a more thorough comparison of two means than p can provide [129] since it takes into account not only the difference between populations, but also the variability within populations. Unlike p, effect sizes do not depend on the number of participants in the study [130];

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therefore, it is a particularly useful statistic for determining a measure of the extent of a phenomenon that is present in the population [131] or the "practical importance" of an effect [132].

Cohen's d is used to measure effect size instead of the correlation r because r becomes discrepant when the size of the groups is very different [121]. Since a gender gap exists in both conceptual understanding *and* the number of students in introductory physics, our group sizes are inherently different. Cohen's d is calculated from the means of the two groups, x_1 and x_2, the number of students in each group, N_1 and N_2, and the standard deviation for each group, SD_1 and SD_2 as shown in Equation 3.3 [133].

$$d = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{(N_1-1)SD_1^2+(N_2-1)SD_2^2}{N_1+N_2}}} \tag{3.3}$$

The numerator of Equation 3.3 represents the difference in means between the two groups, and the denominator represents the pooled standard deviations, weighted according to the number of participants in each group. Considering the gender gap effect size added a more complete picture of the gender gap than the direct reduction in the gender gap could provide [129].

However, neither the direct gender gap nor the gender gap effect size address a common question asked of equity of parity models: Are reductions in the gender gap the result of decreased success for men? To answer this concern, we introduce the normalized gender gap. This parameter examines the gap relative to students' average score as shown in Equation 3.4.

$$< \text{Gap} >= \frac{(S_M - S_F)}{(S_F N_F + S_M N_M)/(N_F + N_M)} \tag{3.4}$$

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We examine the reduction in the normalized gender gap for several reasons. The normalized gender gap communicates that parity is improved when the direct gender gap becomes smaller relative to students' scores, showing that equity of parity can be approached both by reducing the direct gap and by increasing gains for all students. A class that shows no change in the direct gap would still be making steps towards equity of parity if students' average score increased. For example, a posttest gap of 10/70 is better than a pretest gap of 10/30 even though the direct gap shows no change. This has potential to reduce a common concern with equity of parity interventions: that a reduction in the gender gap can be achieved by decreasing men's scores. Also, due to the inherent weighting in the normalized gap, this parameter reduces the importance of courses that may be experiencing ceiling effects for male students.

We determine if there are on average statistically significant reductions in the gender gap for any course type (along with the effect size of these reductions). Using ANOVA constrasts, we compare the reduction in the direct gender gap, the normalized gender gap, and the gender gap effect size between the three different types of courses: IE0, IE1, and IE2 [3].

A benefit of an equity of parity model is the focus on outcomes: it has the goal of reducing posttest gaps between men and women, thereby giving women and men equal starting points for their further physics studies. However, this focus on outcomes also comes with risks. In order to achieve equity of parity, the instructional strategy may need to support women more than it supports men [3]. Though this approach seeks

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[3] We find that all of these variables passed tests of skewness and kurtosis, falling within the 95% confidence interval range (-1.96 to 1.96 as Z-scores): $Z_{skewness} = .81$ for the change in the direct gender gap, $Z_{skewness} = 1.7$ for the change in the normalized gender gap, and $Z_{skewness} = .69$ for the change in the gender gap effect size, $Z_{kurtosis} = .91$ for the change in the direct gender gap, $Z_{kurtosis} = 1.3$ for the change in the normalized gender gap, and $Z_{kurtosis} = .22$ for the change in the gender gap effect size. Therefore, we can use parametric tests to compare the reduction in the gender gap from course to course

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to undo a history of inequity in female students' prior education experiences so that women can enter second year physics courses with an equal background understanding as men, some may perceive this equity model as 'unfair' in the particular course where it is used. Therefore, we also examine the gender gap from an equity of fairness perspective.

Equity of fairness

In contrast to an equity of parity model, an equity of fairness model does not aim to reduce achievement gaps between men and women. Rather, an equity of fairness model focuses on impartial teaching, with the goal of ensuring equal gains for both men and women—regardless of previously existing differences [3]. For example, an equity of fairness model asks questions such as, "Do men and women have equal learning opportunities in collaborative courses?" Rodriguez et al. define equity of fairness as equal normalized gains [3], and we take this analysis approach across the 26 courses in our study.

Rodriguez et al. argue that an equity of fairness model can perpetuate achievement gaps by failing to address the underlying causes for the gender gap [3]. While we agree in the sense that an equity of fairness framework may turn a blind eye to existing gaps, we argue that at least some advances can be made towards both equity of fairness and equity of parity at the same time. Since women typically have lower pretest scores, women need to achieve a greater posttest minus pretest score in order to obtain equal normalized gains to men. Therefore, an equity of fairness model that aims to achieve equal normalized gains for both men and women can also reduce the achievement gap between men and women. We propose that, while the underlying

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goals of equity of fairness and equity of parity appear opposed, steps can be taken towards achieving both goals simultaneously when normalized gains are considered. However, we acknowledge the importance of Rodriguez's caution—that an equity of fairness model could fail to attend to previously existing gender gaps.

We compare men and women's normalized gains to test for equity of fairness for each course condition. Using ANOVA, we contrast the differences between men and women's normalized gains between the three course-types.

Applying equity models to investigate the zero-sum perspective

We cannot examine the gender gap without directly addressing a common concern with gender gap research: Is the gender gap reduced at men's expense? A zero-sum perspective on the gender gap—the belief that increased success for women must be accompanied by decreased success for men—risks exacerbating prejudices if male students feel threatened by female students' rising success [3]. We apply results from all three equity models to investigate if women's improvements come at the expense of men's learning.

3.4 Results

3.4.1 Physics identity mediates gender gaps

Answering our first research question, we determine the extent to which physics identity accounts for the gender gaps in conceptual understanding and retention in physics programs among students at our university. Specifically, we explore physics identity as a potential mediator between gender and posttest scores and between gender and

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retention in physics. To determine if physics identity is mediating the impact of gender on FCI scores and retention in physics, we build several regression models to determine if gender's influence on scores and retention is significantly reduced when physics identity is included in the model.

Mediation of the conceptual understanding gender gap

We begin with a simple regression model to describe the relationship between gender and conceptual understanding. We define gender by the variable x, choosing $x = 0$ to represent men and $x = 1$ to represent women. We normalize the pretest scores, S_i, and posttest scores, S_f, on a 0 to 1 scale to allow for quick comparisons in the regression models. The simple regression equations predicting pretest and posttest scores from gender are given in Equations 3.5 and 3.6

$$S_i = -.16x + .68 \quad (\mathrm{R}^2 = .128) \tag{3.5}$$

$$S_f = -.12x + .79 \quad (\mathrm{R}^2 = .087) \tag{3.6}$$

where R^2 represents the variance in FCI scores explained by each model. All unstandardized regression coefficients in these simple regressions, Equations 3.5 and 3.6, are statistically significant ($\mathrm{p} < .001$). The negative gender coefficients indicate that women scored lower than men on the pretest and the posttest. However, the low R^2 values suggest that gender alone only explains a small amount of the variance in both pretest and posttest scores.

We next consider the role of physics identity, y, normalized on a scale of 0 to 1. We find correlations between pretest scores and preterm physics identity ($r = .431$,

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p <.001, $N = 466$), and between posttest scores and postterm physics identity ($r =$ .679, p <.001, $N = 361$). When we include students' pre-term physics identity in our regression model, the role of gender becomes statistically non-significant in predicting both pretest and posttest scores. The multiple regression expression predicting pretest scores and including two-way interactions between physics identity and gender is given by Equation 3.7.

$$S_i = .62y_i + .02x - .19xy_i + .19 \quad (\mathrm{R}^2 = .248) \tag{3.7}$$

In the multiple regression given by Equation 3.7, the only statistically significant coefficient is the identity coefficient (p <.001). The gender and gender × identity interaction coefficients are not statistically significant ($p = .84$ and .14 respectively). Similar results are found when we predict posttest scores from post-term physics identity and gender in Equation 3.8.

$$S_f = .66y_f - 0.009x - .10xy_f + .32 \quad (\mathrm{R}^2 = .327) \tag{3.8}$$

Again, the only statistically significant coefficient in Equation 3.8 is the identity coefficient ($p < .001$). The gender and gender × identity interaction coefficients are not statistically significant predictors of posttest scores ($p = .93$ and .45 respectively).

Using pretest scores as a measure of students' prior knowledge, we are able to expand our posttest multiple regression model to include students' conceptual background. Pretest and posttest scores correlate with each other as expected ($r = .679$, p <.001, $N = 361$). However, even when we include students' pretest scores in our multiple regression model, we find that pretest and posttest physics identities continue

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to play unique roles in predicting posttest scores. In these multiple regression models, shown in Equations 3.9 and 3.10, gender remains a statistically non-significant predictor.

$$S_f = .59S_i + .16y_i - .012x + .27 \quad (\mathrm{R}^2 = .461) \tag{3.9}$$

$$S_f = .57S_i + .18y_f - .019x + .30 \quad (\mathrm{R}^2 = .548) \tag{3.10}$$

In both of these expressions, $p < .05$ for the pre- and post-term identity coefficients and the pretest score coefficient. The gender coefficient remains statistically not significant with $p > .05$ for both expressions.

Including the interaction terms, the regression model for predicting post-test score from post-term identity, prior knowledge, and gender is shown in Equation 3.11.

$$S_f = .93S_i + .60y_f - .021x + .13xS_i - .60y_fS_i - .11xy_f + .053 \quad (\mathrm{R}^2 = .562) \tag{3.11}$$

Both the pretest score and post-test identity coefficients are statistically significant predictors of posttest scores ($p < .001$, and $p = .014$ respectively) in this model. The R^2 value of .562 indicates that this model accounts for more than half the variance in post-test scores. The gender coefficient remains not statistically significant ($p = .84$), as did the interaction coefficients.

In summary, despite large pretest and posttest gender gaps, when we include physics identity in our regression models, the role of gender in predicting pretest and posttest scores becomes no longer significant. When both prior knowledge and physics identity were included in our model for predicting posttest scores, both identity and prior knowledge were significant predictors while gender was not, and our R^2 value indicated that we had accounted for over half of the variance in posttest scores.

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These regression models point to physics identity as a potential mediator between gender and conceptual understanding. The influence of gender on FCI scores certainly appears to decrease when physics identity is included in the model. But is this reduction statistically significant?

Applying PROCESS [122] as described in Section 3.3.2, we find that physics identity is a significant mediator between gender and pretest scores and between gender and posttest scores. For pre-term identity and pretest scores, we observe the size of the mediation effect to vary between -.077 and -.040 (N = 465). The negative effect size confidence intervals indicate a negative relationship between gender and FCI scores: women ($x = 1$) score lower than men ($x = 0$) on the pretest. Similarly, post-term physics identity mediates the gender gap in posttest scores with a statistically significant effect size ranging from -.10 to -.05 ($N = 292$).

Mediation of the intention to continue in physics gender gap

We find that the second component of the gender gap—persistence in a physics major—is also highly driven by physics identity. Dividing the students into two categories—those who agree or strongly agreed with the post-term survey item, “I hope to major in physics or engineering physics” and those who do not agree or strongly agree, we find the expected patterns: students who plan to continue in physics are more likely to be male, identify more strongly with physics, and have higher conceptual understanding as shown in Table 3.2. Note that posttest scores are a percentage out of 100, identity is measure on a 7-point Likert-type scale, and gender is given by 0 for men and 1 for women. The significance of the difference between the groups of continuing and not continuing is shown by the p column and the effect size of this

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difference is indicated by Cohen's *d*.

Table 3.2: Who continues in a physics major?

	Continuing		**Not continuing**		**Comparison**	
Measure	N	Score	N	Score	p	d
Posttest score	51	88±1%	245	71±1%	$< .001$	.84
Post-term identity	61	5.7±0.1	411	4.48±0.06	$< .001$	1.19
Gender	61	0.28±0.06	406	0.63±0.02	$< .001$	.74

To take a closer look at the factors predicting a student's pre-term or post-term decision to major in physics, C_i and C_f, we build multiple regression expressions. In these regression expressions, we treat students' plan to continue in physics as a scaled item (from 1 to 7), not a binary "yes" or "no" decision as shown in Table 3.2. A binary comparison lumps together students who feel neutral towards continuing in a physics major and those who strongly disagree with the idea of studying physics. Treating future physics plans as a scaled item recognizes that many students have not settled on a major by the end of November (and certainly not in September), and therefore provides a more complete picture of students' plans.

Our first set of models only include gender (0 = men, 1 = women). Without including physics identity, we find gender to be a statistically significant predictor of pre- and post-term plans to continue in a physics or engineering physics major (p $<$.001) as shown in Equations 3.12 and 3.13.

$$C_i = -1.2x + 3.9 \quad (\mathrm{R}^2 = .097) \tag{3.12}$$

$$C_f = -1.4x + 3.7 \quad (\mathrm{R}^2 = .122) \tag{3.13}$$

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However, when we include physics identity in our multiple regression model, we find that gender is no longer a significant predictor of a plan to continue in physics, while physics identity is a statistically significant predictor ($p < .001$) for both pre-term and post-term regression models.

$$C_i = 7.7y_i + 0.7x - 1.5xy_i - 2.1 \quad (\mathrm{R}^2 = .363) \tag{3.14}$$

$$C_f = 6.9y_f + 0.3x - 1.3xy_f - 1.4 \quad (\mathrm{R}^2 = .396) \tag{3.15}$$

Even when we consider conceptual understanding (measured by pretest and posttest scores) in predicting a pre-term or post-term plan to continue in physics, physics identity remains a distinct statistically significant predictor. In Equation 3.16, pre-term identity and pretest score are statistically significant predictors of a pre-term plan to continue in physics ($p < .001$), while the gender coefficient is not statistically significant.

$$C_i = 6.1y_i - .3x + 1.2S_i - 1.7 \quad (\mathrm{R}^2 = .378) \tag{3.16}$$

In predicting a post-term plan to continue in physics (Equation 3.17), identity remains a large statistically significant predictor. Surprisingly, posttest conceptual understanding scores are not statistically significant predictors of a post-term decision to continue in physics when identity and gender are considered in the model, while gender is a small statistically significant predictor.

$$C_f = 6.3y_f - .6x + 1.0S_f - 1.6 \quad (\mathrm{R}^2 = .414) \tag{3.17}$$

The relative sizes of the coefficients also suggest that physics identity is playing a

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particularly large role in predicting pre- and post-term plans to continue in physics. When we include interaction terms between identity, pretest scores, and gender in the pre-term model, only the physics identity coefficient remains statistically significant ($p < .001$). When interaction terms are considered in the post-term model, no coefficients remain statistically significant.

Since these regression models suggest that physics identity may be a mediating factor between gender and plans to continue in physics, but they do not directly test the significance of a mediation model, we again explore this relationship using Hayes' PROCESS method [122]. We find that pre-term physics identity is a statistically significant mediator between gender and a pre-term plan to continue in a physics major. Mediation effect sizes range from -.13 to -.08 (N = 470). Similarly, post-term physics identity is a statistically significant mediator between gender and a post-term plan to study physics; the size of this mediation effect ranges from -.13 to -.08 (N = 467).

We also note that a change in physics identity (from pre- and post-term survey results) correlates positively with a change in plans to continue in physics both for weaker students who scored below 85% on the FCI pretest ($r = .393$, $p < .001$, $N = 169$) and for already well-prepared students who scored above 85% on the FCI pretest ($r = .472$, $p = .006$, $N = 33$).

In answer to our first research question, our data suggest that physics identity is a mediator—unique from prior knowledge—in the gender gap in physics conceptual understanding and persistence in physics programs. Therefore, we expect that creating an environment in which women's physics identities are encouraged to develop could succeed in reducing the gender gap in physics. This led directly into our next

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research question, testing the relationship between engagement with a community of practice and physics identity.

3.4.2 Physics identity is linked to communities of practice

We find strong correlations between students' physics identity and their engagement with a physics community of practice. From our pre-term survey of 471 students, identity and community engagement correlate with Pearson coefficient $r = .78$ (p <.001). Similarly, the post-term survey of 472 students shows a correlation of $r = .85$ (p <.001) between identity and community engagement.

These results go against the stereotypical picture of a physics student and better reflect the actual day-to-day experiences of physicists. On average, students who identify with physics also identify with a physics community: they engage with their peers in meaningful discussions about physics, they prefer to learn in groups, and many of their friends study physics. This is reflective of today's physicist, who often collaborates with colleagues to perform novel experiments.

The correlations between physics identity and physics community engagement show further potential for impacting the gender gap when we examine them by gender. We find preterm correlations between identity and communitiy engagement to be $r = .79$ (p <.001) for women (N = 243) and $r = .71$ (p <.001) for men (N = 227) with no statistically significant difference between these correlations ($p = .16$). However, in our postterm survey, correlations between physics identity and physics community engagement are significantly higher for women than for men ($p = .032$). These correlations are $r = .87$ (p <.001) for women (N = 271) and $r = .78$ (p <.001) for men (N = 196).

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We also examine the change in physics identity for the 205 students who took both the pre- and post-term identity survey. An increase in physics identity correlates with an increase in community engagement for women ($r = .66$, $p < .001$) and for men ($r = .63$, $p < .001$). These data suggest links between students' changing physics identities and their changing engagement with a physics community of practice.

Answering our second research question, we find that engagement with a community of practice correlates strongly with physics identity for both men and women. Our postterm results go one step further to suggest that this correlation may be stronger for women than for men. These results lead us to our next research question: if physics identity plays a significant role in the gender gap, and if engagement with a community of practice is connected to increased physics identity, then can collaborative instructional strategies—community-building activities that may reduce stereotype threat and open the door to further development of women's physics identities—reduce the gender gap?

3.4.3 Meta-analysis: Collaborative instructional strategies make progress towards equity

In order to determine the impact of collaborative instructional strategies on the gender gap, we perform a quantitative meta-analysis on the results from 26 different courses, including 5 courses from our institution. The new data from our university are included in the Appendix A, while results from the other 21 courses can be found in those published works [49, 15, 59, 123, 124, 125, 126] with details directly from those authors. In order to ensure uniformity across studies, we compare standardized test scores (FCI or FMCE) for our pretest and posttest measures of Newtonian

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mechanics conceptual understanding.

Following our course classifications described in Section 3.3.3—IE0 courses centering primarily around a traditional lecture, IE1 courses including some collaborative learning components, and IE2 representing a fully-transformed course with many community-building instructional strategies—we provide a snapshot of the initial populations in these courses. The pretest results indicate no statistically significant differences between incoming students in the three types of courses. As shown in Table 3.3, the statistically significant pretest gender gap is approximately one letter grade, with men outscoring women by approximately a quarter of the average score.

Table 3.3: Pretest results ($p > .05$ for all column-to-column contrasts)

	IE0	IE1	IE2
Men pretest	57±11%	56±5%	55±6%
Women pretest	47±12%	47±6%	43±6%
Direct pretest gap	10±1%	10±1%	12±1%
Normalized pretest gap	.21±.06	.23±.04	.28±.04
Pretest gap effect size d	.59±.04	.62±.08	.65±.06

Equity of Individuality

We begin our equity analysis by first looking away from the gender gap itself to focus on how to best serve each gender individually. We asked: Do women in IE2 courses outperform their own gender in IE1 and IE0 courses, as measured by conceptual understanding gains?

To get a general sense of trends, we begin with correlations. We find that increased collaborative opportunities correlate positively with increased normalized gains for women ($r = .63$, $p = .001$). Even when we control for class size, increased collaboration

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still correlates with increased gains for women (r = .55, p = .004).

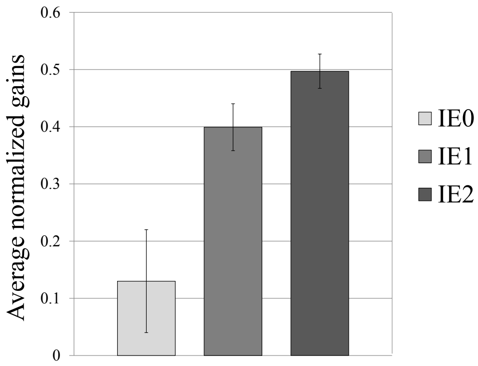

Figure 3.2: Trends show greater normalized gains for women in courses with increased opportunities for collaboration. All error bars in this analysis indicate the standard errors of the means.

Figure 3.2 compares women's normalized gains in each of the three course-types.

Women's normalized gains are significantly higher in IE1 courses over IE0 courses (p = .01, effect size r = .89). While the difference between women's normalized gains in IE2 and IE1 courses is not statistically significant, the effect size for this difference is moderate (p = .096, effect size r = .36). Furthermore, women in IE2 courses far outperform women in IE0 courses (p =.003, effect size r = .93).

These results suggest that increased opportunities for collaboration increase women's conceptual understanding gains. However, a limitation of an equity of individuality framework is the lack of attention to the inequities found in the gap between men and women. We turn then to an equity of parity framework to explore whether collaborative instructional strategies have any impact for reducing the conceptual understanding gap between men and women.

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Equity of parity

Did increased collaborative instructional strategies make steps toward equity of parity? Table 3.4 and the related Figures 3.3, 3.4, and 3.5 show that while equity of parity was not fully achieved in any course category, trends suggest that increased collaboration can contribute to reducing the conceptual understanding gender gap. In order to understand the role of collaborative instructional strategies in making steps towards equity of parity, we compare the reduction in the direct gender gap, the normalized gender gap, and the gender gap effect size.

Table 3.4: Posttest results

	IE0	IE1	IE2
Men posttest	66±8%	78±3%	79±4%
Women posttest	55±9%	68±4%	70±4%
Direct posttest gap	11±2%	10±1%	9±2%
Normalized posttest gap	.19±.06	.15±.03	.13±.03
Posttest gap effect size d	.50±.04	.66±.08	.49±.09

Reducing the direct gender gap

First, a comparison of the direct gender gap reduction in the three course types is shown in Figure 3.3. Since we plot reduction in the gender gap, negative bar plots indicate an increase in the gender gap from the pretest to posttest. We observe a statistically significant reduction in the gender gap in IE2 courses using a dependent sample t-test and a very large effect size for this reduction ($p = .025$, $d = 1.27$), though this result is marginally not significant using the Wilcoxon signed-rank test for small related samples ($p = .062$, effect size $r = .40$). In contrast, we do not

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observe a significant reduction in the gender gap for IE1 or IE0 courses using either a dependent samples t-test or Wilcoxon signed-rank test.

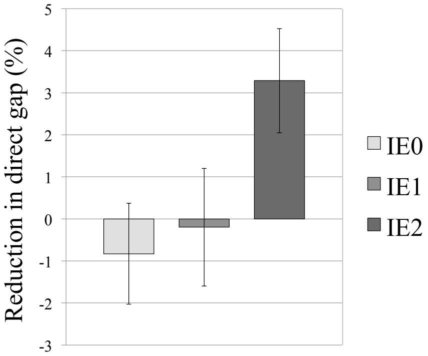

Figure 3.3: We observe greater reductions in the direct gender gap in IE2 courses than in IE1 or IE0 courses.

The reduction in the direct gender gap is significantly higher in IE2 over IE0 (p = .046, effect size r = 67). While statistical significance was not found between IE0 and IE1 (p = .32, effect size r = .35) or IE1 to IE2 (p = .25, effect size r = .25), these differences have medium effect sizes.

These results point to the large variability in the impact of collaborative instructional strategies for improving equity of parity. Though Figure 3.3 suggests that increased collaboration leads to greater reductions in the gender gap, we can only say (with statistical significance) that IE2 courses outperform IE0 courses. Nonetheless, Figure 3.3 suggests that the role of collaborative instructional strategies for reducing the direct gender gap is worth further research; initial trends (albeit with large uncertainties) suggest that IE2 courses may be a step in the right direction for reducing the direct gender gap.

Reducing the normalized gender gap

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In order to highlight courses with the greatest reduction in the gender gap relative to students' overall score, we compare reductions in the normalized gender gap. We observe statistically significant reductions from pretest to posttest normalized gender gaps in IE2 courses with a very large effect size ($p < .001$, $d = 1.24$ using t-test, $p = .003$, effect size $r = .63$ using Wilcoxon signed-rank test) and in IE1 courses ($p = .001$, $d = .73$ using t-test, $p = .006$, effect size $r = .55$ using Wilcoxon signed-rank test). In contrast, we find no statistically significant reduction in the normalized gender gap for IE0 courses using either a t-test or Wilcoxon signed-rank test.

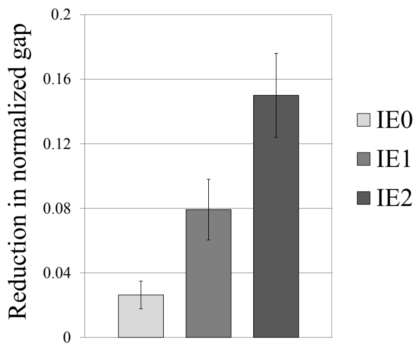

Figure 3.4: Trends show greater reductions in the normalized gender gap in courses with increased opportunities for collaboration.

The reduction in the normalized gender gap is significantly higher in IE1 over IE0 ($p = .004$, effect size $r = .72$). While statistically significant differences in the reduction of the normalized gender gap in IE2 over IE1 courses was not observed, the effect of this difference was moderate ($p = .22$, effect size $r = .30$). Furthermore, IE2 courses exceeded IE0 courses significantly in reducing the normalized gender gap ($p = .004$, effect size $r = .71$). These trends indicate greater reductions of the normalized gender gap in courses with increased opportunities for community participation, as

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shown in Figure 3.4.

Reducing the gender gap effect size

Finally, we compare the pretest and posttest gender gap effect sizes for the three types of courses. We find a statistically significant reduction in gender gap effect size in IE2 courses ($p = .009$, $d = .63$ using t-test, $p = .021$, effect size $r = .49$ using Wilcoxon signed rank test). In contrast, we do not observe statistically significant reductions in the gender gap effect size for IE1 or IE0 courses using either a t-test or Wilcoxon signed-rank test.

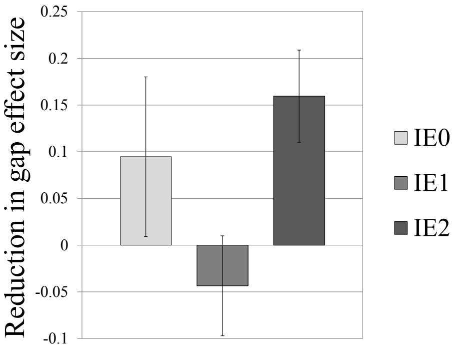

Figure 3.5: Gender gap effect size is reduced in fully-collaborative courses.

While ANOVA revealed no statistically significant differences in the reduction of the gender gap effect size between IE0 and IE1 ($p = .35$) or between IE1 to IE2 ($p = .13$), we found that the size of the difference between IE1 and IE2 reductions in the gap effect size were moderate ($r = .33$). Noting the large error bars especially for IE0 courses in Figure 3.5, we anticipate that a larger selection of studies could reduce the ambiguity of effect size results.

To reduce potential ceiling effects, we repeat these analyses omitting any classes

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in which posttest scores are within one standard deviation of 100%. The remaining five IE2 courses, ten IE1, and three IE0 courses continue to show similar trends; the reductions in direct and normalized gender gaps and gender gap effect size appears to be greater in IE2 courses, though these results are no longer statistically significant with such few classes in the analysis.

These data suggest a trend in which IE2 courses tend to have more success in reducing conceptual understanding gender gaps than IE1 or IE0 courses. However, even IE2 courses still do not fully reach equity of parity. Though we find statistically significant decreases in the gender gap in IE2 courses, we still observe a 9±2% ($d = .49 \pm .09$) direct gender gap and a .13±.03 normalized gender gap on the posttest even in IE2 courses. The gender gap in physics is pervasive, persistent, and multifaceted. Not surprisingly, therefore, we find that these single semester courses are not sufficient to completely eliminate this gender gap. We are encouraged, however, to find positive trends: IE2 courses can go further than IE1 and IE0 courses in reducing this persistent gender gap.

Equity of Fairness

Our final equity model focuses on process rather than outcomes, asking: Do women and men have the same normalized gains in IE0, IE1, and IE2 courses?

As shown in Figure 3.6, women's average normalized gains in IE2 courses are slightly lower than men's on a t-test ($p = .041$, $d = .34$) but the difference is marginally not significant when evaluated with a Wilcoxon signed-rank test ($p = .062$, effect size $r = .40$). In IE1 courses, women's normalized gains are significantly lower than men's using a t-test ($p < .001$, $d = .72$) and a Wilcoxon signed-rank test ($p = .003$, effect

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size $r = .64$). In IE0 courses, women's average normalized gains are not significantly lower than men's ($p = .28$, $d = .52$ using a t-test, $p = .29$, effect size $r = .43$ using a Wilcoxon signed-rank test). However we note that the small sample of three IE0 courses makes statistical significance harder to obtain.

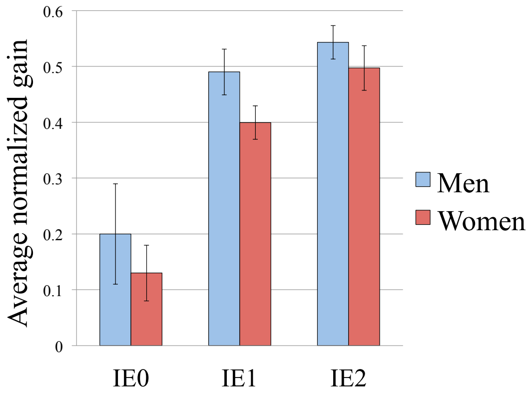

Figure 3.6: Trends show greater steps towards equity of fairness in IE2 courses than in IE1 courses.

Comparing these difference in men and women's normalized gains using ANOVA, we find no statistically significant differences between IE0 and IE1 ($p = .70$) or between IE1 and IE2 ($p = .45$), but we note that there may be a small to moderate effect size for the difference between IE1 and IE2 courses ($r = .18$).

Our results suggest that equity of fairness—equal normalized gains for men and women—is not fully reached in IE1 or IE2 courses. These results point to the zero-sum discussion; reductions in the gender gap is not the result of unfair disadvantages to men in IE2 courses. Men continue to out-gain women in both IE1 and IE2 courses.

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Are gender gap reductions merely the result of smaller class sizes?

Since we observe a negative correlation between class size and collaborative learning opportunities (r = -.50, p = .010), we apply our equity models to see if class size is playing a role in these gender gap reductions.

Taking an equity of individuality perspective, we find that correlations between class size and normalized gains are moderately negative and not statistically significant (r = -.31, p = .12 for men, r = -.35, p = .07 for women). From an equity of fairness perspective, we find no difference between the class size correlations for men or women's normalized gains (p = .90) [134]. These moderate negative correlations between class size and normalized gains for men and women suggest that smaller classes may have benefited both genders. However, when we control for collaborative opportunities, the partial correlations between class size and normalized gain drop to r = -.07 (p = .76) for men and r = -.05 (p = .81) for women. These results suggest that there is no direct connection between smaller class sizes and increased gains for men or women.

From an equity of parity perspective, class size does not correlate significantly with a direct gender gap reduction (r = -.25, p = .20), a reduction in the gap's effect size (r = .06, p = .75), or a reduction in the normalized gender gap (r = -.12, p = .56). These small statistically non-significant correlations suggest that class size does not play a substantial role in promoting equity of parity.

Probing the class size question further, we ask: Is it really possible to achieve higher gains in large IE2 courses than small IE1 and IE0 classes? We compare the five large (>200 students) IE2 courses to the six small (<200 students) IE1 and IE0 courses. Men's normalized gains are .48±.09 in the small IE1 and IE0 courses and

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.54±.03 in the large IE2 courses. Similarly, women's normalized gains are .42±.08 in the small IE1 and IE0 courses and .48±.03 in the large IE2 courses. Though our small sample size makes statistical significance difficult to attain, we find the same patterns as those observed among all the courses: IE2 courses yield higher gains for men and women than IE1 and IE0 courses, even in large IE2 classes.

This is not to say that class size is not important. Sheila Tobias describes class size not as a value on its own, but as a means for enabling instructors to use more innovative teaching strategies [135]. The negative correlation between class size and collaborative instructional strategies (r = -.50, p = .010) suggests that instructors may be more likely to implement multiple community-building activities in smaller classes (likely due to easier facilitation of these activities in small classroom environments). Therefore, small classes may be instrumental in enabling instructors to use the collaborative instructional strategies that can promote equity.

Applying equity models to investigate the zero-sum perspective

A naive interpretation of our equity of parity results—modest reductions in the gender gap for IE2 courses over IE1 and IE0 courses—might assume that IE2 courses favour women at the expense of men. However, an investigation in equity of fairness models suggests this is not the case. Women do not have higher normalized gains than men in any course type. The greatest inequity of fairness instead is found with IE1 courses, with women having significantly lower normalized gains than men in these courses.

Furthermore, from a male equity of individuality perspective, while we marginally did not observe statistical significance in men's normalized gains for IE1 courses over IE0 courses, the effect of this difference was large (p = .072, effect size r = .85).

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Furthermore, we found that men's normalized gains were significantly higher in IE2 courses over IE0 courses (p = .049, r = .91), though not in IE2 courses over IE1 courses (p = .21, effect size r = .28).

These results, in conjunction with the women's equity of individuality results discussed above, show that courses that apply community-building instructional strategies tend yield higher normalized gains than traditional courses for both men and women. This is in line with literature showing that active engagement instructional strategies yield higher normalized gains than traditional lecture-based teaching for all students [4].

Our data suggest that, contrary to a zero-sum perspective on the reduction of the gender gap in physics, courses that promote equity benefit both women and men. We propose that these non-gendered benefits come from i) the increased gains in fully transformed courses that are well-established in the literature [4] and ii) the increased contributions of women in these courses. By enabling women to identify with physics and develop a stronger understanding of Newtonian mechanics, these IE2 courses may be more able to delve into additional nuanced physics discussions since students (both men and women) can better support each other.

It is our hope that these results may address some of the prejudices that can surface in equity discussions [3] and demonstrate that men need not feel threatened by women's increasing success in physics. Both men and women benefit from a collaborative and—perhaps more importantly—equitable classroom environment.

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Case study: An IE2 course at our institution

Our meta-analysis reveals that IE2 courses make steps toward increased equity. Here, we provide a case study of one IE2 course at our institution to illustrate the potential role of community-building instructional strategies in one course context.

This calculus-based introductory physics course for physics majors consisted of 3 one-hour lectures per week. Just-in-Time Teaching [136] and Peer Instruction [62] were applied extensively in lectures. Students also participated in weekly 1.5 hour laboratories (traditional labs in the first semester followed by an inquiry-based lab in the second semester) and weekly 1.5 hour collaborative problem-solving recitation sessions [137]. Outside of class, students completed weekly problem sets, on which they were encouraged to work in groups during a class office hour, where the professor was available for extra help.

For students who wrote both the pretest and posttest, the pretest direct gender gap was initially 13±6% ($p = 0.048$) with men scoring 71±4% and women scoring 58±5%. However, following twelve weeks of this fully-collaborative instruction, the direct gender gap was reduced to 6±5% ($p = 0.31$), with men scoring 85±3% and women scoring 79±4%. The pretest normalized gender gap of .20 was reduced to a posttest normalized gender gap of .07, and the gender gap effect size was reduced from .70 to .31.

Since the posttest scores were quite high, we initially hypothesized that this gender gap reduction was merely the result of ceiling effects. However, if that were the case, we would expect to see the gender gap return on harder tests (midterms or exams) or in second semester measures of conceptual understanding, where the mean score was much further than one standard deviation from 100%. We tested students'

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second term conceptual understanding using the Conceptual Survey of Electricity and Magnetism (CSEM) [138]. We found that the gender gap was not statistically evident on many measures of conceptual understanding and problem solving ability as shown in Table 3.5.

Table 3.5: No statistically significant differences were observed on further assessments

	S_M (%)	S_F (%)	p	d
October Midterm	72 ± 3	72 ± 4	.93	.026
December Exam	61 ± 3	62 ± 3	.95	.021
February Midterm	70 ± 4	75 ± 3	.45	.23
April Exam	58 ± 4	58 ± 4	.98	.007
Weekly Quizzes	85 ± 2	83 ± 2	.64	.15
Final Grade (April)	71 ± 3	73 ± 2	.64	.14
January CSEM	42 ± 3	39 ± 3	.56	.18
March CSEM	67 ± 3	61 ± 3	.22	.38

We hypothesize that these gender gap reductions occurred because this fully-collaborative classroom fostered an inclusive environment where both men and women could identify with physics through equal participation with a community of practice. We therefore qualitatively describe how Wenger's three modes of belonging to a community of practice—engagement, imagination, and alignment—might have been encouraged in this course context.

Engagement with a physics community of practice was encouraged from the first day of class. As students entered the first lecture, the professor asked students to sit in a particular location based on their residence and encouraged them to get to know each other in these groups. For the rest of the year, Peer Instruction then occurred in

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groups comprised not of strangers, but of friends. Students built meaningful, supportive relationships with each other, both inside and outside the physics classroom. This implementation of Peer Instruction followed Kreutzer's recommendation, "affirming domain belongingness in women" to reduce stereotype threat [64].

Imagination occurred as students engaged with their learning communities. In this low competition environment (where stereotype threat is reduced [35, 105]), women were able to better identify with physics. Students were also shown a less stereotyped picture of who a physicist is. Most lectures started with a brief description of a current male or female physicist and his/her work, including non-traditional physics-related careers. By reducing the stereotype threat that could inhibit women's identification with physics, and by reminding students of alternatives to the dominant masculine stereotypes of physicists, we hypothesize that women were better able to identify with physics and were therefore more successful in this class.

Alignment with a physics community of practice occurred as students contributed to their learning teams. During weekly collaborative problem-solving recitations, the teaching assistant directly taught students to value different perspectives by using stories of successful physics teamwork and by encouraging students to look for alternate viewpoints during problem solving. This supports Kreutzer's application of wise schooling, in which "valuing multiple perspectives" is an important component of stereotype threat reduction. Similar alignment occurred during Peer Instruction in lectures. Peer Instruction provided students with timely formative feedback from their peers, allowing students to adjust their conceptual understanding and align their ideas with those of their community.

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3.5 Summary

For decades, educators have expressed concern with sociocultural factors that inhibit women's participation and success in physics [12]. However, despite significant attempts to reduce these barriers, the gender gap has stubbornly remained, as an unseemly fixture in the introductory physics classroom [8, 9, 61, 59]. Stereotypes—both about women and about physics—can inhibit women's identification with physics. Women's depressed physics identities can translate into lower conceptual understanding and lower retention in physics programs.

We found that physics identity played a significant mediating role in gender gaps both in conceptual understanding and intention to pursue a physics degree. Engagement with a physics community of practice correlated with higher physics identities for both genders, with particularly high correlations for women. Therefore, we hypothesized that community-building instructional strategies might create inclusive environments where women could better identify with physics.

To test this hypothesis, we performed a meta-analysis of 26 classes from seven quantitative studies of the gender gap in Newtonian mechanics conceptual understanding. Examining the gender gap from an equity of individuality perspective, we found that increased opportunities for collaboration were correlated with increased conceptual understanding for both genders. From an equity of parity perspective, we found statistically significant reductions in the direct gender gap, the normalized gender gap, and the gender gap effect size in IE2 courses. In contrast, the direct gender gap and its effect size showed no statistically significant reductions in IE0 or IE1 courses. The normalized gender gap was reduced in IE1 courses, though this reduction was significantly less than the reduction of the normalized gender gap in IE2

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courses. From an equity of fairness perspective we found that though women gained less than men in both IE1 and IE2 courses, IE2 courses came closer to achieving equity of fairness. In general, we found that courses that applied many community-building instructional strategies made greater steps towards gender equity.

The results of this meta-analysis suggest that community-building instructional strategies—inclusive environments that can reduce stereotype threat and enable women to identify with physics—may contribute to reducing the gender gap in introductory physics. However, inherent to any meta-analysis is the risk of publishing bias, where certain desirable results may be more likely to be published than undesirable results. While noting this concern, we propose that trends within published data—illustrating steps towards parity in many IE2 courses across several different institutions—suggest that collaborative instructional strategies have potential for reducing the gender gap. Furthermore, this interpretation is supported by research on stereotype threat and identity development in communities of practice as described in Section 3.2. Further research on a large randomized sample of IE0, IE1, and IE2 courses would provide greater clarification of our findings.

Contrary to a zero-sum perspective on the gender gap, we found that collaborative courses made strides towards reducing the gender gap while improving conceptual understanding for both women and men. We hypothesize that men's improved normalized gains in more equitable courses stems both from the well-established success of active engagement for all students' learning [4], and from the increased contributions of their empowered female peers. We anticipate further research to make greater strides toward improved equity in introductory physics while benefiting both genders.

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From instructional strategies to instructor development

As Chapter 3 illustrates, community-building instructional strategies not only outperform the traditional lecture in terms of normalized gains for all students, but these collaboration-focused courses can also make progress towards reducing the gender gap in introductory physics. However, these instructional strategies can only support students in introductory physics if instructors can effectively apply them. In Chapter 4, we describe our research on professional development for teaching assistants who lead introductory physics tutorials. Here, we apply our identity framework to a new context: helping TAs become teaching professionals.

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Chapter 4

TA professional development

Transforming physics educator identities:

TAs help TAs become teaching professionals

Abstract: Professional development programs for graduate TAs can motivate the up-take of research-based pedagogies and subsequent enhanced student learning experiences. However, a lack of TA buy-in, tight finances, and time constraints often limit the effectiveness of these programs. We apply Wenger's communities of practice framework to address these concerns through the development of TAs' physics educator identities in a low-cost, time-efficient professional development intervention. Following our intervention, we observe statistically significant improvements in TAs' identification as physics educators ($p = .031$, effect size $r = .51$). While we did not, on average, find statistically significant changes in TAs' approaches to teaching, our qualitative analyses illustrated dramatic improvements for some TAs and pointed to sponsorship, support, and recognition structures for guiding and enabling TA communities to further TAs' adoption of student-centered approaches.

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4.1 Introduction

Decades of physics education literature have established the success of research-based instructional strategies over traditional lecture-based methods for dramatic improvements in student learning [4, 62, 128, 139, 140]. Interactive student-centered strategies (through which the instructor guides students in changing their conceptual understanding) yield significantly higher learning gains than traditional teacher-centered approaches (through which the instructor merely endeavours to transfer information to students) in many disciplines [141, 142] including physics [143, 144]. However, despite attempts by physics education researchers to disseminate these results, low adoption of research-based pedagogies among faculty [145] and graduate teaching assistants [146] remains a significant concern.

As physics education undergoes reform, graduate teaching assistants (TAs) are a natural target group for assisting in the adoption of student-centered instructional strategies. TAs directly support today's students in tutorials[1] and recitation sessions [41, 42]. Furthermore, during teaching assistantships, TAs learn the teaching approaches that often guide their teaching development and future careers [43, 44].

4.1.1 Why change TA professional development?

One we might expect that TA professional development is well served simply through teaching experience and optional teacher training. This philosophy underlies a common practice for TA professional development, which was in place at our mid-sized

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[1] In this paper, we use the term 'recitation' rather than 'tutorial' to describe a TA-led weekly session focused on problem solving. We choose this definition to avoid confusion with the McDermott and Shaffer *Tutorials in Introductory Physics* [63].

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Canadian university. In this practice, TAs have access to many optional non-discipline-specific teaching workshops, often offered through a university-wide Center for Teaching and Learning. Nearly all physics graduate students at our institution also attend an optional three-hour department-run TA orientation in their first year of graduate studies. TAs in our department have considerable opportunities for experiential learning about physics teaching: TAs typically gain 216 contract hours of teaching experience per year.

Unfortunately, our data suggest that this practice—providing TAs with teaching experience and optional training—does little to develop confident student-centered TAs. When we surveyed 42 physics TAs with zero to six years of teaching experience using measures described in Section 4.3.2, we found statistically non-significant bivariate correlations between TAs' years of experience in teaching and their student-centered approach ($r = -.16$, $p = 0.32$), teaching self-efficacy ($r = -.18$, $p = .26$), and physics educator identity ($r = -.07$, $p = .67$). These negative Pearson correlation coefficients suggest that even if statistical significance could be obtained with a larger sample, the result might only be more discouraging—increased teaching experience might then correlate with reduced student-centered teaching, confidence, and teacher identity. These concerning results, along with prior research [147, 146], suggest that the common practice of providing TAs with teaching experience and access to optional training is not sufficient for developing student-centered teachers.

4.1.2 Barriers to changing TA professional development

Professional development has been found to help TAs become more student-centered and less teacher-centered in their teaching approach [148, 149, 150]. One large study

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across 22 universities found that faculty, who were involved in sustained 60 - 300 hour teaching professional development programs spread over periods of 4 - 18 months, became significantly more student-focused and less teacher-focused (as measured by the Approaches to Teaching Inventory [151]). In contrast, a control group became more teacher-focused and less student-focused after a year of teaching without professional development [147]. With such a significant impact on teaching approach, it is not surprising that teacher professional development programs have profound positive results for student learning [152].

TA professional development shows promise for increasing the adoption of student-centered approaches to teaching; however, several obstacles limit the success of these professional development programs [153, 154]. Three common barriers to implementing TA professional development include:

- **Financial constraints:** With tight finances, adding 60 - 300 professional development hours to TA contracts may not be feasible for many departments. In our context, TAs are unionized and contract hours are limited by financial resources.

- **Time limitations:** A lack of teacher time is a significant barrier for both professional development [155, 156] and the continued use of research-based pedagogy [40]. Our intervention needed to fit into the previously allotted preparation time in the TAs' contracts, and it could not significantly increase the amount of time spent by course instructors.

- **TA buy-in challenges:** This frequently cited barrier includes instructors' tendencies to underestimate i) the effectiveness of active engagement techniques, ii) the importance of developing teaching skills, and iii) the applicability of the

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professional development program to their own teaching [153]. In our intervention, we needed TAs to become convinced that research-based pedagogies were worth learning about and using in their recitation sessions.

Offering professional development within the boundaries set by these financial and time restraints required a creative approach. However, the most challenging issue for our context was a lack of TA buy-in. The literature illustrates the complexity of this barrier. Even requiring TAs to perform prescribed research-based activities is not sufficient. Prior research demonstrates limited success for TAs who simply performed prescribed activities without truly buying into the research-based teaching strategies they were required to use [6, 7]. To address these barriers, we turned to psychology and sociology literature to help us build a low-cost, time-efficient professional development program that targeted TA buy-in.

4.1.3 Need for a teacher identity development framework

A key factor in a TA's decision to buy into research-based pedagogies is the TA's identity as a physics educator. Professional development that is focused solely on teacher competencies—specific research-based instructional strategies that a teacher applies—is not sufficient to create or even define 'good teachers' [157]. Underlying educator competencies are teacher beliefs, which promote or inhibit the development of different teacher competencies [157]. In the same way that we attend to the background knowledge of students when we teach physics, we need to address the beliefs that new teaching assistants bring to the table [158].

Going one step further, these teaching beliefs are then informed by the teacher's

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identity [157]. According to Hamachek, "Consciously, we teach what we know; unconsciously, we teach who we are" [159]. The goal of professional development that TAs can buy into is therefore much more than simply transferring knowledge of good teaching strategies; it involves the development of positive teacher identities [160].

The process of changing teacher identity and thereby fostering TA buy-in is inherently complex as it deals not only with what a teacher does, but who a teacher is [161]. Therefore, in order to develop a TA professional development intervention that could promote identity development, we require a theoretical framework dealing with the psychology and sociology of identity formation. We integrate Wenger's widely recognized concept of communities of practice [46] with Côté and Levine's personality and social structure identity perspective [162] to better understand identity change in the context of TA communities. In this chapter, we outline this theoretical framework, describe its application in a professional development intervention for TAs, and interpret the results of this intervention.

4.2 Practical framework for building teacher identity

Devoting attention to the person—who a teacher is and desires to become—is crucial for changing what a teacher does and how he/she does it. Etienne Wenger asserts that, "Because learning transforms who we are and what we can do, it is an experience of identity. It is not just an accumulation of skills and information, but a process of becoming" [46]. Therefore, we based our TA professional development intervention on the perspective that TAs are learning to *become* teaching professionals.

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Identity is both individual and group-based [163]. Individual and group aspects of identity exist in dynamic equilibrium where social structures form personal identities, and these personal identities in turn shape social structures [164]. Côté and Levine's personality and social structure identity perspective describes this dynamic equilibrium as facilitated through day-to-day interactions with others [162]. This framework, adapted for the specific context of TA professional development, is illustrated in Figure 4.1. Teacher identity is developed as TAs continually transition around this loop, changing both themselves and their social structure.

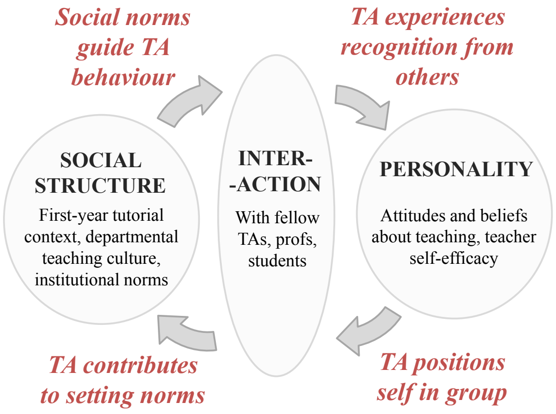

Figure 4.1: Côté & Levine's Personality and social structure perspective adapted for a TA professional development context [162, 163].

4.2.1 Communities of practice in identity development

According to Wenger's communities of practice framework, the identity transformation shown in Figure 4.1 occurs through participation in a community of practice [46]. Prior work with undergraduate learning assistants has found that participation

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in a learning assistant community of practice can positively impact the undergraduate student's physics identity [165]. This model has also been successfully applied to general teacher training contexts [166, 167].

To better understand the role of communities of practice in identity development, we divide Côté and Levine's loop into (roughly) two branches. The lower branch (from personality to social structures through interaction) deals primarily with a TA's action of *belonging* to a community of practice [163]. The upper branch (from social structures to personality through interaction) focuses on the enabled community's *structure* to shape the TA.

TAs belong to a community of practice

Wenger proposes three modes of belonging to a community of practice: engagement, imagination, and alignment [36]. On the lower branch of Figure 4.1, engagement and imagination occur in the first transition between personality and interaction, where the TA positions him/herself in the community [163]. Alignment includes this first transition, but also extends to the next transition between interaction and social structures, where the TA contributes to defining the community.

- **Engagement:** TAs participate together in meaningful and consistent activities to develop a commitment to learning about teaching and to each other. These engaging activities challenge the TAs to use their shared histories of learning, including their experiences as both teachers and students [168], to explore new ideas about teaching.
- **Imagination:** TAs create an image of themselves as a member of the physics teaching community.

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- **Alignment:** TAs not only adopt teaching methods and beliefs that align with the physics education community; they also contribute to that teaching community [46]. For example, this alignment was observed in a learning assistant training program where undergraduate learning assistants not only adopted research-based pedagogies, but also became instrumental in changing faculty norms and inspiring faculty to pay closer attention to student learning [44].

In a teaching community that supports research-based pedagogies, TAs can develop physics educator identities as they engage with the community, imagine themselves as physics educators, and align their practices to those of their physics teaching community.

These communities of practice often develop naturally, with or without administrative guidance [46]. Inherent in the concept of communities of practice, therefore, is the possibility that some communities could choose negative norms—such as a distrust of research-based pedagogy or a disinterest in student learning. The same processes that encourage TAs to identify with positive physics education communities could cause TAs to identify with undesirable norms if they belong to a negative community of practice. Not surprisingly, concern with the impact of these negative teaching cultures has been voiced in the literature [169]. Therefore, it is crucial that we also consider which community structures will guide TA communities in developing positive physics educator identities.

Enabled communities of practice shape TAs

Communities of practice can be shaped by enabling structures [170] so that the community can better define the desired norms and competences for its members [46].

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Wenger promotes sponsorship, support, and recognition structures for enabling communities of practice [171]. Course instructors and administrators have an important role in setting these enabling structures. Sponsorship structures highlight the value of TAs' contributions to defining community norms, as seen in the lower branch of Figure 4.1. This concept of sponsorship is in conflict with a traditional hierarchical model of TA training, in which the course instructor dictates the TAs' role. Support structures bring us to the upper branch of Figure 4.1, where support enables TAs to successfully adopt the active learning strategies promoted by the community. Finally, recognition structures fill the last transition from interaction to personality in the upper branch of Figure 4.1. We adapt these enabling structures in the context of TA professional development as follows.

- **Sponsorship:** The course instructor treats the TA as a teaching professional by including the TA in the process of determining how the recitations should be structured. Administration legitimizes the TAs' ability to solve education challenges by encouraging TA communities to seek creative solutions to difficulties they encounter in their classroom.

- **Support:** TAs support each other by sharing ideas and resources in communities of practice. The course instructor or TA training facilitator provides practical support through easy access to active engagement tools such as context-rich problems or mini-whiteboards. See the Appendix for further description of active engagement tools.

- **Recognition:** TAs celebrate their colleagues' effective student-centered teaching. The course instructor and department provide meaningful performance

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appraisals for TAs that recognize each TA's success beyond his/her own classroom.

We apply this framework to develop an intervention that specifically addresses our most significant barrier to successful professional development: hesitant TA buy-in. Prior research suggests that the social and environmental context for TA development has a profound impact on TA buy-in to research-based pedagogies [6, 172]. Therefore, we hypothesize that a TA professional development intervention based on physics educator identity formation in a community of practice—a process that changes both the individual and the social structure—might help TAs buy into research-based pedagogies and identify as physics educators.

4.3 Methods: Developing and measuring physics educator identity

We applied our physics educator identity development framework of Section 4.2 to create a 12-hour professional development intervention spanning one semester, working with ten TAs in communities of practice.

These TAs taught recitation sessions in four different introductory physics courses—an algebra-based course for life science majors and calculus-based courses for physics majors, engineers and other science majors. The recitation structure varied across these classes, ranging from 1.5 hour slots each week to 2 hour slots every other week. The number of attending students in these recitation sessions varied from ~5 to ~60 students per section. One recitation section of ~30 students was co-taught by two TAs, whereas all other sections were taught by a single TA. Teaching experience for the

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TAs in our study ranged from 0 to 6 years with an average of 2.5±0.7 years.

Addressing each of the three barriers identified in Section 4.1.2 was an important element in the design of our professional development intervention. In order to fit within tight financial constraints on TA contract hours, we reassigned one hour of TAs' preparation time per week (12 hours in total) to weekly community meetings. Since these meetings replaced TA prep time, it was essential that they be designed to prepare research-based activities specifically for each week's recitation section. The facilitator only encouraged research-based pedagogies that could be implemented within tight financial and time constraints. Since this professional development was done by and for TAs, the course instructors did not allocate significant amounts of extra time to the project. We also respected the TAs' limited time by ensuring that each weekly community meeting was always slightly shorter than the allotted hour.

We addressed our most challenging barrier, TA buy-in, by focusing our intervention on physics educator identity development in a community of practice (framework outlined in Section 4.2). We applied this framework to create a professional development intervention that we hypothesized would specifically target physics educator identity.

4.3.1 From framework to intervention: TAs help TAs in a community of practice

We formed four communities of practice for TAs—one for each of the four introductory physics courses. The stated purpose of each meeting was to prepare specific content and student-centered techniques to teach that content for the upcoming recitation session. The underlying purpose of each meeting was to encourage the TAs to belong

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and contribute to a community of professional teaching practice. The first author, who was also a graduate student and a previous TA for first-year physics recitations, planned and facilitated these meetings.

Wenger's framework for building successful communities of practice highlights the importance of support. In this context, support included physics content and active engagement tools. Because the weekly community meetings were intended to replace the preparation that TAs would normally do on their own, the content was directly related to the upcoming week's recitation. The decision to include specific physics content in these weekly meetings was supported by literature that promotes the integration of discipline-specific content and pedagogy in teacher training [173, 174]. The facilitator brought a mini-whiteboard to each meeting, and the TAs worked through the aspects of that week's recitation problems where student misconceptions were most likely to arise. Due to limited time and out of respect for TAs who might resent solving an 'easy' physics problem fully, time was focused on how to teach the hardest concepts. Context-rich problems and/or conceptual questions for Peer Instruction (see Appendix) were supplied by the course instructor, developed by the TAs during the weekly meetings, or provided by the facilitator. Active engagement tools for classroom use such as flash cards or mini-whiteboards were supplied by the facilitator.

In light of Wenger's emphasis on the sponsorship of TAs in communities of practice, and consistent with literature that demonstrates the value of group teaching discussions [175] and peer mentoring [176], each weekly meeting was driven by TA feedback. TAs shared their concerns and teaching ideas with each other, reflecting on the previous week's recitation session as teaching professionals. The facilitator and

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other TAs endeavoured to provide respectful suggestions of specific research-based pedagogies that addressed concerns raised by each TA. For example, one TA shared his frustration that the students seemed to follow his work when he solved a problem on the blackboard, but could not solve a similar problem on their own. The facilitator used that frustration to emphasize the value of learning by doing rather than watching, and offered to help the TA try collaborative problem-solving groups. Fellow TAs offered their ideas and experience to help find creative solutions to the challenges that were raised in these meetings.

Collaborative problem-solving and Peer Instruction were the main research-based strategies promoted in these weekly meetings. Brief descriptions of collaborative problem-solving and Peer Instruction can be found in the Appendix. These active engagement techniques were chosen because of their versatile nature, low cost of implementation, minimal extra time needed to adapt from a traditional recitation, and their strong backing in physics education literature [177, 55, 62, 178, 179, 180, 181, 182].

In designing appropriate interactions to address Wenger's recognition structures and facilitate identity development, we used past work that demonstrated the effectiveness of peer review for teacher improvement [183]. The facilitator attended several recitations to observe how the adopted research-based pedagogies were being implemented or not implemented. The facilitator provided both encouragement and feedback to each TA individually immediately after the recitation and in general at the following week's community meeting. This feedback was constructive and formative with no connection to formal TA evaluations or future employment opportunities. By sharing the specific TA actions that worked to engage students and those that

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did not, the TAs could fine-tune their individual approach and borrow successful strategies from each other.

4.3.2 Mixed methods research approach

We measured each TA's approach to teaching, application of active engagement techniques, teaching self-efficacy, and physics educator identity on pre-intervention and post-intervention surveys. The Approaches to Teaching Inventory is a well-validated instrument consisting of two five-point Likert-type scales [151]. The first scale measures an instructor's information-transfer, teacher-focused approach. This scale consists of eight items and indicates the extent to which the instructor approaches teaching as a 'sage on the stage', delivering content to the students. The second scale measures an instructor's conceptual-change, student-focused approach. It consists of nine items and describes the degree to which the instructor approaches teaching as a 'guide on the side', helping students assimilate knowledge [184]. These scales are available in Appendix 1 of Trigwell and Prosser's 2004 paper [151].

To probe further into the application of TAs' approaches to teaching, we developed a short 4-item active engagement scale to gain a better sense of whether TAs were directly applying research-based instructional strategies in their teaching. Cronbach's alpha for this scale was 0.59, indicating a moderately low reliability for this scale. We expect this low alpha is partially due to the small number of items on our scale, but largely due to the varied nature of the items. Scale items named specific instructional strategies (such as Peer Instruction or collaborative problem-solving teams), and in many cases TAs applied one but not both of these strategies.

In our post-intervention survey, we added an additional scale to measure TAs'

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engagement with their weekly community meetings. It included 6 items on a 7-point Likert-type scale that addressed the TAs' perceptions of the current and future benefits of the weekly meetings. Cronbach's alpha for this scale was 0.87, indicating a good reliability for the items on this scale.

Physics educator identity was measured along with physicist identity. TAs responded to the two statements "I consider myself to be a physicist." and "I consider myself to be a physics educator." on a 7-point Likert-type scale from "strongly agree" to "strongly disagree". We also examined TA self-efficacy using a scale adapted from a prior Personal Teaching Efficacy scale [185] and the New General Self-Efficacy Scale [114]. Six items from these scales were adjusted to specifically apply to the task of teaching physics recitation sessions and scored on a 5-point Likert-type scale. Cronbach's alpha for this adjusted scale was found to be 0.76, indicating reasonable reliability of the items in this scale.

In order to better understand the TAs' perspectives [186] on their engagement with communities of practice, changing identities in those communities, and alignment with student-centered approaches, we turned to qualitative research methods. The facilitator took field notes during and immediately following pre-semester meetings with course instructors and weekly community meetings for all four TA communities. The facilitator attended one of each TA's recitations between weeks three and six to take further field notes. If a TA indicated that he/she had changed his/her practices, a second recitation was observed. Positioning of students and TAs in recitations was noted along with quotes and detailed interactions between students and TAs. At the end of the semester, eight TAs participated in 15-20 minute interviews. The TA interviews were recorded and directly transcribed. The transcribed texts were

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then decontextualized [187] and coded by the primary researcher and an external researcher to reduce bias. Rather than using predefined codes, both researchers reviewed the interviews independently and proposed emergent codes that reflected the themes highlighted by the TAs. The researchers then met and used these codes to organize and recontexualize the data in order to understand the relations between the themes raised by the TAs and previous literature.

This study received ethical approval from the General Research Ethics Board at Queen's University prior to beginning research. All participants provided their consent after receiving letters of information that detailed their voluntary participation, option to withdraw at any time, potential benefits and risks, expected time commitments, procedures for securing confidential data, and the contact information of the primary researcher and General Research Ethics Board.

4.4 Results

We assessed the effectiveness of our professional development intervention through the lens of the identity development framework described in Section 4.2. We examined the role of Wenger's three modes of belonging—engagement, imagination, and alignment—in TAs' development as teaching professionals. Finally, we explored the need for sponsorship, support, and recognition structures to guide communities of teaching practice not only at the level of our intervention, but also at the department and university-wide level.

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4.4.1 Engagement: TAs participate with their community

Engagement with a community of practice, Wenger's first mode of belonging, was essential for our intervention. Since our intervention was structured around weekly community meetings, engagement with these communities was crucial for the success of our intervention. The first questions we sought to answer were: Did the TAs in our study engage with their community of practice? Why did they appear to be engaged or not engaged?

Quantitatively, TAs rated helpfulness of the meetings as a 5.6 ± 0.3 on a 7-point Likert-type scale on the post-semester survey. This suggests that on average, TAs 'moderately agree' to 'agree' that the weekly meetings were beneficial for their current and future teaching. In our qualitative research, we probed further to understand why some TAs chose to engage with their community to different extents than others. During the post-semester interviews, we asked TAs to share the pros and cons of our weekly team meetings. The responses were surprisingly varied; though many of the TAs engaged with their community, they did so for different reasons. Here we summarize the reasons expressed by TAs for engagement with weekly community meetings.

The value of shared experience led some TAs to engage with our weekly meetings. One TA in his first year of teaching told us, "There was a wealth of experience in that room and having access to that was definitely helpful." Another TA in his sixth year of teaching shared, "I really liked... having someone to... check what I'm doing—some[one] to bounce my ideas off of. Because in the past, I would have another TA in the class, but we wouldn't talk about anything." The benefits of sharing experiences and discussing teaching plans with their peers were a common

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theme in TAs' responses, regardless of the TA's level of experience.

Other TAs chose to engage because they appreciated the specific research-based pedagogies provided by the facilitator and their peers. One TA noted that "The [Peer Instruction] questions [the facilitator] prepared and discussing about them—I found that was very, very useful." Another TA mentioned that she appreciated learning about collaborative problem-solving teams: "I really liked the suggestion of the whiteboards." The chance to anticipate student misconceptions led other TAs to engage with their community. One TA found the meetings helpful because it was "good to spot potential problems before they [came] up in class."

We anticipated that the opportunity to share experiences and learn useful pedagogy techniques would encourage TAs to engage with their communities. We were surprised, however, to find that other TAs found the most helpful part of our weekly meetings to be the reassurance that it is okay to not have all the answers to physics and teaching questions. One TA shared, "Sometimes I was... unsure, and I'd be like, 'Oh, I'm stupid for not knowing the answer.' But then I would realize that... [another TA in the group] didn't know the answer either, so that made me feel better." Another TA noted, "I found what was useful was that I could come and ask ... questions [about physics content]." These TAs highlight a subtle unexpected advantage of putting a fellow graduate student, rather than a professor, in the meeting facilitator role. It was not uncommon for a TA to confuse a fundamental concept. While it might be embarrassing for a graduate student to ask a question about introductory physics content in front of a professor, the TAs felt more comfortable discussing these tough concepts with their peers.

Another advantage of filling the facilitator role with a peer was the prompting

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of critical thinking. A naive interpretation of Wenger's enabling structures might suggest that strong direction from a course instructor would be essential for guiding TA communities. Therefore, we initially regretted the lack of course instructor time, assuming that having an expert professor at these weekly meetings could have helped convince TAs to adopt research-based pedagogies. While course instructors do play an important role, the presence of an instructor in each meeting could have in fact stifled TAs' contributions to their community of practice. This effect could be analogous to the student who simply copies what an instructor writes on the blackboard without thinking critically about its application. However, when students teach each other, they are often suspicious of their peers' answers and think critically about what they are learning. Similarly, in our intervention, the facilitator had credibility as an experienced first year recitation TA and physics education researcher, but as a peer and fellow graduate student, she had no authority to persuade TAs to adopt research-based pedagogies. This encouraged TAs to question the student-centered approaches she suggested, and may have led to deeper critical thinking about teaching as a professional activity.

Some TAs did not appear to be engaged during weekly community meetings. Interestingly, however, the TAs who considered the meetings to be unhelpful specifically mentioned the value of their TA community outside of these meetings. As one TA shared, "[the meetings weren't] that useful for me because all the TAs for this course are really really close anyways... I can see [if the TAs were not already close friends], that it would be pretty useful to share ideas."

However, other TAs, who were good friends prior to our intervention, still found that forming a community of practice—one specifically focused on their TA work—was

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beneficial for them despite their prior peer connections. One of these TAs compared his experience in a TA community with peers to his other TA experience: "[It is helpful] just having someone to either call you on something that isn't going to work or to reinforce, 'Yeah that is probably a good thing to try.' For instance, this term, I'm doing a tutorial and ... it's just my tutorial and I plan the whole thing, and sometimes I don't know if I'm going to go in and just have blank faces or just totally miss the mark." Though this TA already knew his teaching community well, he still valued time designated specifically to talking about and improving his teaching. In general, we observed a moderate to strong level of TA engagement with their communities of practice—either during the weekly meetings or outside of the meetings. This engagement with a teaching community supported the development of the TAs' physics educator identities, as we will describe in the following section.

4.4.2 Imagination: TAs develop physics educator identity

Imagination is a pivotal mode of belonging in Wenger's communities of practice model. As outlined in Section 4.2.1, imagination refers to the process of TAs creating an image of themselves as a member of the physics teaching community. Though teacher identity is developed through all modes of belonging, it is perhaps most evident here. We took particular interest in the TAs' self-identification as physics educators because prior work has shown the impact of identity on beliefs and buy-in to research-based pedagogies [157, 6]. We sought to answer two questions in this realm: First, did TAs' physics educator identities improve during our intervention? Second, how do TAs understand their changing teacher identity?

We addressed the first question quantitatively through pre- and post-intervention

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surveys. We found that the TAs' physics educator identities showed statistically significant improvement with a large effect size. To provide context, we also measured if TAs' physicist identities changed over the same time period. Not surprisingly, TAs' physicist identities did not change significantly from the beginning to the end of the intervention. Using the Wilcoxon signed-rank test to compare small samples of paired data that are not normally distributed, we found teacher identity improved from 4.5 ± 0.3 to 5.8 ± 0.5 on a 7-point Likert-type scale ($p = .031$ and effect size $r = .51$), as shown in Figure 4.2. In contrast, we found that TAs' identification as physicists did not change significantly—from 5.7 ± 0.3 to 5.8 ± 0.4 on a 7-point Likert-type scale, ($p = .655$, effect size $r = .11$) as expected.

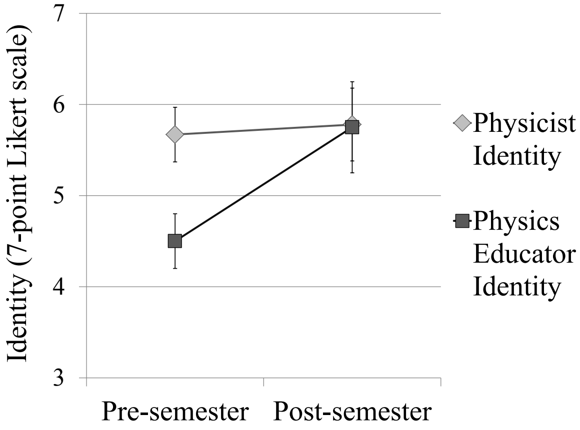

Figure 4.2: Physics educator identity showed statistically significant improvement while physicist identity, not the target of the intervention, remained relatively constant.

The quantitative increase in teacher identity surpassed our expectations for improvement. Therefore, we sought to better understand how TAs perceived their changing teacher identities through our qualitative interviews. One interviewed TA noted the connection between her improved teacher identity and her increased teacher

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self-efficacy. She attributed this change in identity and confidence to her interactions with the students. When asked if she identified herself as a physics teacher, she responded:

> **TA:** Actually, I do consider myself more of an educator now than I did last fall... I was actually thinking about this the other day. Last fall, I never would have considered [applying for a teaching position], but I have a lot more confidence now than I did before, so it was a no-brainer for me to want to audition.
>
> **Researcher:** What do you think changed it for you?
>
> **TA:** Part of it was the way we interacted with students this year in the tutorials. It was easier to engage the students this year. I'm sure it was partly due to the format we were using, and partly due to the fact that I simply had more experience.

Côté and Levine's personality and social structures perspective on identity development provides a framework for this TA's response. Identity is developed between personality and interactions with others (see Figure 4.1) as the TA positions him/herself in a particular role—in this case, the role of a physics educator interacting with students. This TA viewed the weekly team meetings not as a primary source of her increased teacher identity, but as a *resource* (through recitation format suggestions) to support the positive student interactions. She felt that these student interactions then built her identity, as is reflected in Côté and Levine's framework.

The picture of improved teacher identity is not entirely clear, however. Teacher self-efficacy, a contributor to teacher identity, changed for individual TAs, but on average remained constant over the course of our intervention at 3.9±0.2 on a 5-point

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Likert-type scale ($p = .52$). One potential explanation for this unexpected finding is that teacher self-efficacy began so high on the scale ('4' corresponds to 'agreement' with statements of confidence in one's teaching) that it had effectively plateaued prior to our intervention.

The qualitative interviews also suggested that while teacher identity did show statistically significant improvement, there still remained room for further identity development. When asked, "How *did* you learn to teach?" and "How *would* you learn to teach if you were to be a professor or have some teaching position in the future?" (emphasis added), TAs provided surprisingly dissimilar answers. All of the eight TAs interviewed stated that they learned their current approach from observing students, and four TAs added that they also learned their approach from their experiences as students themselves. However, when asked how they *would* learn to teach if they were in a teaching position in the future, only one TA mentioned student observations. Five TAs stated that they would access university teaching resources or colleagues to learn about teaching, three TAs stated that they would make use of physics education literature and conference workshops, and two TAs were not sure how they would go about learning to teach in the future.

This disconnect between present and future teaching could be partially due to the question order—perhaps TAs did not want to restate an idea they had previously mentioned. However, this discrepancy does suggest that the TAs still saw a substantial difference between the work they were currently doing as a TA and the work they would do as a 'real teacher' in the future. Therefore, we suggest that while TAs' teacher identity improved during this intervention, our TAs still have opportunities for growth in their physics educator identities.

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4.4.3 Alignment: Changing TAs' approach to teaching

Helping TAs identify as physics educators was a major accomplishment for us. Next, we sought to help our TAs align their practices with research-based pedagogies in their teaching communities.

In this arena, we sought to answer three questions: Does educator identity correlate with alignment with the scholarly teaching community, as suggested by Wenger's alignment framework? Second, did TAs in our intervention align their teaching practices with a more student-centered and less teacher-centered approach? Third, for what reasons did TAs choose to align or not align their actions with a teaching community of practice?

We investigated the first question with 42 graduate TAs at our university (including the ten TAs who participated in our intervention) by exploring the connections between teacher identity, self-efficacy, and teaching approach. We found that physics educator identity correlated with teaching self-efficacy ($r = .50$, $p = .02$), as expected from previous research [188]. Teaching self-efficacy also correlated with a conceptual-change, student-focused approach ($r = .49$, $p = .001$), but not with an information-transfer, teacher-focused approach ($r = .08$, $p = .47$).

Among the ten TAs who participated in our intervention, correlations between a student-centered teaching approach and the use of active engagement strategies were moderate, but marginally not statistically significant (Kendall's $\tau_b = .49$, $p = .06$). Kendall's τ_b was reported since the small sample of ten TAs was not normally distributed.

We found that pre-intervention physics educator identity and teacher self-efficacy were strongly predictive of active engagement applications. Bivariate correlations

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between pre-intervention physics educator identity and post-intervention active engagement application were strong ($r = .86$, $p = .006$ and Kendall's $\tau_b = .74$, $p = .02$). Bivariate correlations between pre-intervention self-efficacy and post-intervention active engagement were similarly strong ($r = .81$ ($p = .008$) and Kendall's $\tau_b = .54$ ($p = .04$). Further analysis of these correlations was required since teacher self-efficacy was connected to physics educator identity. When we controlled for pre-intervention teacher self-efficacy, we found that the partial Pearson correlation between pre-intervention physics educator identity and post-intervention active engagement remained strong and statistically significant: $r = .75$ ($p = .05$). When we controlled for pre-intervention physics educator identity, the partial correlation between pre-intervention teacher self-efficacy and post-intervention active engagement was reduced to $r = .67$ ($p = .10$). These results underscore the prevailing role of physics educator identity in predicting alignment with the use of active engagement techniques.

To answer the second question—did our communities of practice intervention help TAs to align their teaching practices with a more student-centered approach?—we explored quantitative and qualitative results. As shown in Figure 4.3, the Approaches to Teaching Inventory indicated a slight increase in TAs' student-centered, conceptual change approach and a small decrease in the TAs' teacher-centered, information transfer approach, but neither of these changes was statistically significant. The average student-centered, conceptual change approach was 3.6 ± 0.1 on the pre-intervention survey and 3.7 ± 0.1 on the post-invention survey as measured by a 5-point Likert-type scale ($p = .17$, effect size of $r = 0.33$). The average teacher-centered, information transfer approach was 2.9 ± 0.5 on the pre-intervention survey and 2.8 ± 0.5 on

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the post-intervention survey, as scored on a 5-point Likert-type scale ($p = .779$, effect size $r = .066$).

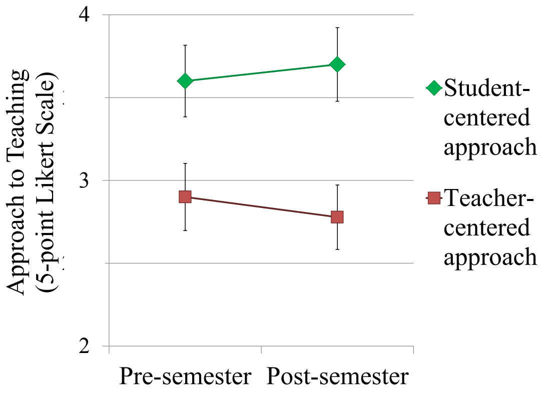

Figure 4.3: General trends in TAs' approaches to teaching suggested improvement, but were not statistically significant

Measures of the TAs' use of active engagement activities followed a similar trend to their student-centered approach. TAs reported that their use of active engagement teaching strategies was 3.8±0.2 on the pre-intervention survey and 4.2±0.2 on the post-intervention survey, as measured by a 5-point Likert-type scale ($p = .17$, effect size $r = .31$).

While we observed significant changes in the TAs' educator identities (Figure 4.2), we hypothesize that these changes did not have sufficient time to translate into modified TA actions and setting of norms as outlined in Figure 4.1. Such a change to actions required TAs to change their practices mid-term. An interesting follow-up study would be to examine TA practices in subsequent courses, now that they better identify as educators. Furthermore, the effect sizes of .33 for the change in TAs' student-centered conceptual change approach and .31 for the change in TAs' use of active engagement strategies suggest that statistically significant improvements might

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be observable with a larger sample of TAs.

Our qualitative data revealed that several TAs did adopt a more student-centered approach. For example, one TA, Alice [2], explained the student-centered approach she learned during our intervention.

> **Alice:** I think one of the main things I've learned is to let students talk more, and me talk less. Sometimes, there are these moments when I really want to help them, and explain or re-explain something to them. But if I hold myself back and give them a chance to think, they'll pipe up and make a connection that is really important on their own. You just have to give them the chance. If they are really stuck, they will ask you. But if you jump in and explain it, they won't gain any confidence in themselves, and gaining confidence is more than half the battle—as I've learned for myself too!

This TA felt that she experienced improvement as a teaching professional through our intervention; however, she entered our study with a teaching approach that was already quite student-centered. To demonstrate the dramatic change that occurred for some of our TAs, we present a case study of one TA, Tim, who began with a strong teacher-centered approach and made notable changes to adopt a student-centered approach.

Case study: Adoption of a student-centered approach

Tim was originally hesitant to align his practices with research-based methods, commenting in one of our early weekly meetings, "I don't want to use the whiteboards

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[2] Pseudonyms are used throughout this qualitative analysis

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because I got some positive feedback from the students last week, and I want to keep that going." For the first half of the semester, Tim took a fairly traditional approach to teaching recitations. He told the students to work individually on a specific problem for ten minutes, and then wrote out the solution on the board. During these ten minutes, some students attempted the problem, but many stared blankly at their pages, waiting for Tim to write out the solution. Few students were successful in finishing the problem. While Tim worked out the solution on the board, there was a noticeable disconnect between his understanding of what the students knew and what the students actually knew. At one point in his solution, Tim turned to the class to check for understanding:

> **Tim:** Is that clear why the force of friction is acting downward here?
>
> **Student:** (speaking softly) No.
>
> **Tim:** (nodding head) Yes?

Some students were frustrated with Tim's teaching and commented to each other that they didn't have to attend these recitation sessions. Approximately 10% of the students remained after class to ask Tim additional questions.

During the weekly meetings, Tim brought concerns regarding students who were not engaged or motivated in his recitations, and the TAs discussed strategies for improving student engagement and motivation. Despite his initial hesitation, seven weeks into the term, Tim decided he would try collaborative problem-solving in his recitation sessions. He started his class with a brief explanation of how these collaborative problem-solving teams would function (see Appendix for details). As the groups solved two context-rich problems, Tim circulated to the different groups, asking, "What are your first thoughts?" when a group looked quiet.

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For the first 30 minutes of class, 5-7 of the 30 students were not engaged in their group. However, when these students realized that Tim would not be taking up the solutions, only 1-2 students were not engaged in the second half of the recitation. Students asked each other basic questions that they might be embarrassed to ask a TA. For example, one student asked her peer if the free-body diagram showed the friction force of a spring, and her peer explained that the friction came from the table, since ideal springs do not involve friction. When the bell rang at the end of class, 90% of the students continued working on task until the room was needed for another class. After our weekly meetings ended, Tim continued to make use of collaborative problem-solving groups in his second semester teaching. Tim also continued to discuss his teaching with the facilitator and some members of his TA community after our weekly meetings ended.

Understanding inertia: Reasons for non-adoption of a student-centered approach

Though some TAs changed their teaching practices considerably, we also encountered considerable inertia; several TAs remained resistant to student-centered approaches. One TA, Sam, maintained the perspective that teaching was simply a matter of style choice. He felt that students appreciated his traditional lecture-based style, and chose to continue this approach. In his words, "It once again depends on the teacher's style... Some people may have inherent talent explaining things in a very clear way." Sam added, "[The students] really want me to do a couple of problems on the board."

Another TA, Zach, expanded on this belief that students prefer the traditional lecture. He also added the role of his prior beliefs about teaching to explain why he

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chose to continue using a teacher-centered approach.

> **Researcher:** What new teaching techniques did you try this semester? What worked, and what didn't?
>
> **Zach:** I tried the Peer Instruction stuff a bit. It didn't work that well... I guess I got discouraged on it, and I probably gave up a little too easy, to be frank. But I mean, when it worked a little bit, it was exciting. But I don't know, I just found my [students] weren't too excited about it.
>
> **Researcher:** What went wrong?
>
> **Zach:** I guess through my own sense of 'something should always be happening in the class' and just me being silent—like, not doing, you know, at least walking around, but still.

Unlike Alice and Tim, Zach and Sam did not buy into the value of research-based pedagogies. Their beliefs in the effectiveness of a clear lecture, their perception of what students would like, and their general sense that they ought to be telling their students about physics all contributed to their decision to continue using a teacher-centered approach. Sam also provided further insight into external factors that inhibited his adoption of a student-centered approach.

> **Sam:** I didn't necessarily feel comfortable just going on my own, taking the initiative, and doing [active engagement activities because] I guess eventually it might frighten [the course instructor].

Sam's comment should raise an eyebrow. He identified an important aspect of our study; our weekly community meetings were not isolated events. They occurred in the

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context of a broader teaching culture. In our department culture, some instructors may be suspicious of active engagement strategies and might not support a TA who adopts these strategies.

This raises an important issue regarding alignment with a community of practice. As described in Section 4.2.1, communities of practice can have both positive and negative influences. It is possible that Zach and Sam did not fail to align with a community of practice; rather, they may have aligned with a community that embraced teacher-centered approaches instead of aligning with a community that embraced student-centered approaches.

This possibility was strengthened by the fact that many TAs perceived conflicting norms in the department. General concern with physics teaching in the department (not necessarily in first year courses) was voiced in seven of the eight TA interviews.

Fortunately, Côté and Levine's framework suggests that TAs can make significant changes to their community. Wenger provides a context for this process, promoting the use of enabling structures to guide TAs as they shape their communities of practice in the desired directions. The TAs identified the importance of these structures for shaping not only the small communities which we created in our study, but also the broader physics department community.

4.4.4 Enabling successful communities of practice

Communities of practice—whether they are weekly community meetings or broader department-wide teaching communities—are guided and nourished by enabling structures, as described in Section 4.2.1. These structures primarily guide the social structure to personality branch of Côté and Levine's identity model. In their interviews,

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TAs identified the need for investment in sponsorship, support, and recognition structures to further their professional development.

Sponsorship structures: Treating TAs as teaching professionals

At their core, sponsorship structures are about respect from course instructors and physics education researchers. If the goal is to train TAs to become teaching professionals, then TAs need to be treated as teaching professionals. TAs should be actively included in the process of determining how their recitation sections should be run. As one TA put it,

> **TA:** I think [it would be beneficial] to have some sort of positive feedback between profs and TAs so that TAs could actually have a say in how the tutorials ... are structured.

When we give TAs a voice and respect their ideas, they can become teaching professionals. We suggest ensuring that TAs have an active role in setting the structure of the recitation session at the start of the year and resolving educational challenges that arise.

A humbling highlight of our TA interviews was a second call for respect and sponsorship from physics education researchers.

> **TA:** I wouldn't call myself an expert—far from it, because I'm not studying it or anything, but ... I do feel like I've kind of built up my own repertoire of teaching techniques, and so I think it has always a bit of give and take.

It may be helpful to draw an analogy to effective student engagement. As outlined in a study from Clemson University [64], an effective TA would respectfully approach

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a student who has gotten off track, affirm his/her ability, and guide him/her in the right direction. In the same way, when a TA uses an unsuccessful teaching approach, physics education researchers should be a respectful ‘guide on the side’, not a ‘sage on the stage’ for the TA. In order to foster physics educator identity, we need to take the same respectful guiding approach to training TAs that we want our TAs to take in teaching physics.

Support structures: Providing the right tools for active engagement

Within our weekly community meetings, TAs valued the support and resources they received from their peers, the facilitator, and the course instructor. One TA stressed the value of the course instructor’s support.

> **TA:** The support we received was really, really good. But that’s a function of [the course instructor] really caring ... He was really supportive—like if you did a review session he’d send out the questions, book the room ... [he said] thank you.

Outside our weekly meetings, the support of university-wide communities is important to consider because this shapes the culture to which TAs can align themselves. We identified a concerning relationship between our TAs and university-wide supports in our qualitative research. Only three of the eight TAs interviewed were aware of the Centre for Teaching and Learning, our main university-wide teaching support structure. Of the TAs who were aware of the Centre’s existence, one responded to its mention:

> **TA:** There is a certain caution to be had [with resources from the Centre for Teaching and Learning] because of... this divide between the context

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> of the course and something without any context at all.

This TA's suspicion of general teaching workshops draws attention to the importance of discipline-specific training. We suggest that university-wide support structures, such as Centres for Teaching and Learning, are best accessed when these centres approach TAs with materials adapted specifically for their discipline, rather than inviting TAs to attend general (and sometimes distrusted) workshops.

Departments play a crucial role as a bridge between education experts and physics experts. Investment in TA training personnel who hold credibility both as physicists and educators would be very beneficial for providing professional development that TAs can trust and apply directly to their teaching. The importance of physics teaching resources was noted by another TA, who also drew attention to the negative teaching culture that can develop when these resources are not available:

> **TA:** A little more [in physics teaching resources] could definitely go a long way... A number of [TAs] come into this venture totally unprepared... and I think that [a lack of resources] does create a culture of people who teach without really caring about teaching.

In addition to discipline-specific professional development, support structures include the practical resources that TAs need to successfully implement student-centered instructional strategies. Here, it is important that we pay close attention to the types of resources we provide to TAs. For example, if a course instructor simply gives TAs lecture-based resources, such as textbook-style problems with solutions, the TA is likely to write these solutions on the blackboard and teach a lecture-based recitation. However, if an instructor gives a TA specific resources for active engagement, such

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as context-rich problems and whiteboards for collaborative problem-solving or flash card and ConcepTests for Peer Instruction, the TA will be more likely to use student-centered approaches. The Appendix provides a description of the resources TAs in our study used to implement collaborative problem-solving and Peer Instruction.

Recognition structures: Applauding successful student-centered teaching

Integrating TA communities of practice into the department culture through weekly TA meetings provides a starting point for improving recognition structures. Structuring regular opportunities to share and discuss teaching ideas encourages peers to recognize and celebrate each other's work. It also sends a positive message that the department values good teaching.

However, one TA noted the need for further recognition structures beyond these weekly community meetings:

> **TA:** Any extra [teaching] effort isn't really rewarded with any form of gratification or thanks... It's seen as something you do to get money. [But it is the main thing] you're doing [that's] useful for the department, so it's kind of funny how they don't acknowledge really how important it is, or [whether] you do a good job or not a good job at all.

Some recognition structures beyond weekly community meetings do exist in our institution: two of the TAs in our study, who applied both Peer Instruction and collaborative problem-solving teams for their first time during our intervention, earned nominations for faculty-wide teaching awards for their recitation sessions. One of these TAs also won a faculty-wide award for her teaching. Regular recognition of effective student-centered teaching is an important part of enabling communities of

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practice, which can then guide TAs to become teaching professionals.

4.5 Summary

TA professional development has the potential to benefit both current students and future students as TAs take on teaching and teaching-related roles in their future careers. As one TA said, “[Teaching assistantships are] the first contact [TAs] have with teaching, and [professional development] is a way to form them for the future when they—some of them will become professors.” Though most departments recognize the value of TA professional development, many face barriers such as financial constraints, time limitations, and a lack of TA buy-in to research-based pedagogies. To address these barriers, we integrated Côté and Levine’s personality and social structures perspective with Wenger’s community of practice framework to create a 12-hour, 12-week, cost-effective professional development intervention focused on TAs helping TAs *become* teaching professionals.

Even with a population that had on average 2.5±0.7 years of TA experience prior to our study, this short community-focused professional development intervention yielded positive results. TAs’ physics educator identities showed statistically significant improvements: from an identity just above neutral to an identity on par with their physicist identities. We observed positive (though not statistically significant) trends in TAs’ approaches to teaching: several TAs adopted student-centered approaches during our intervention.

Along with these positive results, however, we found that some TAs chose to continue using teacher-centered approaches. We propose that a TA’s choice not to adopt a student-centered approach was likely not the result of a failure to align with

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a community of practice. Instead, we note the presence of competing norms in communities of practice in our department. While we hoped that TAs would align with a community that supported research-based pedagogies, some TAs may have instead aligned or continued to align with a community that promoted a teacher-centered approach. Wenger's framework provides helpful insights into shaping communities so that they can foster teaching professionals who apply research-based instructional strategies. We describe the role of sponsorship, support, and recognition structures in guiding these communities. Though our single semester intervention made strides in TA professional development by improving TAs physics educator identities, we anticipate further longitudinal research to craft TA communitees that could better promote student-centered approaches and make lasting change in physics departments.

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Chapter 5

Conclusion

Persistent gender gaps in both conceptual understanding and retention in physics programs cost society as women's potential for making valuable contributions to physics is considerably underutilized. Moreover, these gender gaps point to concerning sociocultural factors such as stereotype threat that may be inhibiting women's success and retention in physics programs. In this research, we addressed two opportunities for promoting equity in introductory physics—first through a focus on student learning and second through a focus on instructor professional development.

First, in our student-focused research, we applied literature from physics education, sociology, and psychology to hypothesize that the gender gaps in conceptual understanding and retention may be mediated by physics identity. To test this hypothesis, we developed and validated a physics identity survey based on Hazari et al.'s four components of physics identity: competence, performance, recognition, and interest [5]. We tested student results from this survey using a bootstrapping regression-based mediation model, and we found that physics identity is a statistically significant mediator for gender gaps in both conceptual understanding and intention

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to continue in a physics program.

We examined the application of Wenger's framework for identity development in communities of practice to the physics classroom, finding that increased participation in physics communities correlates with higher physics identities for both men and women. The mediating role of physics identity in the gender gap along with the connection between identity and community led to our next hypothesis: Collaborative, community-building instructional strategies may enable equity in introductory physics.

We tested this hypothesis through a meta-analysis of results from over 5000 students in 26 courses across three continents. Following a similar classification to some of the earlier high-profile studies within our meta-analysis [15, 59], we categorized courses as primarily lecture-based (IE0), partially transformed containing some community-building instructional strategies (IE1), and fully transformed containing many collaborative pedagogies (IE2). Recognizing the different equity definitions of different readers, we compared these course-types according to three different equity models: equity of individuality, equity of parity, and equity of fairness.

We found that IE2 courses outperformed IE1 and IE0 courses on most measures in these three equity perspectives. From an equity of individuality perspective, women in IE2 courses had significantly higher learning gains than women in IE0 courses and higher (but not significantly so) gains than women in IE1 courses. From an equity of parity perspective, we observed statistically significant reductions in the direct gender gap, gender gap effect size, and normalized gender gap in IE2 courses. These gender gap reductions were significantly larger than the gender gap reductions observed in IE1 and IE0 courses for several measures. Finally, we approached equity of fairness

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in IE2 courses, but did not quite achieve it; women gained significantly less than men in both IE1 and IE2 courses, but this difference had a smaller effect size in IE2 courses. We suggest that community-building instructional strategies contributed to the steps towards equity observed in IE2 courses. These pedagogies may have reduced stereotype threat and enabled women's identification with physics, thereby improving women's success in these courses.

Carrying Wenger's framework for identity development in communities of practice into a new domain, we addressed our second opportunity for promoting equity: to support TAs as they learn to implement community-building pedagogies in their tutorials/recitations. We used Wenger's communities of practice framework along with other literature to build a low-cost, 12-week professional development intervention for TAs who led introductory physics recitations. The goal of this professional development program was not to simply prescribe teaching strategies, but instead to help TAs *become* teaching professionals. We applied both quantitative and qualitative research methods to measure the effectiveness of this intervention, using Wenger's modes of belonging—engagement, imagination, and alignment—for our assessment.

We found that TAs tended to engage with their communities of practice. TAs rated the helpfulness of their community meetings as 5.6±0.3 (between moderately agree and agree) on a 7-point Likert-type scale. TAs reported varied reasons for engagement with a community of practice—from the opportunity to tap into the expertise of their peers to the positive reassurance they gained from their peers that it was okay not to have all the answers. Even TAs who did not engage in the structured weekly community meetings mentioned the value of their TA community outside of our intervention.

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With regards to imagination, we observed a statistically significant improvement in TAs' physics educator identities from pre- to post-intervention surveys ($p = .031$, $r = .51$). While qualitative interviews generally supported these quantitative results, there remained room for improvement; TAs still exhibited a disconnect between their view of their current teaching role and an image of themselves as a 'real' instructor in the future.

TAs varied considerably in their alignment with a physics education community of practice. While some TAs made dramatic changes to their approach to teaching during our intervention, other TAs did not buy into research-based pedagogies. We suggest that these TAs did align with a community of practice; however, the community to which they aligned did not hold positive education values. These results suggest that a communities of practice model for TA professional development can make gains in helping TAs become teaching professionals. However, we also identify a need for change beyond the small communities within our intervention. We describe TAs' call for sponsorship, support, and recognition structures to enable positive teaching communities in the department as a whole.

In conclusion, the research of this thesis sheds further light on the persistent gender gap in physics, suggesting potential solutions to address this equity concern. Furthermore, we identify strategies for increasing TAs' adoption of pedagogies that could promote equity and improve physics learning for all students.

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Appendix A

Gender gap data

In Chapter 3, we included in our quantitative meta-analysis the results from several courses at our mid-sized Canadian university. Course A1 and A2 are two different years for a calculus-based course for physics majors taught by the same instructor, but different TAs, in both years. Course B and C are calculus-based physics courses for science students and engineers, respectively. Course D is an algebra-based course for life science majors. Table A.1 lists the pre- and post-gender gaps by course.

Table A.1: FCI results from our institution

			FCI Pretest score (%)					**FCI Posttest score (%)**				
	N_M	N_F	S_M	S_F	$S_M - S_F$	p	d	S_M	S_F	$S_M - S_F$	p	d
A1	26	17	73±4	59±5	14±6	0.028	0.72	90±2	79±5	11±5	0.037	0.81
A2	24	16	71±4	58±5	13±6	0.048	0.70	85±3	79±4	6±5	0.31	0.33
B	11	16	65±5	62±4	3±6	0.55	0.24	87±5	79±3	8±6	0.16	0.63
C	143	85	68±2	57±2	11±3	<0.001	0.56	78±1	71±2	7±3	0.005	0.41
D	14	38	60±7	49±3	12±6	0.084	0.54	73±7	59±4	12±7	0.086	0.55

In order to eliminate the possibility of an artificially reduced gender gap (in which

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female students with particularly low pretest scores might drop the course and therefore not take the posttest), we only included data from students who wrote both the pretest and posttest. This restriction lowered the number of students in our study substantially. To determine if the sample of students used to describe each class still represented approximately 'average' students in the course, we examined these students' grades (where available) and compared trends to the larger population who wrote one of either the pretest or posttest when grades were not available. These comparisons are shown in Table A.2.

Table A.2: Comparing course grades: Is our sample 'average'?

	Wrote pretest and posttest		**All in study**	
Course	Men's grade	Women's grade	Men's grade	Women's grade
A1	86±2%	83±2%	84±2%	80±4%
A2	73±3%	73±2%	71±2%	73±2%
B	85±2%	85±2%	83±2%	80±2%
C	77±1%	74±1%	77±1%	74±1%

Course grades were not available for course D, so we compared the trends observed among students who took both pretest and posttest to the trends for all students in the study. The 49 men who took the pretest scored 57±3% compared to 60±7% for the 14 men who wrote both tests. The 133 women who took the pretest scored 45±2% compared to 49±3 for the 38 women who wrote both tests. The 42 men who wrote the posttest scored 71±3% compared to 73±7% for the men who wrote both tests. The 85 women who wrote the posttest scored 58±2% compared to 59±4% for the women who wrote both tests. Whether we consider all the students in the study or the subset of students who wrote both tests, a pretest and posttest gender gap of

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~12% was observed on the pretest and the posttest in course D. From these data, we find that while larger samples of students would have been preferable, the students within our smaller samples do tend to resemble the average student in our study for each class.

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Appendix B

Pedagogies adopted by TAs

B.1 Collaborative problem solving

Collaborative problem-solving recitation sessions follow a student-centered approach that involves students' social construction of knowledge and creative problem-solving abilities [110, 140]. These collaborative problem-solving recitations have been found to result in significantly higher student learning gains than computer-based recitations [189], traditional lecture-based recitations [177], *and* individual problem-solving recitations [182]. In addition to improving academic performance, collaborative learning settings have also been found to improve students' attitudes towards learning and retention in science-related disciplines [55]. Considerable research has been done to optimize these collaborative problem-solving environments [64, 71, 104, 137, 177, 190, 191, 192, 193, 194, 195]. We include a brief description of how TAs successfully implemented collaborative problem-solving, drawing on this literature.

In short, collaborative problem-solving recitations involved students working in teams to solve a context-rich problem on a shared 2ft x 2ft whiteboard. To keep

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cost of whiteboards low, the facilitator purchased plain white Barker tile in 4ft x 8ft sheets from a local hardware store, where she had the tile cut into eight 2ft x 2ft whiteboards, at a total cost of approximately $3 per board at the time of writing. As students solved problems in their teams, the TA circulated between groups using guiding questions to prompt groups in the right direction.

Setting groups for the best student engagement

As recommended by the literature [137], the TAs in our study created student groups of three or four, seated such that students could all see each other. To reduce stereotype-threat concerns, TAs avoided putting a single minority student or female student in a group (for example, groups of two women and one man tend to function better than groups of two men and one woman [137]). Since mixed-ability groups tend to be more successful than homogeneous-ability groups (even homogeneous groups of high ability students)[137], some TAs used pre-term Force Concept Inventory [37] scores to create mixed ability groups. In our first year courses, it was common to have a very large spread of abilities. Therefore, to ensure that all students in the group were able to successfully communicate with each other, TAs formed heterogeneous groups of high to middle ability and middle to low ability students. These groups were changed throughout the term.

Creating context-rich problems to train problem solvers

TAs developed context-rich problems during community meetings, borrowed problems from other resources, or used problems assigned by the course instructor. The type of problem chosen directly impacted the extent to which students learned to

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become problem solvers in the recitation sessions. Standard 'textbook-style' problems—questions that refer to idealized objects with little connection to the student's reality such as a block of mass, m, on an inclined plane—encourage students to follow formulaic steps and spot patterns. In contrast, context-rich problems—questions based in the student's experience that require the student to decide which variables they need to know and what assumptions can be made—focus the discussion on "What physics concepts do we need to apply?" rather than "Into which formula can I plug these variables?" [137] Though these context-rich problems were often more difficult than textbook-style problems, they were attainable when students shared the learning load in their teams.

TA as a 'guide on the side'

The role of the TA in collaborative problem-solving recitations was to mentor and guide students as they learned to become problem solvers. In light of literature which has found that weaker students benefit from the TA providing a very brief five minute introduction to review physics concepts at the start of class [193], the TAs began recitation sessions with a short, often interactive review. Following this, the TA formed student groups, shared the marker rule (described below), and told the students, "Go!". The TA then actively walked from group to group saying, "So tell me about what you're doing here" or "Let's go back to what you know" [64] when a group appeared to be off track. Rather than sharing solutions with groups, the TA asked guiding questions such as, "Now what happens to the moment of inertia of the merry-go-round when the kid moves towards the center?" The TA remained constantly circulating between the groups to keep groups on task and encourage

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students to interact with the TA.

Addressing concerns in group dynamics

Common issues in collaborative teams were (i) whiteboard-takeover, which occurs when one student knows (or thinks he/she knows) the answer and quickly writes everything down while the team remains bewildered, and (ii) disengagement, when a less confident student doesn't participate. Helpful literature has been written on the benefits of assigning group roles to deal with these concerns [137, 191]. In our recitation sessions, TAs applied 'the marker rule' borrowed from Randall Knight, which was a simple introduction to handling challenging group dynamics. The TA told the class, "If you're holding the marker, you can only write down a peer's ideas. So if you're not sure where to start, grab the marker and your friends will teach you." This rule prevented whiteboard-takeover and empowered struggling students by giving them an important role in the group. The TA regularly reminded students of this rule as necessary.

B.2 Peer Instruction

Most of the introductory physics recitation sessions that we studied focused on problem-solving, so collaborative problem-solving was a natural teaching strategy to choose. Some TAs and course instructors, however, placed more emphasis on a conceptual review at the start of the recitation. For these recitations, we introduced the TAs to Peer Instruction. Peer Instruction has been found to yield considerably higher conceptual gains that traditional lectures [178, 180, 181, 62, 179]. In our weekly meetings, we reduced the lectures that TAs had used in previous years and integrated

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conceptual questions (ConcepTests) into these review sessions.

Prompting critical thinking individually

The TA began Peer Instruction by asking a challenging conceptual question (called a ConcepTest [62]) with multiple choice answers. We borrowed many helpful ConcepTests from Mazur's book, *Peer Instruction: A User's Manual* [196], which contains questions on introductory physics topics ranging from mechanics to fluid dynamics to electromagnetic waves. Students took approximately one minute to think about the ConcepTest and vote individually. In lectures, voting was often done through electronic response systems; however, TAs did not have easy access to this technology for recitations. Instead, TAs used photocopied flash cards with A, B, C, and D options. TAs asked the students to hold their flashcards under their chins, so that students weren't intimidated to participate by classmates looking at their answers. To encourage all students to participate, the TA had all students vote at once by saying phrases like, "One, two, three, vote!"

Launching peer teaching

After the student vote, the TA made a decision. Following Mazur's suggestions [196], if more than approximately 80% of the class answered correctly, the TA summarized the solution and moved on. If fewer than 40% of the students answered correctly, the TA provided some additional background before launching the class into Peer Instruction. If the question was at the right level, however, 40% to 80% of the class answered correctly. In this case, the TA said phrases like, "Turn to your neighbor, convince them of your answer, or be convinced by their answer. You have one minute. Go!"

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The students discussed with question with their neighbour while the TA circulated the room, engaging quiet groups. The TA paid close attention to the atmosphere of the discussions; when the room grew quieter, the TA brought the students back to summarize what they learned.

Summarizing

The TA re-polled the students, asking them to vote again. As expected in the literature [62], often the students showed a large improvement. The TA shared estimations of the students' improvement with the class to recognize the students' success in teaching each other when large gains occurred. The TA then provided a brief summary of the solution that the students reached during their peer discussions.

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Appendix C

Surveys

In Chapters 3 and 4, we reference the use of multiple instruments for quantitatively measuring different variables. Some instruments, such as the Approaches to Teaching Inventory [151], the Conceptual Survey of Electricity and Magnetism, and the Force Concept Inventory [37], are widely used and easily available in published works. However, others were adapted from a variety of previously published works [117, 5, 114] as described in Chapters 3 and 4. These surveys are separated into the different scales and included here. In their original form (as given to students), the items were scrambled so that students would be less likely to find patterns; however, we have organized the items into their respective subscales here.

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C.1 Physics identity scale

For the following questions, please indicate if you:
1 - strongly disagree
2 - disagree
3 - slightly disagree
4 - neither agree nor disagree
5 - slightly agree
6 - agree
7 - strongly agree

Interest:

I am interested in understanding the physics in everyday life.

I am interested in solving challenging physics problems.

I notice applications of the physics I know in my everyday life.

What I learn in this class will be useful in my planned degree or career.

Competence:

I can understand most physics concepts that I am taught.

Even when the material is tough, I can learn new physics concepts.

I am confident in my understanding of physics concepts.

I believe I can learn most physics-related content if I set my mind to it.

Performance:

When solving challenging physics problems, I am certain that I will succeed.

I can apply my physics knowledge to an assignment or test.

I will be able to achieve most of the goals that I have set for myself in this course.

Recognition:

Most of my family and friends see me as a physics person.

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Most of my physics instructors see me as a physics person.

My friends say that I'm good at physics.

C.2 Physics community engagement scale

For the following questions, please indicate if you:
1 - strongly disagree
2 - disagree
3 - slightly disagree
4 - neither agree nor disagree
5 - slightly agree
6 - agree
7 - strongly agree

Discussing physics problems with my classmates is valuable to me.

I am interested in telling others about physics concepts.

I can carry on a conversation or debate regarding a physics topic with a classmate.

I learn physics concepts better when I teach them to someone else.

Many of my friends enjoy physics.

I talk about physics topics with my friends or family.

I can explain a physics concept to someone else.

Learning in groups is not helpful because I have to take exams individually. (reversed)

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C.3 Active engagement scale

For the following questions, please indicate if you:
1 - only rarely
2 - sometimes
3 - about half the time
4 - fairly often
5 - almost always

During my class, I am constantly checking to see if my students are really getting it.

I use Peer Instruction when I have a lecture section.

I have my students solve problems in groups during class.

For the following question, please indicate if you:
1 - strongly disagree
2 - disagree
3 - slightly disagree
4 - neither agree nor disagree
5 - slightly agree
6 - agree
7 - strongly agree

Students learn more when they explain a concept to me than when I explain a concept to them. (adjusted to 5-point scale)

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Appendix D

Ethics approval

The General Research Ethics Board of Queen's University reviewed all studies performed with students and teaching assistants. Approval was granted for both the work on gender equity in introductory physics, described in Chapter 3, and the research into TA professional development, described in Chapter 4. These letters of approval are included below.

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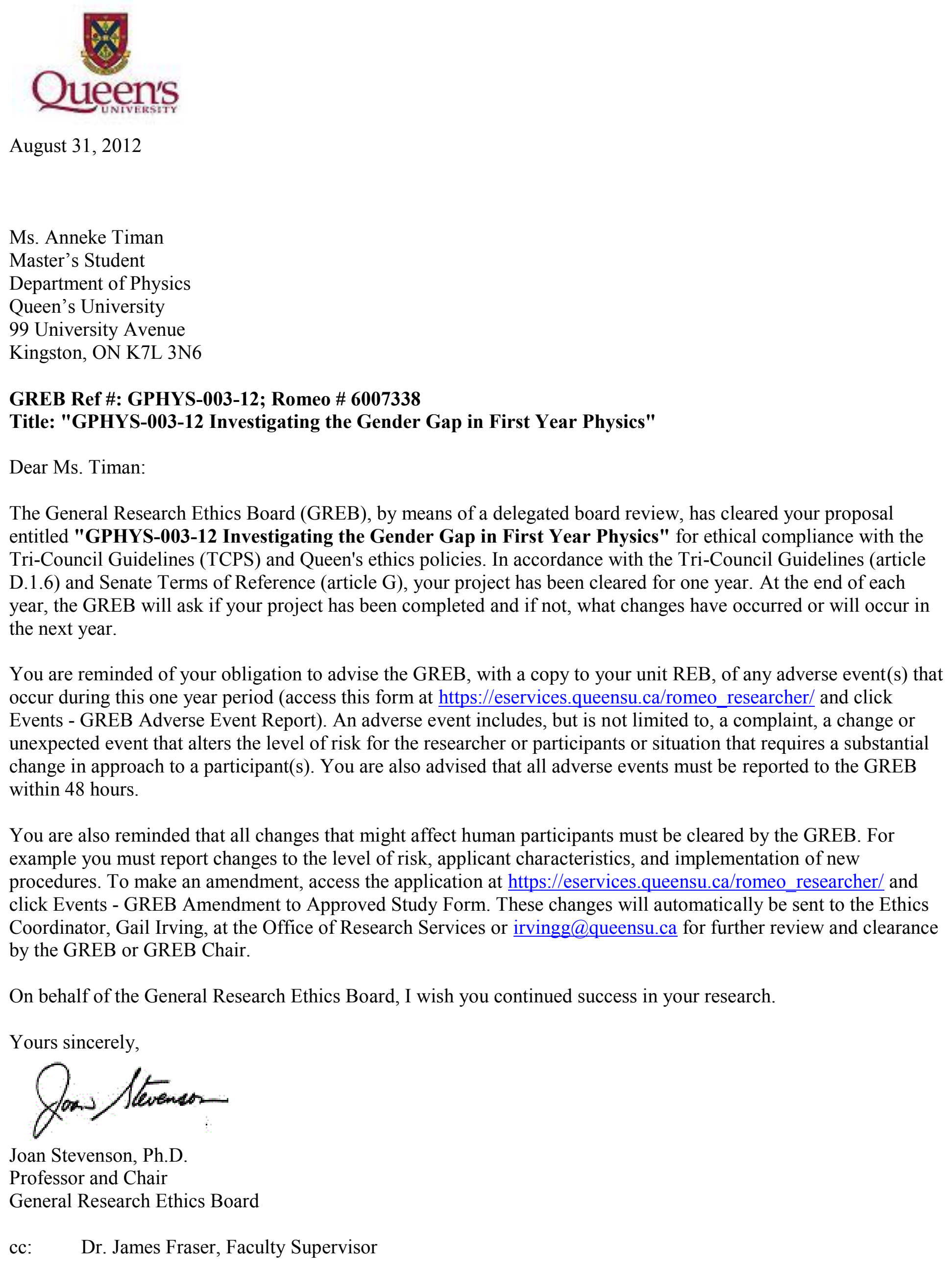

August 31, 2012

Ms. Anneke Timan
Master's Student
Department of Physics
Queen's University
99 University Avenue
Kingston, ON K7L 3N6

GREB Ref #: GPHYS-003-12; Romeo # 6007338
Title: "GPHYS-003-12 Investigating the Gender Gap in First Year Physics"

Dear Ms. Timan:

The General Research Ethics Board (GREB), by means of a delegated board review, has cleared your proposal entitled **"GPHYS-003-12 Investigating the Gender Gap in First Year Physics"** for ethical compliance with the Tri-Council Guidelines (TCPS) and Queen's ethics policies. In accordance with the Tri-Council Guidelines (article D.1.6) and Senate Terms of Reference (article G), your project has been cleared for one year. At the end of each year, the GREB will ask if your project has been completed and if not, what changes have occurred or will occur in the next year.

You are reminded of your obligation to advise the GREB, with a copy to your unit REB, of any adverse event(s) that occur during this one year period (access this form at https://eservices.queensu.ca/romeo_researcher/ and click Events - GREB Adverse Event Report). An adverse event includes, but is not limited to, a complaint, a change or unexpected event that alters the level of risk for the researcher or participants or situation that requires a substantial change in approach to a participant(s). You are also advised that all adverse events must be reported to the GREB within 48 hours.

You are also reminded that all changes that might affect human participants must be cleared by the GREB. For example you must report changes to the level of risk, applicant characteristics, and implementation of new procedures. To make an amendment, access the application at https://eservices.queensu.ca/romeo_researcher/ and click Events - GREB Amendment to Approved Study Form. These changes will automatically be sent to the Ethics Coordinator, Gail Irving, at the Office of Research Services or irvingg@queensu.ca for further review and clearance by the GREB or GREB Chair.

On behalf of the General Research Ethics Board, I wish you continued success in your research.

Yours sincerely,

Joan Stevenson

Joan Stevenson, Ph.D.
Professor and Chair
General Research Ethics Board

cc: Dr. James Fraser, Faculty Supervisor

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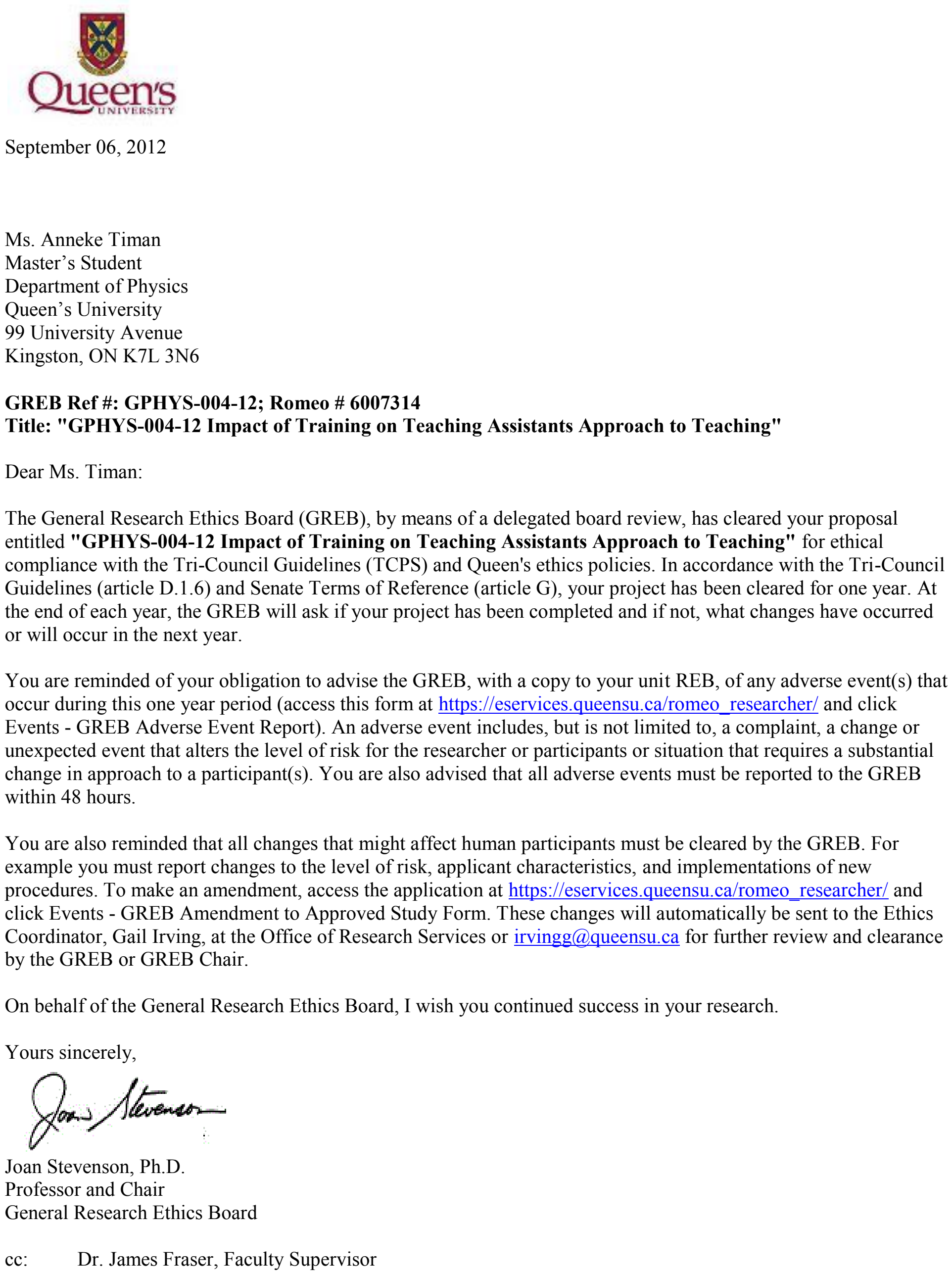

Queen's
UNIVERSITY

September 06, 2012

Ms. Anneke Timan
Master's Student
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99 University Avenue
Kingston, ON K7L 3N6

GREB Ref #: GPHYS-004-12; Romeo # 6007314
Title: "GPHYS-004-12 Impact of Training on Teaching Assistants Approach to Teaching"

Dear Ms. Timan:

The General Research Ethics Board (GREB), by means of a delegated board review, has cleared your proposal entitled **"GPHYS-004-12 Impact of Training on Teaching Assistants Approach to Teaching"** for ethical compliance with the Tri-Council Guidelines (TCPS) and Queen's ethics policies. In accordance with the Tri-Council Guidelines (article D.1.6) and Senate Terms of Reference (article G), your project has been cleared for one year. At the end of each year, the GREB will ask if your project has been completed and if not, what changes have occurred or will occur in the next year.

You are reminded of your obligation to advise the GREB, with a copy to your unit REB, of any adverse event(s) that occur during this one year period (access this form at https://eservices.queensu.ca/romeo_researcher/ and click Events - GREB Adverse Event Report). An adverse event includes, but is not limited to, a complaint, a change or unexpected event that alters the level of risk for the researcher or participants or situation that requires a substantial change in approach to a participant(s). You are also advised that all adverse events must be reported to the GREB within 48 hours.

You are also reminded that all changes that might affect human participants must be cleared by the GREB. For example you must report changes to the level of risk, applicant characteristics, and implementations of new procedures. To make an amendment, access the application at https://eservices.queensu.ca/romeo_researcher/ and click Events - GREB Amendment to Approved Study Form. These changes will automatically be sent to the Ethics Coordinator, Gail Irving, at the Office of Research Services or irvingg@queensu.ca for further review and clearance by the GREB or GREB Chair.

On behalf of the General Research Ethics Board, I wish you continued success in your research.

Yours sincerely,

Joan Stevenson

Joan Stevenson, Ph.D.
Professor and Chair
General Research Ethics Board

cc: Dr. James Fraser, Faculty Supervisor

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