Professional development of physics faculty and undergraduate students

by

Tra Huynh

B.S., Ho Chi Minh City University of Pedagogy, Vietnam, 2015

AN ABSTRACT OF A DISSERTATION

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DOCTOR OF PHILOSOPHY

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Abstract

This research presents the investigation of physics students' and physics faculty members' professional development and a design methodology via which we could best support them in their professional development. In particular, the first part of this dissertation will focus on undergraduate upper-division physics students' conceptual learning and equity within lab groups. The second part of this dissertation will describe a fundamental study of faculty professional development focusing on their own experiences over time. In the last part of this dissertation, I present a study of one design methodology that can help produce more student-centered and faculty-centered professional development programs.

In the first project of part I, I explore how upper-division physics students make sense and use mathematics in their physics problem-solving process. The literature has shown that students' struggles with mathematics are not simply because they lack mathematical competence. Rather, fluent and productive use of mathematics requires one to understand the physical meanings embodied in mathematical symbols, operators, syntax, etc., which can be a difficult task. For instance, in algebraic symbolization, the negative and positive signs carry multiple meanings depending on contexts.

In the context of electromagnetism, I use conceptual blending theory to demonstrate that different physical meanings, such as directionality and location, could be associated with the positive and negative signs. With these blends, I analyze the struggles of upper-division students as they work with an introductory level problem where the students must employ multiple signs with different meanings in one mathematical expression. I attribute their struggles to the complexity of choosing blends with an appropriate meaning for each sign, which gives us insight into students' algebraic thinking and reasoning.

The second project in part I investigates another aspect of student learning, focusing on the dynamics of lab groups that support or inhibit individual learning. In this work,

I use the inchargeness framework, where inchargeness is associated with one's authority in driving the activity. I study how inchargeness changes within a collaborative group when its members have differing expertise. I present a case study of a group of three students working in an upper-division undergraduate physics laboratory. One of them has less on-task expertise than her peers due to missing a day, which reduces her relative inchargeness across two storylines: "catching up" and "moving forward".

Part II of this dissertation investigates how faculty engage in long-term professional development activities, continually learning and applying various innovations into their teaching practices. I take an asset-based and agentic perspective to explore faculty experiences with on-going processes of change. We conducted longitudinal interviews with physics and astronomy faculty members from diverse backgrounds and carried out an ethnographic study regarding their long-term professional trajectories. Disciplinary professional development programs and on-going relationship with disciplinary colleagues are significant for faculty in making, appreciating, and sustaining changes. Additionally, faculty often pay attention to contextual constraints for structuring and creating changes. This analysis contributes another view to the current literature, which often focuses on how these constraints inhibit faculty processes of change.

Part III of this dissertation moves from fundamental studies of professional development of students and faculty to an exploration of a methodology for effective design: personas. Personas are life-like characters that are driven by potential or real users' personal goals and needs when interacting with a product. We argue that personas can support user-centered design in educational contexts. However, the use of personas in educational research and design requires certain adjustment from its original use in human-computer interface. In this study, I propose a process of creating personas from phenomenographic studies, which helps create data-grounded personas effectively. I illustrate this process with two examples: the design of a professional development website and an undergraduate research program design. Using these examples, I hope to provide education designers and researchers a clear method of creating personas that is relatable and applicable to their own design problems.

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Part I

Upper–division physics students' cognitive learning and equity dynamics in groups

Chapter 1

Review of related literature and studies for part I

1.1 Map of dissertation

Earlier physics education research had focused on student learning physics and teacher preparation especially in K-12 level. As the field of physics education research has continued to expand, the movement of classroom reform had shifted to include college level. Particularly, recent reform efforts have been largely observed at the college level. The development of PER at the college level composes of the increase in the number of physics education research-intensive institutions and PER graduate programs. This growth in PER has contributed the knowledge of process of physics learning and makes way for changes in college instruction[(7)].

Over the development of physics education research in college level, the topical focus of the field has shifted as well. This field started out with interest in investigating and correcting student misconception in physics qualitative and quantitative problem solving[(8)]. The research in this strand has been particularly applied with the direct application to devise instructional curriculum for college students. The last 10 years has observed the shift of PER focus into the researching the structure of knowledge, the inter-relationship between physics instructions, programs and students attitudes toward science; and support faculty around adopting research-based curriculum.[9]

The subject of physics education research has continued to evolve to include a variety of topics from theory to practice. My research interest starts with investigation of students learning and group dynamics to faculty professional development and to the practice of design using fundamental understanding of students and faculty from my other studies. This dissertation is situated in some of the contemporary trends in physics education research, which focus on theories around students learning, faculty professional development, and designs practice in physics education.

I arrange the content of my research in this dissertation into 3 parts. Part I investigates students fundamental professional practice, which includes chapter 1 to chapter 4. This practice includes their individual learning (chapter 2) and their learning within the relationship with other members in their group (chapter 3). I review related literature about these two activities of students in chapter 1 and give a summery and overview of future work on this branch of research in chapter 4.

In part II, I study faculty members' on-going professional development, which contains chapters 5, 6, and 7. I start with chapter 5 where I review relevant studies on faculty professional development, including some key definitions, common theories and results in this branch. In chapter 6, I delve into our research questions about faculty long-term processes of change. I draw on the theory of the Reasoned Action Approach to explore influential factors of their continuous professional development. I summarize this study and discuss some future directions of this research in chapter 7.

In the last part – part III, I switch from fundamental research of students and faculty professional development to research on a design method called personas. I explore a methodology that can help bring our understanding of faculty's and students' practices into effective design by focusing on their real needs and goals. Part III includes 4 chapters – chapter 8, 9, 10, and 11. I first present a overview of personas as a methodology under the user-centered design umbrella in chapter 8. In chapter 9, I compare personas with other methodology and present our methodology to build personas via a design example of faculty professional development website. Although personas is used originally for website-based design, in chapter 10, I show how personas can benefit non-website-based design as well, such as study of undergrad research program design. Chapter 11 summarizes the studies in part III as well as the research in this dissertation as a whole.

1.2 Introduction to part I: Research on student professional development

When thinking about student professional development, researchers have been addressing different aspects of growth that take place during their pursuit of undergraduate programs. These aspects change and evolve as students engage in characteristically different activities in their programs from freshmen year to senior. Within undergraduate physics program, students often take physics courses and engage in those courses' laboratory elements. Besides, many physics programs support students to participate in authentic physics research experiences. The nature of physics scientific and cultural aspects evokes great attention from PER field to investigate students' growth, including knowledge learning and identity development, to better devise instruction to support them.

How students learn physics is one of the original interest of PER. Research in this branch often addresses student conceptual understanding. The most common theoretical lenses are misconception[(10)], knowledge in pieces or resources[(11;12)], and ontological categories[(13;14)]. These studies often construct models and frameworks to address the knowledge structures to infer classroom interventions for productive construction of knowledge.

Another research branch around student learning takes place in the physics problem solving process, as solving physics problems is one of the key elements of mastering physics. Researchers often take interest in different ways students solving physics problems: how expert and novice student characterize and approach their problem differently[(15;16)], how they use mathematics and multiple representation to solve the physics problem[(17;18)], etc.

An emerged research branch in studying students learning physics applies and adopts cognitive psychology into physics education[(8)]. Researchers in this branch often focus on exploring students' cognitive process related to their conceptual understanding and problem solving. Yet the work in this branch has been more discovery than applied to classroom practice[8]. In chapter 2 of part I, I focus on the first aspect of student professional development – student learning. The theory I use is conceptual blending theory, which originates from linguistics. I investigate students' mental processes when reasoning with mathematical symbols in their physics problem solving. This study situated in the intersection of these main branches of research on student learning: the theory is driven by cognitive sciences, the context is grounded in problem solving, and the goal is to study how students blend conceptual physics with mathematical representations.

Another aspect of student professional development is the development of their identity within physics. Research in this field often address the nature and culture of physics, and how physics programs interact with students' overall development and success. One large group of research focus on devising assessment and survey to explore students' attitudes towards physics. Meanwhile, other researchers focus on the systematic issues of physics as a field and explore how stereotypes and bias in physics has created disadvantages and continue to influence underrepresented population in physics.

Researchers have called out how inequity in physics affect individual learning and identity development. Yet more work need to be done for us to fully understand the mechanism and dynamics of this power distribution. Chapter 3 in this current part will explore the equity dynamics in lab group work – one common setting of physics classes. This work drawn theories from social psychology and physics education research to address possible influential factors that inter-create inequity dynamics – group members' differing on-task expertise.

While chapters 2 and 3 present studies on student learning and group work dynamics separately, I will continue the discussion of situating the outcomes of these work in current literature in chapter 4. I also bring up potential directions of individual projects, each extension will add meaningful and important understanding into our current literature of students learning and identity development. Furthermore, I also address the need and opportunities to compare and combine these two branch of research in the future to gain a holistic picture of student professional development.

Chapter 2

Blending conceptual physics and mathematical signs

2.1 Introduction

The language of mathematics, like other languages, evolves over time where a mathematical symbol, such as a sign, can bear multiple mathematical meanings. Especially when mathematics is used in specific scientific contexts, such as physics, different physical contexts tag different specific meanings to the signs. In other words, the meaning of that symbol can diverge from the standard mathematical convention to bear additional physics meanings. This is probably one of the reasons why many students across levels struggle with integrating mathematical formalism, including seemingly trivial symbols such as positive and negative signs.

For a long time, the challenge of making sense with signs has been noticed and investigated. In mathematics, researchers have rigorously investigated the meanings of positive and negative signs that students use[19;20] and collected ways to teach young students to make sense of positive and negative signs in mathematical expressions[21;22]. In physics, physics education researchers have been interested in addressing how students ascribe meanings to positive and negative signs in very specific physical situations: kinetics physics[23], energy[24], etc. In this work, I want to investigate students' use of signs with different meanings to reason in the context of electrostatics.

However, I am interested in not only different kinds of physical meanings the students assign to positive and negative signs but also the mechanism and the dynamics of the meaning association through out problem solving. Many of the works in mathematics and physics commonly has used metaphor theories to produce a rigorous list of various meaning students could associate with signs[25;20]. I notice the phenomenon of meaning multiplicity is complicated and the dynamic mechanism of this phenomenon could go beyond the explanatory power and the interest of metaphor theories[26]. Therefore, I argue to approach this investigation from another prominent linguistic perspective – conceptual blending theory.

Conceptual blending theory accounts for the construction of new meaning via the conceptual integration network. In this theoretical integration network, mapping between inputs and selectively projecting inputs into the blended space gives rise to emergent meanings[1]. Conceptual blending proposes a mechanism that also covers metaphorical interpretation[1;27]. In some cases, metaphor is considered a 'collateral feature' of blending networks[28]. Conceptual blending shows its power not only in explaining human meaning construction but also analyzing the multiplicity meaning of words – polysemy[28;29]. I contend that conceptual blending theory offers us an investigate framework to study the dynamic mechanism of polysemous meanings of positive and negative signs that we are interested in.

In this chapter, I pull out two conceptual spaces which might be affiliated with sign in physics: location and direction. Using the machinery of conceptual blending, I show how those two spaces may blend with sign to produce five different blends due to selective projection. Each of these blends accounts for a meaning that our students potentially ascribe to positive and negative signs. I illustrate the blends in a one-dimensional problem from electrostatics, first with a principled solution and then with two student solutions in genuine settings. My goal is to present substantial theoretical discussion grounded in a simple physical scenario, to show how even a simple problem and the relatively limited space of signs have rich conceptual complexity undergirding them. This study is not an exhaustive accounting of all that students can do with positive and negative sign, or even with the problem of interest. Rather, I would like to call for researchers' and instructors' attention to polysemous meanings and their dynamics in physics contexts.

Research in the realm of students' reasoning and through the lens of conceptual blending has mostly paid attention to an individual crucial moment of reasoning or an individual outcome of an integration network. My epistemological and theoretical perspectives lead us to our interest of paying attention to the problem solving as ongoing processes. These processes constitute of series of thinking, reasoning, and decision-making actions where reasoning constitutes a chain of meaning making networks or blends. I want to use the theory of conceptual blending to deeply investigate the problem solving process to gain insights of students' dynamic reasoning.

2.2 Mathematical signs in education research

Historically, the concept of negativity was attached to the operation of subtraction. The minus sign is first introduced to describe a quantity yet to be subtracted[19;30]. A precise difference between the minus sign that assigns a negative number and an operation (such as subtraction) was not clearly defined until the development of algebra, when negative numbers gained the status of a mathematical object[31;30]. Although research suggests that negative number sense could be acquired by extending and stretching the set of grounding metaphors for counting-number arithmetic to the set of integers[25], cognitive and epistemic gaps between the two concepts has been prevalent and students' struggles with negativity are persist and pervasive[32;20].

A large research strand in mathematics education often works with young students to investigate their conceptualization of negative integers and explore various contexts (e.g., temperature, debt/assets) and models (e.g., neutralization, number line) to teach integers[22]. Each of these contexts and models affords metaphorical reasoning for some but not completely all aspects of reasoning with negative numbers. Therefore, many recommend to combine various approaches to teach negative numbers.

Meanwhile, Vlassis[32] approaches this problem from a explicit perspective that it is not the nature of the negative number itself but the negative sign itself that causes difficulties. Based on previous research[33;34], Vlassis[32,35] constructs a framework of the nature of negativity to categorize the meaning of negative sign. According to this categorization, a negative sign has three functions: unary function (predicate or structural signifier), binary function (operational signifier for subtraction), symmetric function (operational signifier for taking the opposite or inversion). Research has found that although students can interpret negative signs in various ways, they are usually unaware of the multiplicity of negative sign's meaning, which affects their operational fluency with negative signs[36;32].

In physics, negative and positive signs embody additional characteristics for quantities. The meaning of such signs varies specifically with contexts. Making sense of negativity and being explicit about assign meanings to signs in various contexts are challenging even with teachers and algebra-based students[37;38;39].

For example, negativity in reasoning about energy can be particularly challenging[40;41;42]. Depending on the given context, energy and the sign attached to energy are differently interpreted. Two common ontological metaphors for energy are substance (energy contained in objects) and vertical location (higher or lower energy level)[24]. These two ontological metaphors correspond to the common metaphors used in mathematics for integers. Similarly, each ontology has both advantages and drawbacks in making sense of different aspects of negativity in energy context. For example, the substance ontology is more helpful in making sense of operational function of signs as transference of energy, where the vertical location ontology offers a greater affordance for conceptualizing the unary function of the sign in negative energy[42]. Therefore, research also suggest to combine or blend these ontological metaphors together in learning and teaching with the perspective that flexibly choosing the signs' meaning is significant for making sense in physics[43].

As a scalar, energy itself does not have a direction. However, when it comes to vector quantities, positive and negative signs carry the additional meaning of directionality. Similar to the case of scalar quantities, signs can have multiple functions, which associate with multiple possible meanings the vector quantities may carry directionality-wise. Misaccounting for possible meanings causes us running into the risk of misinterpreting the physics scenarios. For example, middle school physics teachers inappropriately interpret the signs of acceleration using the speed model[37]: accelerating is always in the positive direction and decelerating is always in the negative direction. The speed model makes sense from a person-centric motion perspective: we usually move forwards and think of that as the positive direction. Walking backwards is rare; if we need to go back, we usually turn around and walk forwards. However, this interpretation of acceleration conflicts with scenarios where motion is set in the negative direction.

Reasoning about sign for both scalar and vector quantities is complicated by mathematical formalism in physics; in one-dimensional problems, we often treat quantities flexibly as either vectors or scalars. For example, consider the kinematics equation for final velocity as a function of initial velocity, acceleration, and time:

$$\vec{v_f} = \vec{v_i} + \vec{a}t \tag{2.1}$$

If an object is slowing down, there must be something subtracted from $\vec{v_i}$ [1]; the consequent negative sign can be interpreted to be an operation (remove $\vec{a}t$ from $\vec{v_i}$) or as opposite directions between $\vec{v_i}$ and $\vec{a}$, or simply as a negative acceleration (as in the speed model). Students may be unaware of the multiple meanings, or may switch meaning implicitly, confusing themselves in the process[23].

Furthermore, physicists also flexibly use literal symbols to represent those quantities as signed quantities (variables) or unsigned quantities (positive constants). Research has documented students' struggles with literal symbols in mathematics and physics[44;45;23]. In the prior example, students sometimes treat the acceleration symbol $\vec{a}$ as a constant (or a unsigned symbol) a which is always positive and used the "outer minus" to obtain its negative value. In other cases, the student treats the symbol as a variable (or a signed symbol) which could contain the "inner minus" and be negative itself. While the "inner minus" often has unary function, "outer minus" is usually operational, leading to inconsistent solutions or

[1] In this writing, I use the typographic convention that vectors are have superarrows (vector $\vec{a}$) while scalars are *italic*: scalar a.

interpretation[23].

In the recent series of studies[38;39;45], Brahmia and Boudreaux have investigated student understanding of negativity and positivity across various introductory physics contexts. The researchers has constructed assessments to ask students to explicitly explain what physical meaning is embodied in individual negative and positive quantities in different mechanics and electromagnetism contexts using Vlassis' categorization of negativity. The results show that even though students' flexibility in interpreting the meanings of signs is highly context-dependent, they generally struggle with the symmetrical meaning more than unary and binary functions. The further work develops a framework of the nature of negativity in introductory physics (NoNIP) to categorize the various meaning of signs in physics context more holistically[46]. Clearly, combining more than one nature of sign in a single calculation appears to present significant challenges to introductory and upper-division students.

Altogether, these disparate accounts of signs in mathematics and physics suggest that students struggle with flexibly choosing and applying specific meanings of signs, from children to intermediate-level undergraduate physics students. This is not surprising: there are multiple meanings of positive and negative signs which may vary among problems and within a given problem or expression. Although, the positive sign is commonly easier for learners to make sense and reason with, accounting for meanings that are assigned to the positive sign can help imply the complex meaning embedded in the negative sign due to the analogous relationship between positivity and negativity.

2.3 Theoretical Framework

I turn to conceptual blending theory to help us make sense of the various meanings of signs in physics and the dynamic mechanism accounting for meaning usage.

2.3.1 Conceptual blending theory

Conceptual blending theory was developed by Fauconnier and Turner[1] to account for how people create meaning. The theory posits a mental network model that processes and forms new meaning (Figure 2.1). The mental network model is composed of at least two input spaces containing information from discrete domains, a generic space containing common information and structures, and a blended space where new meaning emerges. The input elements in one space connect to their counterparts in the other spaces via vital relations, such as time, space, change, cause-effect, identity, etc. When projected into the blended space, these vital relations could be compressed into the same types, or more often, different types of relations in the blended space.

The process of generating new meaning in the blended space involves three operations: composition, completion, and elaboration. Composition sets up the input spaces and the relation between them. Completion is where the conceptual structure and knowledge from long term memory are recruited to complete the composed structure. Elaboration is where the blend is developed through an imaginative simulation according to the new principles and structure in the blend, and possibly creates other new principles and structures in the blend itself consequently. In other words, new meaning is created via a process of setting up the mental spaces, matching across the spaces, locating shared structures, projecting input elements into the blend, projecting backward to the inputs, recruiting new structures to the inputs or the blend, and running various operations in the blend itself. This is usually a fast process, happening at a subconscious level.

In the mental network model, the projection of elements from input spaces into the blended space is selective, which means not all elements and structures in input spaces will be projected into the blended space. This characteristic leads to different scopes of blending. Single-scope blending occurs when two or more inputs have different organizing frames but only one of those organizing frames is projected into the blended space. This model is usually referred to as basic metaphor: an idea is mapped from a source domain to a target domain. In contrast, double-scope blending occurs when the organizing frames of two input spaces are involved in the creation of new structures for the emergent meaning in the blended space.

Selective projection allows multiple blends with different imaginative networks to be constructed from the same two input spaces. This is largely overlooked in the literature. Indeed, researchers have built a substantial number of rigorous blends, showing the construction of meaning in the context of everyday life where the given input spaces mostly produce only one blended space with specific and predictable meaning. In this study, I emphasize the possibility that the same input spaces can produce different meanings due to different ways of projecting input elements into the blended space. Therefore, even though constructing blends might be fast, easy, and subconscious, selecting an effective blend or emergent meaning for a specific context could be more difficult.

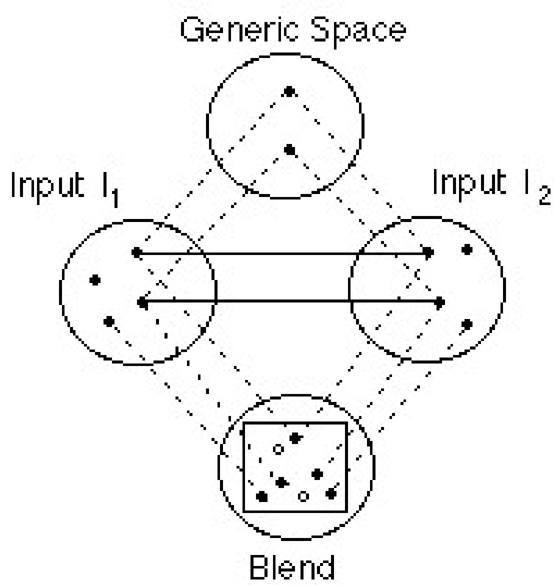

Figure 2.1: *Mental network model*[1]

2.3.2 Conceptual blending theory and polysemy

Linguists have extensively studied the multiplicity of meanings associated with words dating back to the late of last century as collected in Nerlich et al.[29]'s work. Linguists use polysemy and homonymy to describe properties of a word that can have multiple meanings. While homonyms have their meaning discreet and not directly related to each other, polysemous meanings connecting and relating to each other. Polysemous and homonymous meanings can be easily distinguished in some cases. However, it is not always clear to tell their distinction.

Because of the ambiguous distinction, linguists argue that all meanings of one word connect to each other like links in a chain. Polysemous meanings are next to or very close to each other on the meaning chain. Meanwhile, homonyms are more distant from each other on that chain. In other words, homonyms are considered as polysemous to some extent. Linguists generally find it less productive to differ polysemy and homonyms. Rather, they focus on explaining the mechanism of making meaning of polysemy in particular and of new meaning in general.

In this work, I am using a framework of conceptual blending from linguistics to explain the meaning making of polysemy in the context of mathematics and physics – blending the meaning of physics and the symbols of positive and negative signs. Conceptual blending theory is a popular theory in the study strand of polysemy (28) which considers the selective projection mechanism to explain the relation between meanings of one word.

Further investigation and theoretical development are needed to reveal the complete mechanism of sign meaning construction. However, this work is our attempt to take a different approach towards student struggles with signs. It is not simply because they unskillfully fail to think of the right metaphors where the correct meanings situate. Student struggles with sign could be a natural product of language learning process: making choices of projecting appropriate input elements and constructing appropriate mappings.

I am showing in the later sections the framework of conceptual blending and applying this framework to a physics problem in the electromagnetic context. The reason to do so is essentially because our available oral exam data with upper-division students shows exemplary processes of constructing and choosing between multiple meanings associated with signs.

2.3.3 Conceptual blending theory in science education research

The theory of conceptual blending has been extensively applied and studied in many fields and plays a central role in discovering and developing new mathematical ideas. In physics education research, studies have focused on choosing appropriate inputs and building blended spaces to explore how students understand specific concepts such as energy (43) and waves (47). For instance, the idea of a wave propagating as an object comes from blending a wave input with a ball input whereas the idea of a wave propagating as an event comes from blending a wave input with a domino input. Other works investigate how students blend among different physical representations, such as sound waves, string waves, and electromagnetic waves (48); how students blend hand gestures when reasoning about mathematical ratios (49); and how students use arrows to mean vector quantities in the context of electric fields (50).

Research uses blending theory to investigate the ways students blend mathematics and physics together and make sense of the physical world as well. Bing and Redish (51); Hu and Rebello (52) have attributed students' struggles in using mathematics not to their lack of prerequisite knowledge and skills but to their inappropriate mapping or blending between mathematics and the physical world. For instance, a student who frames a physics problem as only a mathematical one might wind up on the wrong track for an extended period of time, even when that student excels at mathematical reasoning (53). Therefore, the effective use of mathematics in making sense of the physical world involves blending reciprocally between mathematics and physics contexts rather than just applying mathematics to physics.

These diverse studies of the conceptual blending theory in physics education research have investigated how students choose input spaces, project ideas forward to a blended space, and operate within a blended space. They tend to focus on how different input spaces can create different blends (43;48;50;47). The process of making meaning with blends can be effortful and fraught (53;51;52;50), and careful curriculum development can guide students to choose appropriate inputs and elaborate appropriate blends (48;53).

In my study, I bring forward ideas from both literatures. From cognitive linguistics, I take up the idea that the same input spaces can produce multiple blends via selective projection, but that the process of blending can be very fast and unconscious. From physics education research, I take up the idea that making meaning with blends can be effortful, and that coordinating ideas from multiple representations (particularly algebraic) can be difficult. I attribute students' struggles to solve a problem to the difficulty in choosing appropriate blends from the same input spaces, not to difficulty choosing input spaces or difficulty running the blend. My argument is driven by theory and supported with case-study observational data; recommendations for how to teach this material are outside the scope of this paper.

2.4 Problem of interest and general solution

I ground my argument in one problem from introductory electrostatics. Suppose we have two charges at $-a$ and $+a$ on the x-axis as in Figure 2.2. What does the electric field look like along the x-axis?

The electric field contributions from both charges change in direction and vary in magnitude as you move along the axis. These contributions are commonly represented with arrows such as those shown in Figure 2.2.

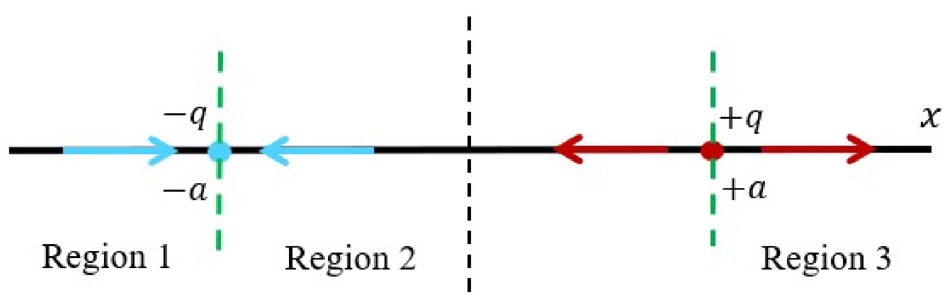

Figure 2.2: *Electric field contributions caused by the charges $-q$ (light blue arrows on the left) and $+q$ (dark red arrows on the right) along the x axis.*

Coulomb's law gives the electric field $\vec{E}$ caused by a point charge $\pm q$ as $\vec{E} = k\frac{\pm q}{R^2}\hat{R}$, where k is a (positive) constant. In this equation, $\vec{R}$ is the vector distance pointing from the point charge to a field point along the axis, where $R_{+q} = x - a$ and $R_{-q} = x + a$. Electric field contributions from different charges superpose to yield the electric field at any point.

You could divide the axis into three regions – left of both charges, right of both charges, and between the two charges – and consider each region separately. In this approach, one can flexibly take the magnitudes of the field contributions $E = |k\frac{(\pm q)}{R^2}|$, project the electric field direction on the x axis, and obtain the following solutions for each region as:

General:

$$\vec{E} = \vec{E}_{+q} + \vec{E}_{-q} \tag{2.2}$$

Region 1:

$$\vec{E}_1 = k\frac{q}{(x-a)^2}(-\hat{x}) + k\frac{q}{(x+a)^2}(+\hat{x}) \tag{2.3}$$

Region 2:

$$\vec{E}_2 = k\frac{q}{(x-a)^2}(-\hat{x}) + k\frac{q}{(x+a)^2}(-\hat{x}) \tag{2.4}$$

Region 3:

$$\vec{E}_3 = k\frac{q}{(x-a)^2}(+\hat{x}) + k\frac{q}{(x+a)^2}(-\hat{x}) \tag{2.5}$$

Other methods are possible; however, solving the problem correctly requires simultaneous consideration and consistency in treating directionality, algebraic values of location, and distance in the denominators. Using conceptual blending theory, my study investigates the multiple meanings that might be associated with the signs in this problem.

2.5 Blends of interest

In the context of this electric field problem, I claim that the signs carry two domains of meaning. First, the electric field is a vector quantity, so the signs bear the meaning of directionality. Second, the electric field expression involves the calculation of distance between the point charge and the field point, which depends on how one accounts for the locations

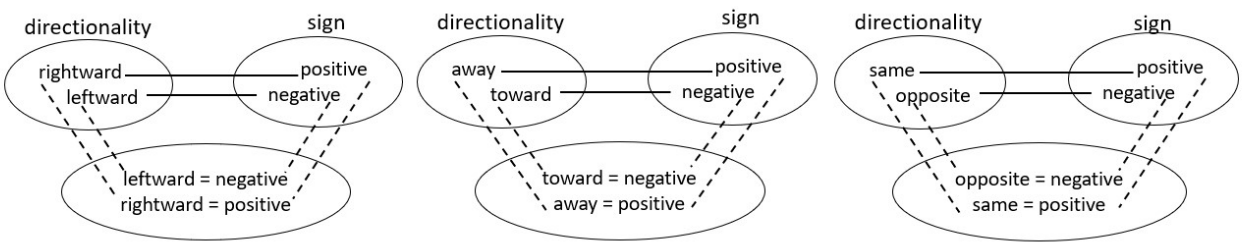

Figure 2.3: *From left to right: space-fixed blend (□), body-fixed blend (△), and comparative blend (○).*

of these points relative to the origin and to each other.

Thus, we have two different input spaces to blend with algebraic *sign*: *directionality* and *location*. Depending on which input elements are used, the same two input spaces may produce different blends, which could then lead to different conclusions about the physics involved.

The blends from the two domains would not necessarily cover the meaning of signs in all cases as compared to other categorization frameworks (32;46). However, these domains help us relate the polysemous meanings that our students associated with signs and look for insight when decoding their meaning choosing patterns in this problem.

2.5.1 Blending between directionality and sign

I propose three different blends between directionality and algebraic sign (54). In each blend, there are two input spaces – *directionality* and *sign*. The *directionality* input can contain elements expressing direction in one dimension such as rightward, leftward, away, toward, same, opposite, up, down, etc. The *sign* input contains the elements of negative and positive. The blending between the first three pairs of these *directionality* elements and these *sign* elements makes space-fixed, body-fixed, and comparative blends, respectively (symbolically referred as shown in Figure 2.3). The elements of up and down are not applicable in this horizontal system, and hence their blend is not shown.

A space-fixed blend (□) occurs when rightward and leftward from *directionality* are projected into the blended space. This blend is common and appropriate in a space-fixed problem, such as when there is a coordinate axis in a one-dimensional problem. This axis could be positive leftward or rightward. From *directionality*, rightward and leftward map to positive and negative (respectively) from *sign*, projecting forward the convention that leftward is negative and rightward is positive. Running the blend yields a unit vector (e.g. $\hat{x}$) which is positive when it points to the right as a convention for one-dimensional, space-fixed coordinate systems in physics.

Alternately, one could select away and towards from *directionality* to map to positive and negative in *sign* (respectively). This is common in body-fixed coordinate systems: moving away from me is positive velocity and moving toward me is negative velocity in person-centric motion[(37)]; radial vectors are positive away from the source. Consider the equation that expresses Coulomb's law for the electric field caused by a point charge, $\vec{E} = k\frac{\pm q}{R^2}\hat{R}$. Because the distance vector $\hat{R}$ always points away from the point charge, the positive sign accounts for the pointing-away electric field in the blended *directionality-sign* space, and negative sign accounts for the pointing-toward electric field accordingly. This meaning is established in electromagnetism and requires a connection to the meaning of the distance vector $\hat{R}$. We see students implicitly and unconsciously refer to the body-fixed blend ($\triangle$) when making charges carry signs, rather than discussing the inward and outward directions of electric fields.

Another emergent meaning of sign comes from the blend of *sign* with the relative direction of two vectors where the characteristics of *directionality* are now sameness and oppositeness. This comparative blend ($\bigcirc$) might originate formally from the mathematical property of the inner product of two vectors; the inner product of two opposite vectors is negative. Apart from comparing the signs of pairs of vectors, such as $\hat{x}$, $\hat{E}$, and $\hat{R}$, the meaning that emerges from this comparative blend also sometimes shows up when students consider the interference of two fields. For instance, $\vec{E}_1$ and $\vec{E}_2$ are destructive if their directions are opposite. Thus, one might insert an outer negative sign accordingly to account for that destructiveness in the expression for the total field strength. Note that constructiveness and destructiveness come from relative direction, which is represented by the inner sign of the vector quantity. If students treat direction and magnitude separately, they might bring both inner or outer

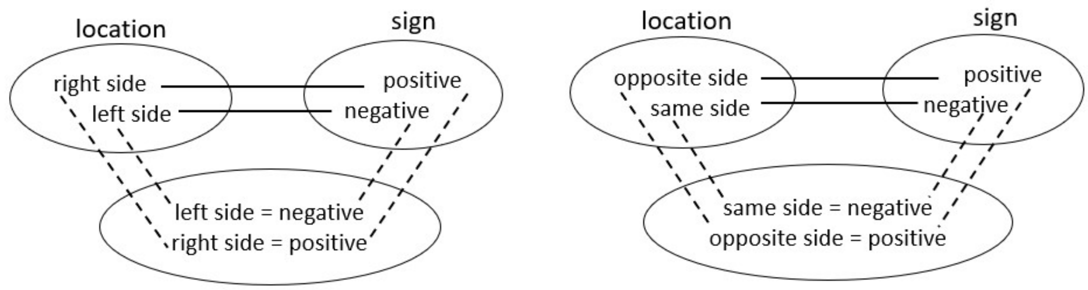

Figure 2.4: *From left to right: signed blend (■) and unsigned blend (▲).*

signs into the direction comparison and double account for the meaning of relative direction.

A quick typographical note is in order. We have introduced the symbols △ (body-fixed blend), ○ (comparative blend), and □ (space-fixed blend) for the three blends between *directionality* and *sign*. We're about to introduce the symbols ■ (signed blend) and ▲ (unsigned blend) for two blends between *location* and *sign*. We chose the fill of these symbols to connect to *directionality* (open) and *location* (filled); the actual shapes are for typographical ease. Compressing the names of the blends into the symbols allows us to compactly describe a series of blends in problem solving, which is important to the work of this paper.

2.5.2 Blending between location and sign

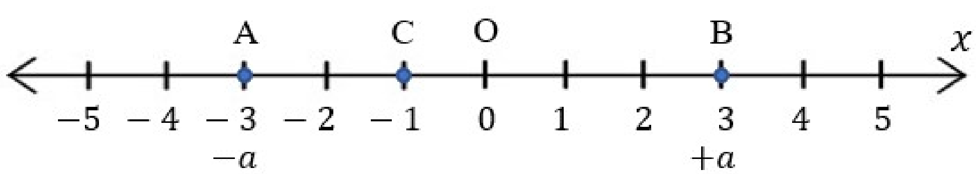

Figure 2.5: *Axis and number line*

In addition to the three blends between *directionality* and *sign*, we construct two blends between *location* and *sign*, to fully cover the problem at hand. The *location* input can contain elements expressing location in one dimension such as right of origin, left of origin, opposite side, and same side. Blending between pairs of these location elements and the positive and negative sign elements makes signed and unsigned blends, respectively (symbolically referred as shown in Figure 2.4).

In the signed blend, the location of a point to the left or right of the origin maps to negative and positive signs respectively. This blend yields the signed coordinate of a point on an axis consistent with the conventional choice of rightward-positive axis. For example, in Figure 2.5, one can read out the coordinates of points A and B accordingly as $x_A = -a$ and $x_B = +a$. In this example, the letter a is a positive, constant, "unsigned" number. However, the symbols x_A and x_B could carry signs inside them and be positive or negative: they are "signed" numbers. Unsigned and signed numbers are also termed "positive constants" and "variables" (respectively) [(23)], though we note that other definitions of variable don't exactly match our sense of signed number: one can take a derivative with respect to a variable, but not with respect to a signed number. When taking up the signed blend, the distance between two points is drawn from the formal mathematical operation of *difference*. For example, the distances AC and BC as shown in Figure 2.5 are $AC = |x_C - x_A| = |-1+3| = 2$ and $BC = |x_C - x_B| = |-1-3| = 4$. This blend showed up in our data when the students checked that the difference in location between two points is zero when those two points are on top of each other.

On the other hand, one could treat coordinates as unsigned numbers and view them as the length of some distance from the origin. Under the unsigned blend (Figure 2.4), the total distance between two points is subtracted when the two points are on the same side of the origin and added when the two points are on opposite sides of the origin. For instance, the distances AC and BC in Figure 2.5 are found as $AC = |-3| - |-1| = 2$ and $BC = |3| + |-1| = 4$.

The signed and unsigned blends independently give the same answers for the distance between two points. However, the blends require different thinking about the nature of coordinates, and therefore different operations to find the distances. The signed blend is especially useful and necessary when the coordinates of the points of interest are undefined whereas the unsigned blend is more useful when all coordinates are well-defined.

In the particular case of positive signed numbers, distinctions between the corresponding blends for variables and constants is unnecessary. Taking the difference of two signed numbers located on the same side of the origin (signed blend) is formally the same as and interchangeable with subtracting those two lengths (unsigned blend). Otherwise, one must be consistent in using one or the other approach, or else errors will occur.

Even though producing multiple blends from the same input spaces is permitted in conceptual blending theory via the process of selective projection, this aspect of the theory has been largely ignored in the science education literature. In this work, we are interested in the polysemous meanings that one can associated with signs while using mathematics to make sense of physics. While the various meanings of *directionality* and *location* are polysemous to each other to various extents, their relations may not be apparent to students. It could be that choosing among these different blends from *sign* and *directionality* and from *sign* and *location* contributes to what makes working with positive and negative signs hard for students. Further, students may struggle with flexibly deducing one meaning from the others or merging them together. Although running these blends is fast and subconscious, choosing an appropriate blend or flexibly shifting the meaning of the sign is complicated, and hence hard.

2.5.3 Exemplar solution with blending

We illustrate multiple ways to solve the problem with the blends we build. We start with the body-fixed blend (△), which is embedded in Coulomb's law (Table 2.1, line 1). For each charge, we get:

$$\vec{E}_{+q} = k\frac{(+q)}{R_+^2}\hat{R}_+ \tag{2.6}$$

$$\vec{E}_{-q} = k\frac{(-q)}{R_-^2}\hat{R}_- \tag{2.7}$$

In this solution, we will treat the signs of $\vec{E}_{+q}$ in each region using blends between *directionality* and *sign* in two ways: first, with the space-fixed blend (□) and then with the comparative blend (○), arguing that similar blends can be made for $\vec{E}_{-q}$. Then, we will blend *location* and *sign* to consider the denominators in terms of x and $\pm a$.

First we determine the direction of $\vec{E}_{+q}$ and $\vec{E}_{-q}$ using the space-fixed blend (□). For

Line	Region	Blend	Reason	Math
1	General	△	Coulomb's Law	$\vec{E}_{+q} = k\frac{(+q)}{R_+^2}\hat{R}_+$; $\vec{E}_{-q} = k\frac{(-q)}{R_-^2}\hat{R}_-$
2	1&2	□	$\vec{E}_{+q}$ points left	$\vec{E}_{+q}$ is negative
3	3	□	$\vec{E}_{+q}$ points right	$\vec{E}_{+q}$ is positive
4	1&2	○	$\hat{E}_{+q}$ and $\hat{x}$ oppose	$\hat{E}_{+q} = -\hat{x}$
5	3	○	$\hat{E}_{+q}$ and $\hat{x}$ parallel	$\hat{E}_{+q} = +\hat{x}$
6	1	□	$\vec{E}_{-q}$ points left	$\vec{E}_{-q}$ is positive
7	2&3	□	$\vec{E}_{-q}$ points right	$\vec{E}_{-q}$ is negative
8	1	○	$\hat{E}_{-q}$ and $\hat{x}$ oppose	$\hat{E}_{-q} = \hat{x}$
9	2&3	○	$\hat{E}_{-q}$ and $\hat{x}$ parallel	$\hat{E}_{-q} = -\hat{x}$
10	1 2 3		Superposition	$\vec{E} = (-E_{+q} + E_{-q})(+\hat{x})$ $\vec{E} = (E_{+q} + E_{-q})(-\hat{x})$ $\vec{E} = (E_{+q} - E_{-q})(+\hat{x})$
11	General	■	x, x_{-q}, and x_{+q} are signed numbers	$R_+ = x - x_{+q} = x - (+a) = x - a$ $R_- = x - x_{-q} = x - (-a) = x + a$
12	left of origin	▲	x, x_{-q}, and x_{+q} are unsigned numbers	$R_+ = x + a$ $R_- = x - a$
13	right of origin	▲	x, x_{-q}, and x_{+q} are unsigned numbers	$R_+ = x - a$ $R_- = x + a$

Table 2.1: *Exemplar solution. Space-fixed blend = □. Body-fixed blend =△. Comparative blend =○. Signed blend = ■. Unsigned blend =▲.*

instance, in regions 1 and 2 in Fig. 2, $\vec{E}_{+q}$ points to the left and hence is negative (Table 2.1, line 2). In region 3, however, $\vec{E}_{+q}$ points to the right and is therefore positive in that region (Table 2.1, line 3).

Alternatively, we can explicitly compare (○) $\hat{E}_{+q}$ with $\hat{x}$. Then, $\hat{E}_{+q}$ and $\hat{x}$ are in opposite directions in regions 1 and 2, and therefore $\hat{E}_{+q} = -\hat{x}$ in these regions (Table 2.1, line 4). $\hat{E}_{+q}$ is parallel to $\hat{x}$ in region 3, however, and thus $\hat{E}_{+q} = +\hat{x}$ in this region (Table 2.1, line 5). Both approaches correctly lead to the same expression for $\vec{E}_{+q}$ in each region, but the blends are different. The difference between them is subtle but can be distinguished in most cases through observations of students' word choices, diagrams, and gestures. Similar reasoning yields the signs for $\vec{E}_{-q}$ in all three regions (Table 2.1, lines 6-9).

To find the total field, the student might use the superposition theorem, where the signs of the component fields are consistent with their relative directions: opposite → negative, same → positive (○) (Table 2.1, line 10).

The complete solution requires the determination of R_+ and R_- in terms of x and $\pm a$. There are two possible blends here with *location* and *sign*. Using the signed blend (■), x, $x_{-q} = -a$, and $x_{+q} = +a$ are signed numbers. The differences between them are given in Table 2.1, line 11. Alternately, you could use the unsigned blend (▲) to yield x and $x_{-q} = x_{+q} = a$ as unsigned numbers and find the distance between them with the sense of length (Table 2.1, line 12 & 13). While the signed blend (■) approach gives the same value for R_+ and R_- along the x axis, the unsigned approach (▲) presents additional difficulties at the origin. Although the two approaches will reveal the same physical properties, using the signed blend (■) is more proper.

Altogether, we have articulated two possible blending paths for the directionality of $\vec{E}_-$ and $\vec{E}_+$ (using ○ and □) and two possible blending paths for the denominators (using ▲ and ■). In combination, this is four solution paths to this problem:

$$\triangle \rightarrow \bigcirc \rightarrow \bigcirc \rightarrow \blacktriangle \rightarrow \blacktriangle \tag{2.8}$$

$$\triangle \rightarrow \bigcirc \rightarrow \bigcirc \rightarrow \blacksquare \tag{2.9}$$

$$\triangle \rightarrow \square \rightarrow \square \rightarrow \blacktriangle \rightarrow \blacktriangle \tag{2.10}$$

$$\triangle \rightarrow \square \rightarrow \square \rightarrow \blacksquare \tag{2.11}$$

2.6 Instructional context

The data is drawn from an upper-division Electromagnetism I course, taught in the Fall 2013. The course enrollment was around 20 students and was taught by a white female instructor with experience. The course covered the first seven chapters of *Introduction to Electrodynamics* (4^{th} edition) by David J. Griffiths. Throughout the semester, the class met four times per week for fifty minutes each, during which the students solved tutorials or problems in groups of three or four and interacted with the instructor intermittently. The class instruction focused on how physics and mathematics work together and on the process of exploring physical systems, and not on memorizing procedures and formulas. The grading criteria for this course placed emphasis on the process of physical sense-making and mathematical reasoning and checking. Additional details on how the course was structured and students' activities during class are available in other papers[55;56]; this paper does not dwell on the instructional details of the course. The students in this course had relatively strong mathematical backgrounds and mathematical sense-making skills compared to introductory students.

Two oral exams were mandatory for all students. One covered problems with electric fields, and the other covered problems with magnetic fields. Each oral exam lasted approximately 30 to 40 minutes, and each student was encouraged to think-out-loud as they solved the problem on the whiteboard; almost all oral exams were video-recorded. The class was videotaped throughout the semester and hence, most of the students felt comfortable with working in front of a camera. The data is drawn from the first oral exam that the students took individually during the fourth week of the course. This was after the class had covered major topics in electrostatics such as Coulomb's law, Gauss's law, conductors, and the method of separation of variables. Because we are interested in students' conceptual understanding of mathematics meaning in physics problem solving, student oral exams are an appropriate source for data selection[57].

Four male students (three white, one Asian) were given this problem as part of their individual oral exam. The problem was more thought-provoking for these students than one might initially assume, due to their struggles with making sense of the signs coming from multiple sources. Indeed, none of them achieved success in the first few tries.

2.7 Methodology

When investigating the data, I looked for evidence that students employ multiple blends and switch among those blends to handle the given problem. Since the input elements of blends are fairly distinct in most cases, we could easily recognize and differentiate students' choice of blends via their verbal reasoning, gesture, diagram, and mathematical representations. Indeed, as the problem involves multiple positive and negative signs with different meaning, I observed that the students often put negative signs next to or in the brackets with the quantities that they think the signs belong to. Yet, those students with relatively strong algebraic backgrounds sometimes assisted their reasoning with formal mathematics and skipped some intermediate steps on the board. Therefore, it is important to attend to students' coordination among multiple representations.

For instance, accounting for the charge signs in the equation indicates the body-fixed blend. The words *pushing that way*, or $\vec{E}_{+q}$ *points in* $-\hat{x}$ along with a constant pointing gesture indicate the direction of left or right, and thus the space-fixed blend. The words *coming destructively* or $\vec{E}_{+q}$ *and* $\vec{E}_{-q}$ *have opposite signs* along with gestures or diagrams that represent two opposing objects reveal the comparative blend. Vaguely stated reasoning, such as $\vec{E}_{+q}$ *is negative*, is insufficient when attempting to draw conclusions about students' input spaces, and hence their blends. Such reasoning might or might not be clarified with other representations' assistance.

Verbal reasoning also provided us with indications of students' metacognitive awareness. Metacognition refers to thoughts about thoughts or reflections upon one's actions[(58)]. The study of metacognition has developed across disciplines and has shown a positive correlation between students' performance and their metacognitive ability[(59)]. Recent work[(60)] investigated how metacognitive talk could reveal students' thinking-like-a-physicist behavior. Three types of metacognitive talk were identified in our analysis: understanding, confusion, and spotting inconsistency. Even though I am not interested in thinking-like-a-physicist behavior here, paying attention to students' metacognitive awareness hints at their choice of blend actions and reasoning: picking blends, checking blends, and changing blends. Therefore, I prefer the pieces of data where students are metacognitively good at expressing their thoughts as they assign meaning to signs.

I transcribed the data and wrote narratives with detailed descriptions of students' coordination between verbal reasoning and other presentations, such as mathematics and gesture. Along with the video, I broke students' reasoning into mathematical steps. This was sensible because students usually completed their choices on the roles of signs temporarily as they worked through those steps. I mapped students' ideas in each step to the input elements of blends, and then converted the meaning they associated with signs into corresponding blends. In some steps, I observed the students employ more than one of the blends, which was also appropriate since multiple signs can simultaneously appear in a single mathematical expression. Significantly, I consider instances when students recognize conflicts between ideas of positive and negative signs with different meanings, deploy some of those meanings, or affiliate one meaning with another meaning, to be supporting our claims. Two researchers reviewed all of our blending results; a committee of three additional researchers reviewed a subset and came to consensus on them.

In the next sections, I will analyze two case-studies within our data. With overall differences in approach, these two cases help us illustrate the existence of the multiple blends that students can construct and employ when attempting to solve the problem.

2.8 Oliver case study

Among four students solving the same problem of interest, we choose to first look at Oliver's reasoning with signs. Although Oliver did not struggle much with signed and unsigned numbers, his reasoning with signs and directionality was typical among our students. Oliver usually tried to express his mathematics in a manner consistent with the way that he thought about physical systems, i.e., he put the sign in the bracket with the variables to which he thought that sign belonged. He was also good at thinking aloud, which helped us to understand his thoughts on signs and the blends he was using. Part of this case study is given in detail in our previous work[(54)].

Oliver started by recording the superposition formula of the general total electric field $\vec{E} = \vec{E}_{-q} + \vec{E}_{+q}$, and then defined each contribution using Coulomb's law (Table 2.2, move 1), where the body-fixed blend ($\triangle$) is embodied in each charges' sign. Oliver spent a few minutes to recall the definition of $\vec{R} = \vec{r} - \vec{r}'$ to determine distance R_{+q} and R_{-q}, which suggests that the signed blend was used. Throughout his work, the denominators $R_{-q} = x + a$ and $R_{+q} = x - a$ were persistently ascribed to $\vec{E}_{-q}$ and $\vec{E}_{+q}$, respectively (Table 2.2, move 1).

Despite of the different values of R_{+q} and R_{-q}, Oliver treated their directions as separate

Move	Region	Blend	Reason	Math
1	General	○ ■ △	$\hat{R}$ and $\hat{x}$ parallel Definition of $\vec{R}$ Coulomb's Law	$\hat{R} = \hat{x}$ $R_{-q} = x + a,\ R_{+q} = x - a$ $\vec{E} = \vec{E}_{-q} + \vec{E}_{+q} = k\frac{-q}{(x+a)^2}\hat{x} + k\frac{q}{(x-a)^2}\hat{x}$
2	General	□	$\vec{E}_{+q}$ and $\vec{E}_{-q}$ could point left	$\vec{E}_{+q}$ and $\vec{E}_{-q}$ could be negative
3	1	○	$\vec{E}_{+q}$ and $\vec{E}_{-q}$ destructive	$\vec{E}_1 = \vec{E}_{-q} - \vec{E}_{+q} = k\frac{-q}{(x+a)^2}\hat{x} - k\frac{q}{(x-a)^2}\hat{x}$
4	1	□	$\vec{E}_1$ points right	$\hat{E}_1 = +\hat{x}$
5	1	○	$\hat{E}_{+q}$ and $\hat{E}_{-q}$ oppose	$\vec{E}_1 = k[\frac{-q}{(x+a)^2} + \frac{q}{(x-a)^2}]\hat{x}$
6	1	□	$\hat{E}_{+q}$ points left, $\hat{E}_{-q}$ points right	$\vec{E}_1 = k[\frac{q}{(x+a)^2} - \frac{q}{(x-a)^2}]\hat{x}$
7	2	□ △	$\hat{E}_{+q}$ and $\hat{E}_{-q}$ point left Coulomb's Law	$\hat{E}_{+q} = \hat{E}_{-q} = -\hat{x}$ $\vec{E}_2 = \vec{E}_{-q} + \vec{E}_{+q} = k\frac{-q}{(x+a)^2}(-\hat{x}) + k\frac{q}{(x-a)^2}(-\hat{x})$
8	2	○ □	$\hat{E}_{+q}$ and $\hat{E}_{-q}$ parallel $\hat{E}_{+q}$ and $\hat{E}_{-q}$ point left	$\hat{E}_{-q} = \hat{E}_{+q}$ $\vec{E}_2 = \vec{E}_{-q} + \vec{E}_{+q} = k[\frac{q}{(x+a)^2} + \frac{q}{(x-a)^2}](-\hat{x})$
9	3	○ □	$\vec{E}_3$ and $\vec{E}_1$ oppose $\hat{E}_{+q}$ points right, $\hat{E}_{-q}$ points left	$\vec{E}_3 = \vec{E}_{-q} + \vec{E}_{+q} = k[\frac{-q}{(x+a)^2} + \frac{q}{(x-a)^2}]\hat{x}$

Table 2.2: *Oliver derives solution. Space–fixed blend =* □. *Body–fixed blend =*△. *Comparative blend =*○.

from their magnitudes and equal: $\hat{R}_{+q} = \hat{R}_{-q} = \hat{R}$. Indeed, Oliver first thought that $\hat{R}$ depended on where he picked the field point but then he decided to just change into $\hat{x}$ since "we [consider] the whole x axis". For illustration, a positive sign commensurate with the *sameness* (○) of the $\hat{R}$ and $\hat{x}$ directions was added for his replacement reasoning (Table 2.2, move 1). This incorrect comparison between $\hat{R}$ and $\hat{x}$ lead Oliver to an expression that conflicted with other blends that he would later use. "But it can be *negative* and so it won't work" – As Oliver pointed *left* and used the space–fixed blend (□), he noticed that his math did not satisfy the variation in the electric field direction along the x axis (Table 2.2, move 2). He then defined the field vectors on the diagram and decided to divide the given region into three smaller ones (Fig. 2.2).

In region 1, Oliver inserted a negative sign between the two terms because "they are going to be *destructive* (○)... Out here, [$\vec{E}_{-q}$] has greater effect than the contribution from

[$+q$ charge][...] It is going to be [$\vec{E}_{-q}$] *minus* [$\vec{E}_{+q}$]" (Table 2.2, move 3). While recording the result with two negative terms, he recognized "it doesn't seem right" due to the conflicts with his earlier reasoning of the total field "[$\vec{E}_1$] is going to *face to the right* [pointing *right*] (□), [...] *plus* $\hat{x}$" (Table 2.2, move 4). Oliver sensed that fields should have *opposite signs* when one field tends to reduce the other but in his math showed that "[...] they are both negative, [...] it looks like they kind of add together". Therefore, he decided to deploy the destructiveness meaning of sign and changed the second negative term back to positive to satisfy the relative opposing directions (○) of $\vec{E}_{-q}$ and $\vec{E}_{+q}$ (Table 2.2, move 5). Oliver did this without regard to the direction of each electric field component in relation to $\hat{x}$.

From his mathematical expression, the instructor pointed out that $\vec{E}_{+q}$ was now pointing in the $+\hat{x}$ direction. He became frustrated manipulating the multiple signs appearing with the different meanings of directionality. Oliver was certain that "[$\vec{E}_{+q}$] *points in* $-\hat{x}$ direction out here, and then [$\vec{E}_{-q}$] *points in the positive* right here (□), because it is pointing in" as shown in the diagram. He changed the signs of the terms accordingly (Table 2.2, move 6) and explained his thoughts on the final signs' meaning: "Ok, I know what I did wrong... Because... see the charges, I should have just figured it out or thought about which direction it is. This is exactly what is changing the signs, not necessarily the *sign of the charges*." Clearly, Oliver had not figured out that the root of all conflict was in the comparison of $\hat{R}$ and $\hat{x}$, but he was beginning to understand that the body-fixed blend (△) was not as useful to him as the space-fixed (□) and comparative (○) blends .

Although Oliver had assigned appropriate directionality meaning to the signs in the electric field expression in region 1, he failed to repeat this reasoning in region 2. Oliver first reasoned that "[the fields] are going to be constructive [...] and by constructive I mean they are both going in the same direction [pointing *left*] □" . He also blended the effect of the charge signs (△) into his math. For example, "[for the charge $-q$] it is *minus* charge (△) but it can have *negative* $\hat{x}$ *direction* [...] since it's *backwards* [pointing *left*] (□)" (Table 2.2, move 7). "That doesn't make sense" – Oliver got stuck when he contrasted: "[They should be in] the *same* direction (○) [...] *to the left* (□), so $-\hat{x}$ [...] Yea, I am confused". Oliver again struggled with affiliating multiple meanings to signs. As the instructor reminded him of his correct reasoning about signs in region 1, Oliver reminded himself to "not worry about the sign [of charge], just worry about the field [direction]". Oliver was now ready to adjust his expression by deploying the body-fixed blend. He wrote down expression from his earlier reasoning, which involved the comparative (○) and spaced-fixed (□) blends (Table 2.2, move 8).

In region 3, Oliver quickly recognized that "[$\vec{E}_3$] is going to be much like the [field in] region 1, except exactly the *opposite* (○)". As he recorded the solution (Table 2.2, move 9), Oliver clearly stated that "[$\vec{E}_{-q}$] is going to be *negative* $\hat{x}$ [pointing *left*], and [... $\vec{E}_{+q}$] is going to be positive $\hat{x}$, because... so for this charge [$-q$], the field is pointing *inwards* [pointing *left*] and for this charge [$+q$], it's pointing *out* [pointing *right*] (□)." Despite Oliver's use of the words *inwards* and *outwards*, I argue that Oliver might not have been referring to the body-fixed blend. First, he arrived at the solution initially by gesturing and by mathematically expressing the left-right direction; the explanation was to reaffirm the directions on the diagram. Second, the meaning of the body-fixed blend is inseparable from the charges' signs and the distance vector $\hat{R}$, which Oliver has not correctly defined or projected on $\hat{x}$ yet.

We see that Oliver has a strong algebraic background because he is quite good with formal mathematics. Oliver also acknowledged the different meanings that could be designated to positive and negative signs but was not certain about the relationship between those different meanings. Rather than treating them as deducible from each other, in most cases, he treated them as discrete meanings as he failed to merge them.

At first, he tried to collect all the signs with different meanings into his math and simplify with formal mathematics. He spent much of his time reading out the directionality meanings of the remaining signs, flexibly switching among them, comparing and contrasting with the help of the diagram in order to assign appropriate meanings for the signs. Oliver could not eventually resolve his struggles with affiliating all meanings with the physical system. However, he successfully combined other meanings together (such as the destructiveness in comparative blends, the comparison between the component field and the $\hat{x}$ or space-fixed blend) which lead him to correct answers.

Altogether, Oliver's solution path through this problem is:

$$(\bigcirc, \blacksquare, \triangle) \rightarrow \square \rightarrow \bigcirc \rightarrow \square \rightarrow \bigcirc \rightarrow \square \rightarrow (\square, \triangle) \rightarrow (\bigcirc, \square) \rightarrow (\bigcirc, \square) \tag{2.12}$$

In contrast to each example solutions (Equations 2.8-2.11), Oliver's solution is considerably longer and uses all of the blends between *direction* and *sign*.

2.9 Charlie case study

In contrast to the case of Oliver, we will look at Charlie's reasoning with signs in the process of solving the same problem of interest. Charlie also struggled with the ways in which signs in the numerator indicate directionality. Apart from that, he had particular difficulty determining distances between point charges and field points. He is good at metacognitively communicating with the instructor but lacked stability and consistency in his reasoning throughout solving the problem.

Charlie first recorded the electric field direction caused by each charge on the diagram – "Positive charge – out, negative charge – in, [in the middle] it's coming over to the negative." (Fig. 2.2). He then recorded Coulomb's law with total charge $Q = -2q$ (Table 2.3, move 1). Charlie then treated $\hat{R}$ and R separately where he indicated $\hat{R}$ as being "*along* the x direction (○)"; hence $\hat{R} = \hat{x}$ and $R = 2a$ – "that's a plus another a" (▲) (Table 2.3, move 2). He was quite suspicious of the result – "I feel like uh... it's more for a... like a point [charge], right?". However, Charlie still inserted signs and concluded about the electric field for each region – "Well, for [region 1], it is in the positive direction, then [in region 2] it is in the negative direction, and [in region 3] it is in the positive direction." (Table 2.3, move 2). Charlie's reasoning was vague here, but we argue that he was using the space-fixed (□) with helps of the total vector fields on the diagram he just drew. Realizing that the electric field varies along the x axis, Charlie decided to consider the electric field in different regions using the superposition theorem (Fig. 2.2).

Move	Region	Blend	Reason	Math
1	General	○	$\hat{R}$ and $\hat{x}$ parallel	$\hat{R} = \hat{x}$
		▲	x_{-q} and x_{+q} are unsigned number	$R = a + a = 2a$
		△	Coulomb's Law	$\vec{E} = k\frac{(-2q)}{R^2}\hat{x}$
2	1	□	$\hat{E}_1$ points right	$\vec{E}_1 = k\frac{2q}{R^2}\hat{x}$
	2	□	$\hat{E}_2$ points left	$\vec{E}_2 = k\frac{-2q}{R^2}\hat{x}$
	3	□	$\hat{E}_3$ points right	$\vec{E}_3 = k\frac{2q}{R^2}\hat{x}$
3	1	▲	x, x_{+q}, x_{-q} are unsigned numbers	$R_{+q} = x + a$, $R_{-q} = x - a$
		△	Coulomb's Law	$\vec{E}_1 = \vec{E}_{+q} + \vec{E}_{-q} = k[\frac{q}{(x+a)^2} + \frac{-q}{(x-a)^2}]$
4	1	○	$\hat{E}_{+q}$ and $\hat{E}_{-q}$ distructive	$\vec{E}_1 = \vec{E}_{+q} - \vec{E}_{-q} = k[\frac{q}{(x+a)^2} + \frac{q}{(x-a)^2}]\hat{x}$
5	1	□	$\hat{E}_{+q}$ points left, $\hat{E}_{-q}$ points right	$\vec{E}_1 = \vec{E}_{+q} + \vec{E}_{-q} = k[\frac{-q}{(x+a)^2} + \frac{q}{(x-a)^2}]\hat{x}$
6	2	■	x_{-q} is a signed number	
		▲	summing distance	$R_{-q} = x + (-a)$
7	1	■	x_{-q} is a signed number	
		▲	x_{+q} and x are unsigned numbers, subtracting distance	$R_{-q} = -x - (-a)$, $R_{+q} = -x - a$
8	1	■	checking tool	$R_{-q} = x + a$, $R_{+q} = x - a$ $\vec{E}_1 = \vec{E}_{+q} + \vec{E}_{-q} = k[\frac{-q}{(x-a)^2} + \frac{q}{(x+a)^2}]\hat{x}$
9	2	■	x_{-q} and x are unsigned numbers	$R_{-q} = x - (-a) = x + a$
		▲	x_{+q} and x are signed numbers	$R_{+q} = -x + a$
		△	Coulomb's Law	$\vec{E}_2 = \vec{E}_{-q} + \vec{E}_{+q} = k[\frac{-q}{(x+a)^2} + \frac{q}{(x-a)^2}]\hat{x}$
10	2	□	$\hat{E}_{+q}$ and $\hat{E}_{-q}$ points left	$\vec{E}_2 = \vec{E}_{-q} + \vec{E}_{+q} = k[\frac{-q}{(x+a)^2} + \frac{-q}{(x-a)^2}]\hat{x}$
11	3			$\vec{E}_3 = \vec{E}_{-q} + \vec{E}_{+q} = k[\frac{-q}{(x+a)^2} + \frac{q}{(x-a)^2}]\hat{x}$

Table 2.3: *Charlie derives solution. Space-fixed blend =* □. *Body-fixed blend =*△. *Comparative blend =*○. *Signed blend =* ■. *Unsigned blend =*▲.

Starting with region 1, Charlie spent some time to figure out what is the distance R and how to define x (Fig. 2.6a). He obtained $R_{+q} = x + a$ and $R_{-q} = x - a$, which indicates his use of unsigned number (▲) sense and blended the effect of the charges' signs (△) into the field expression (Table 2.3, move 3). With unsigned x, Charlie realized that the total field, which must be in the positive $\hat{x}$ direction as he previously mentioned (Table 2.3, move 2), now was negative because "the field [$|\vec{E}_{-q}|$] is going to be bigger than [$|\vec{E}_{+q}|$]". To make the total field positive, Charlie thought that he should have a negative sign connecting the two terms –

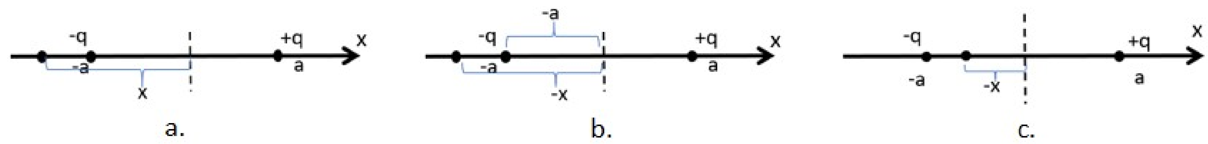

Figure 2.6: *Charlie sketches on the diagram.*

"[. . .] but I don't know why, I think I am missing something that makes my negative sign".

Later, he inserted a negative sign between two terms and ascribed it to *destructiveness* (○) of the fields (Table 2.3, move 4) as "[$\vec{E}_{+q}$] points [leftwards] [. . .] [$\vec{E}_{-q}$] points [rightwards] [. . .] Contribution *subtracts*". However, the result then had both component fields in the positive $\hat{x}$ direction. He then added a negative sign in front of the $+q$ charge to account for its contribution of "*pushing* away" in the $-\hat{x}$ direction. His pointing gestures to the left and to the right suggested a space-fixed blend (□). Charlie reached a his ending solution and checked the sum to make sure the total field is positive "because [$\vec{E}_{+q}$] has negative direction, now [$\vec{E}_{-q}$] will be bigger [. . .] so [$\vec{E}_1$] would be positive" (Table 2.3, move 5). Notably, even though the result is correct with positive x, later when treating x as a negative signed number, Charlie had to come back to this solution and make changes in these terms accordingly.

Moving on to the middle region, Charlie soon realized that x can be negative to the left of the origin and that he had been treating x_{+q}, x_{-q}, and x as unsigned numbers in region 1. From this point forward, Charlie encountered an array of difficulties and inconsistencies when mixing unsigned and signed blends in his attempts to find distance. In his first try for a field point to the right of the origin, Charlie clearly stated "[R_{-q}] is gotta be x plus the negative $-a$. . . So this *distance* right here is *distance* x and [x_{-q}] is like a *distance* $-a$. So this *distance* [R_{-q}] should be $x - a$". This means, he treated x_{-q} as a signed number (■) but summed (▲) it with distance x to get $R_{-q} = x - a$ (Table 2.3, move 6). Following similar failed attempts, Charlie even suggested switching the direction around, but he quickly realized that would not solve his problems. Therefore, he continued with the given axis and decided to extract the signs out of the variable x and make it stay positive; Charlie preferred working with unsigned numbers.

Charlie then went back to his solution in region 1 and consistently made changes in his mathematical expression. His marks on the diagram (Fig. 2.6b) and gestures showed that, even when he treated $x_{-q} = -a$ as a signed number (▲) and x as an unsigned number (■), he subtracted these two distances (■) – "*negative x minus negative a*" – to obtain $R_{-q} = -x-(-a) = -x+a$ (Table 2.3, move 7). For $R_{+q} = -x-a$, Charlie's reasoning was vaguer. Charlie seemed to have his sense of signed and unsigned numbers extremely entangled.

To help Charlie become unstuck, the instructor introduced a checking tool that can help activate knowledge of signed numbers and the signed blend (■). For instance, when the field point is put right on top of $-q$, Charlie found that the value of $x = x_{-q} = -a$ and the distance R_{-q} should equal zero. From his current expression of $R_{-q} = -x + a$, Charlie decided to bring the negative sign back into x – "Can we just keep it like this and then the negative sign [...] will be *inside* the x whenever it is on *the other side* of the axis?" – and treated x as a signed number (■), turning R_{-q} into $R_{-q} = x + a$. Similarly, Charlie obtained $R_{+q} = x - a$ and accordingly replaced the denominators in the field $\vec{E}_1$ (Table 2.3, move 8).

Despite getting the correct answer for region 1, Charlie was still inflexible with the checking tool, and especially tended to treat x as an unsigned number. When starting over in region 2, Charlie marked a field point to the left of the origin and recorded the distance as $-x$ on the diagram (Fig. 2.6c). He then paused for a while, realizing his unsigned approach: "See if I don't put the negative [outside of x in his recent answer], why am I now calling this *negative x* and even earlier called that *negative x*?" Charlie then went back to the signed blend, which lead him to $R_{-q} = x - (-a) = x + a$: "See, what my thought is,... [R_{-q}] should be *x minus negative a*. Okay, that makes sense [...] Because then, if x is negative, as it approaches [$-a$], it will get to 0." He then quickly arrived at $R_{+q} = -x + a$ without much additional reasoning. This was because when considering a positive number, for instance x_{+q}, there is more flexibility in choosing signed and unsigned blends. Hence, the reasoning is more straightforward.

In this case, his diagram and verbal reasoning of "*negative x plus a*" suggested that he might have used the blend of unsigned number to sum (▲) the two distances a and $(-x)$, which is positive now. Plugging in R_{-q} and R_{+q} and blending the signs of the charges (△) into the superposition theorem, Charlie arrived at a field expression that disagreed with the relative directions among $\vec{E}_{-q}$, $\vec{E}_{+q}$, and $\hat{x}$ (Table 2.3, move 9). Adjusting the sign of each term such that "[the fields] are both *pushing* in the $-\hat{x}$ direction [pointing *left*] (□)", Charlie arrived at the correct expression for the electric field in region 2 (Table 2.3, move 10).

In region 3, Charlie quickly recorded the total field with no further struggles or explanations (Table 2.3, move 11). We see that Charlie had successfully affiliated the meaning of signs in denominators with the relative direction between the electric field and $\hat{x}$ after working on the last two regions. Moreover, Charlie's ease in this region could be partially because in this region, signed and unsigned numbers do not matter and hence effective blends of them are not important.

Charlie could do formal math quickly, and sometimes he skipped a few math steps as well, indicating a facility and ease with algebra. Charlie was also able to connect the destructiveness meaning into the relative direction of two vectors: "It should not be *subtracted* from the other, should it? I feel like the electric fields both *add* up together, and in one case, just in this case, it's *negative*". Apart from the similar procedure of determining the appropriate directionality meaning for signs, however, Charlie also spent a lot of time and effort working with the denominators, where he struggled to employ consistent and helpful ways to think about the distance between two points. The problem is subtly challenging because both variables a and q were introduced as unsigned numbers. Therefore, it seems natural to treat x as an unsigned number as well. In fact, we see via Charlie's diagram and gesture, that he preferred treating x as an unsigned number, where increasing and decreasing the distance was associated with positive and negative signs. Even though Charlie finally made sense of the checking tool and the signed blend, he tended to go back to an unsigned number and unsigned blend whenever he was in a positive region.

Altogether, Charlies's solution path through this problem is:

$$(\bigcirc, \blacktriangle, \triangle) \rightarrow (\square, \square, \square) \rightarrow (\blacktriangle, \triangle) \rightarrow \bigcirc \rightarrow \square \rightarrow \tag{2.13}$$
$$(\blacksquare, \blacktriangle) \rightarrow (\blacksquare, \blacktriangle) \rightarrow \blacksquare \rightarrow (\blacksquare, \blacktriangle, \triangle) \rightarrow \square$$

In contrast to each example solution (Equations 2.8-2.11), Charlie's solution is considerably longer and uses all of the blends between *direction* and *sign* and *location* and *sign*.

2.10 Discussion: Oliver and Charlie in Comparison

Oliver and Charlie had similar approaches to their solution derivations, especially in the way they sought signs with appropriate meanings to include in their mathematical expressions. Their verbal, diagrammatic, gestural, and mathematical reasoning indicated that they could distinguish various meanings associated with the signs. In addition, both students showed their sound background in algebra by efficiently carrying out operations involving negative signs such as adding, subtracting, and multiplying. These formal mathematical steps assisted them in thinking about the signs with different meanings and affiliating those meanings together. Therefore, their struggles with the problem were not because they had not been equipped with the necessary mathematical tools but could be plausibly attributed to the challenging task of understanding and manipulating the physical meaning embodied in algebraic signs.

Charlie clearly struggled with the problem much more than Oliver because he struggled to comprehend not only the directionality meaning, but also the location meaning of the signs – how to treat coordinates and what blends to use to find the distance between two points. Oliver seemed to have a better physical sense of the situation from recalling Coulomb's law and the superposition theorem whereas Charlie inappropriately treated the system as just a bigger point charge initially. However, there still exists a pattern in their directionality reasoning. Starting considering directionality, both Charlie and Oliver naturally collected the signs that embedded the charge effect of the body-fixed coordinates (△) and the relative relation $\hat{R} = \hat{x}$ (○) into the field expression. In the second region, they repeated the choice of the body-fixed coordinates (△). Both students tried hard to combine this meaning (△) with others and eventually affiliate it with the signs showing the directions of the vectors $\vec{E}_{+q}$ and $\vec{E}_{-q}$, either in the directional comparison with each other (○) or in their leftwards – rightwards direction (□), with the latter tends to be more favored.

Remarkably, in their first attempt at fitting their expression for region 1 with the diagram, both students considered destructiveness as being separate from opposite directions. Even though Charlie thought that both destructiveness and opposite direction are embodied in the same signs, he eventually inserted an extra negative sign to account for a destructive combination. Later, we observed that interference no longer bothered Charlie or Oliver. In region 2, this could have been because the effect of constructive interference is consistent with the positive signs in the superposition theorem. For region 3, this could have been because both Charlie and Oliver had already firmly affiliated the interference effect with signs that indicate relative direction.

Oliver's solution path: (Equation 2.12)

$$(\bigcirc, \blacksquare, \triangle) \to \square \to \bigcirc \to \square \to \bigcirc \to$$
$$\square \to (\square, \triangle) \to (\bigcirc, \square) \to (\bigcirc, \square)$$

Charlie's solution path: (Equation 2.13)

$$(\bigcirc, \blacktriangle, \triangle) \to (\square, \square, \square) \to (\blacktriangle, \triangle) \to \bigcirc \to \square \to$$
$$(\blacksquare, \blacktriangle) \to (\blacksquare, \blacktriangle) \to \blacksquare \to (\blacksquare, \blacktriangle, \triangle) \to \square$$

Notably, Oliver and Charlie might have obtained correct answers sooner if they could have appropriately defined the relative direction between the distance vector $\hat{R}$ and $\hat{x}$. Both correctly defined the magnitudes of R_{+q} and R_{-q} but failed to determine the directions of $\hat{R}_{+q}$ and $\hat{R}_{-q}$ as they tended to treat magnitude and direction separately. Consequently, neither student could reason consistently between the signs in $\bar{E}\hat{E}_{\pm q}$ and $\hat{R}$ that occur in Coulomb's law, and the signs that resulted from the blends of relative direction between $\vec{E}_{+q}$, $\vec{E}_{-q}$, and $\hat{x}$.

2.11 Conclusion

Human uses language not only to express ideas, but also to develop new knowledge and understanding. In this work, we are interested in how students deal with polysemous meanings that associate to signs when they use the language of mathematics to make sense of a physical systems. Conceptual blending theory provides a mechanism for polysemy through the selective projection of elements from the same input space.

In the context of an electrostatics problem, we built five different blends to illustrate how different meanings of positive and negative signs might be constructed. In the blended space of directionality with sign, different elements projected into the blended space could lead the signs to be associated with space–fixed coordinates, body–fixed coordinates, or comparative directions. Similarly, in the blended space of location with sign, the signs could account for location on the left or right side of the origin, as well as with operations for determining distance between two points on the axis according to combinations of signed and unsigned numbers. This is important because prior work in PER usually focuses on only one blend resulted from each pair of spaces; the difficult work is in selecting input spaces, not selecting the blends resulted from selective projection of input elements.

Among the six blends, the blends between location and sign could closely relate to the triple natures of the minus signs in elementary algebra[32]. For instance, the negative sign in the negative signed number $x = -a$ purely carries the unary function (a location relative to an origin). With the sense of getting shorter or longer distances in an unsigned blend, we claim that the negative sign in such expressions as $(x - a)$ is used as a binary function of taking away. Especially when treating x as a positive number and realizing that x could be negative in the left region, Charlie's attempts to extract the negativity out of the variable x, turning it from a signed to an unsigned number, suggest the minus sign in $-x$ falls into the symmetry category on Vlassis's map. On rare occurrences, we might see all three meanings of the negative sign appear in a single mathematical expression: $R_{-q} = -x - (-a)$ (Table 4, move 7).

Although helpful, the map developed by Vlassis does not fully account for the negative signs that come from vector algebra. The negative sign associated with opposite relative direction could be symmetrical (in the case of a relative sign) or binary (in case of the connecting sign in a mathematical expression of interference). In addition, there seems to be no good match for the body–fixed coordinate or the space–fixed coordinate convention. Since the map of different uses of the negative sign is highly context–sensitive, the transposition of meaning from elementary algebra to physics will require inevitable adjustment and expansion.

Meanwhile, the recently proposed framework of the nature of negativity in introductory physics (NoNIP) can well capture meanings associated with signs that we discussed this problem(46). Indeed, part of our analysis in the Oliver case has been re–analysed with new and harmonic insights. However, using conceptual blending supports us to define the input spaces and view this phenomenon from different angle and discussion: relation between meanings assigned to signs.

By considering five different blends within the context of conceptual blending theory, we analyzed two case studies to see why an introductory–level physics problem turns out to be challenging to upper–level undergraduate students. We scrutinized the existence of these blends throughout the students' reasoning. Most of the blends were constructed and employed subconsciously and without effort, while others were employed deliberately and with more effort. Students were observed to continuously switch among the meanings to use, combine those meanings, and affiliate meanings to the last signs left in the expression. We claim that the problem is challenging for students because there are not only multiple signs coming within a single expression, but also multiple meanings with which the signs could associate, where students need to carefully choose what blends to use. This is important because blending work outside of PER suggests that the process of blending is fast and automatic, whereas work within PER indicates that it can be slow and difficult.

Adding to the current literature of multiple representations associated with a concept, we affirm that the multiple physical meanings that can be associated with a simple algebraic symbol could also cause difficulties. One possible source of these difficulties is students' lack of understanding of the meaning embedded in a sign. For example, both Oliver and Charlie never explicitly talked about the body–fixed meaning but kept using them unwittingly as having been drawn from an authoritative source. Eventually, Charlie affiliated the body-fixed blend with other blends, while Oliver decided to just ignore it. An implication from this study is that students need more help to better understand, distinguish, and link the deeper meaning of algebraic signs that instructors often overlook and talk about implicitly. This might then lead to more successful problem solving.

Chapter 3

Equity in lab group work

3.1 Introduction

Undergraduate physics students commonly work collaboratively in laboratory settings, spending most of their time cooperatively working to accomplish the same goal in groups of 2 – 4. Advanced undergraduate laboratory courses provide students with unique environments to develop their physics identities and interest to persist in the field. In the curriculum, these courses sit at an intermediate level between prescribed introductory labs and authentic experimental research labs[(61)]. We situate our work within the body of research investigating various aspects of students' group interaction in the instructional laboratory setting as an effort to better understand and further assist students' learning experimental techniques and concepts.

Previous work has argued that equitable group work supports individual learning[(62)], where equity is defined as the "fair distribution of opportunities to learn or opportunities to participate"[(63)]. Because learning occurs through the mediation of discourse in group work, students' opportunities to participate in learning activities are closely linked with their authority and power in carrying out discursive actions. In this work, we are looking at group interaction dynamics through the lens of inchargeness, which characterizes the authority and power in driving group activities through discourse[(64)]. We qualitatively study group members' inchargeness in relation to their on-task expertise, which is defined as students' relevant skills and knowledge of the task at hand. The differential on-task expertise of group members in upper division laboratories also closely simulates authentic research labs, where it is likely for new members to join on–going projects. If a member lacks on-task expertise, their inchargeness within the group diminishes, which in turn reduces their quality of learning and collaboration as well as their opportunities to engage.

3.2 Theoretical framework

Positioning Theory helps explain the process through which discourse participants take up, or are assigned, positions, which are associated with their rights and obligations of speaking and acting[65]. Their positionings are only holistically specified by their communication acts (both linguistic and paralinguistic) in reference to the storyline of the activity. Storylines are the implicit or explicit patterns by which interactions develop and through which discursive actions are understood. Positioning, storylines, and communication acts dynamically interact. Changes between storylines can entail changes in the participants' communication acts, which can challenge their initial position and cause them to reposition. The new positionings can then influence the ways in which participants act and storylines evolve.

The inchargeness framework is rooted in Positioning Theory. Inchargeness characterizes one's power in directing the flow of an activity, which is intimately associated with other participants' positionings and communication acts in the current storyline[64]. An individual with high inchargeness is positioned within the group such that their acts are more likely to include successful bids to steer an activity. Paying attention to the combination of behavioral markers (who sets and limits the group activity; who asks and answers questions to direct that activity; types of discourse; whether communication acts are overlapped or sequential; and to whom the acts are done) helps us infer the group's inchargeness distribution. The group's inchargeness distribution dynamically changes over the course of interactions. However, within a determined storyline, individual inchargeness tends to shift within only a small range[62;64].

Inchargeness differs from on–task expertise. For example, in a panel session at a conference, the person with high inchargeness (the presider) is often not the most expert on the discussed topics (the panel members). While the inchargeness and expertise distribution in the conference panel storyline is well–known, other storylines are more emergent. Emergent storylines can have varying patterns of inchargeness, and differential on-task expertise may influence the participants' inchargeness. In this work, we investigate the relationship between inchargeness and on-task expertise throughout two emergent storylines: "catching up" and "moving forward".

3.3 Context and methodology

We studied video recordings of the group work of three second-year physics students – "Charlie", "Abbey", and "Will" – in an upper division laboratory course at a US university. This course includes classic experiments in modern physics including X–ray diffraction (XRD), where X–ray diffraction is used to ascertain crystals' structure, and Lifetime of muon (LoM), where oscilloscopes measure the time required for muons to decay in a scintillator. Students usually spend three lab meetings of about three hours each to complete each lab, producing individual lab reports. Charlie, Abbey, and Will all attended all of the meetings for their first lab (LoM). For the XRD lab, however, Abbey missed the first day. While the group members' on-task expertise was all similar in the LoM lab, Abbey started the second day of XRD with noticeably less on–task expertise than Charlie or Will. Group dynamics were consistent throughout these lab meetings, so we present the parts that are unaffected by the instructor or the teaching assistant; i.e. about the first 25 minutes. We qualitatively analyze the interaction of the students with each other and with the lab environment to identify storylines, communication acts within those storylines, and the students' positioning and inchargeness as enacted in those communication acts.

From the preliminary observation of the students' relative positionings and inchargeness in driving group activities, we fixed on two emergent storylines in the XRD lab: "catching up" and "moving forward". These storylines are associated with Abbey's significantly reduced authority to participate in lab activities, which resulted from her lack of on–task expertise. By contrast, in the LoM lab, there is a storyline of "conventional group work", where all members have relatively equal authority in group activities. We iteratively analyzed the interaction within each storyline using behavioral markers to further clarify how bids are made and taken up, which eventually identifies the students' relative inchargeness. We refined storylines, synthesized the overall inchargeness distribution within each storyline, and compared the inchargeness distribution across the three storylines. The analysis was collaboratively discussed until a consensus was reached among the group of authors.

3.4 Analysis

The XRD lab did not require students to set up equipment, but the students did need to figure out how to operate the X–ray apparatus with different crystals as well as collect, read, and interpret the data from the computer. In the first day of the XRD lab when Abbey was absent, Charlie and Will explored the apparatus and the physics of the experiment as well as collected several sets of data. On the second day, the group, including Abbey, seemed to perceive her lack of on–task expertise. Abbey expressed this by repeatedly asking for information about the ongoing lab. Charlie and Will also occasionally paused to explain to her what was happening. Abbey could not immediately engage in specific on-task discussions with Charlie and Will. Rather, she first needed time to catch up with the general lab activities while Charlie and Will progressed in the lab. We find that the group interactions in this lab period are characteristically different from other periods because there is a gap in their on–task expertise. We found two concurrent storylines — "catching up" and "moving forward" -– to show how students engage in positionings and communication acts and allow us to determine their inchargeness.

3.4.1 "Catching up"

The "catching up" storyline involves activities and discussions where Abbey socially and intellectually catches up with her peers after missing a meeting. These discussions were mostly about general procedural aspects and discussions on sharing materials and writing up the LoM lab reports. These tasks were also parts of the lab activity, in which Abbey could have engaged with Charlie and Will if she had attended the previous meeting.

Because Abbey leans on Charlie and Will to catch up on relevant understanding of the on–going lab, Abbey usually waited for Charlie and Will's availability to initiate questions. In response, she usually received dictating, narrative, or expository responses from them (Table 3.1) or was told what to do. These discussions were usually interrupted by Charlie and Will's communication acts that steered the activity away from giving Abbey information and back towards other on–task activities (as underlined in Table 3.1). Occasionally, discussion in this storyline was initiated by Will and Charlie. For example, as Will and Charlie ran the experiment, they showed Abbey how to turn off the X–ray properly. Similarly, Abbey also initiated activities around lab materials by offering Charlie and Will the XRD lab printout and her LoM lab report write–up or asking for further help on lab reports. This communication act of Abbey might be viewed as her effort to contribute to and gain inchargeness within the group or in return for Will's and Charlie's help on the current and previous labs. However, these activities usually died off quickly with only brief or even no response from Charlie and Will.

Although Abbey initiated many of the activities and her questions were usually addressed throughout the "catching up" storyline, her peers often intervened with other topics, steered the activity away, or withdrew from her topic before giving her full details, resulting in her repeatedly asking similar questions. These behavioral markers show that Abbey had significantly lower inchargeness than Charlie or Will during this lab. We claim that Abbey's reduced on–task expertise caused her to position Charlie and Will as knowing more than her, which reduced her inchargeness. Charlie and Will were in relatively higher positions of inchargeness than Abbey as they were an important source of information for her, from whom she actively sought responses and attention. Therefore, Charlie and Will's acts strongly impacted the way the activity proceeded when compared to Abbey's acts as an information receiver.

Table 3.1: *Excerpts from "Catching up" storyline*

Abbey: Do you want to do a quick review of what you've been doing?
Will: Hm...
Charlie: [to Abbey] Right now, we're calibrating.
Will: This shoots X-ray that hits crystals [...]
Charlie: [overlapping to request Will] Do you [want to] stand by the switch?
Will: This is the step motor, which turns that...
Charlie: [interrupting to direct Will again] Yep, just in case, hold on, it's still good.
Will: Hm... [to Abbey] this piece of tape stops it if it goes pass through that kind of traffic, don't let it do that, so you shut if off before it...
Charlie: [to Abbey] Yea [audio], so you have to stop.
Abbey: And then what, we just read the stuff off from the computer?
Will: Yea. Hm... We already did an experiment where we we look at the characteristics of the X–ray off the crystal [audio].
[Charlie intervenes and directs the group working on the experiment.]

3.4.2 "Moving forward"

The "Moving forward" storyline primarily consisted of extended discussions between Charlie and Will about the intellectual aspects of specific tasks need to make progress in the lab (such as measuring specific quantities or addressing specific questions in the lab book). In this storyline, Charlie and Will almost exclusively set the topics. They sequentially asked and answered each other's questions, built on each other's ideas to make further decisions, and took actions without explicitly addressing their speech to Abbey. Abbey appeared attentive to these discussions even though she didn't say much. For example, Charlie and Will did not include Abbey in their discussion when clarifying what "question 3" means. During this discussion, Abbey reached for her lab manual, and tried to figure out what the question was about. It was not until Charlie and Will came to the end of the discussion that Abbey joined the conversation just to confirm the topic – "Oh, we are already right here, right? This is where we're at? [pointing at her lab manual] [...] So you guys already did everything else." Charlie and Will also alternately spoke up to suggest ideas and approaches as well as evaluations of those ideas and approaches, while Abbey gave barely any on–task suggestions or evaluations of suggestions.

Occasionally when running the experiment, Charlie purposefully addressed his speech to Abbey in the form of assigning her simple tasks such as clicking the computer mouse or operating the X–ray (Table 3.2). Abbey clearly took up Charlie's bids. Her speech and actions throughout these discussions were not to steer the discourse away, but rather to ensure that she correctly followed up with the topic that Charlie set. Although Will didn't speak up much in those task–assigning discourses, the expertise he had built by previously operating the X–ray allowed him to intervene and successfully direct Abbey's X–ray operating actions as shown in Table 1.

Table 3.2: *Excerpts from "Moving forward" storyline*

Charlie: [to Abbey] Alright, you can strat the X-ray, and I will start acquiring the data. Abbey: So, I start now? Charlie: Yea. [Abbey fails to operate the X-ray. Charlie comes over to check the X–ray.] Charlie: Hold on. Abbey: Am I doing it wrong? Charlie: No, it's me, it's just not be... Will: Make sure it gets on the back because [audio] [Charlie follows Will's instruction then gets back to the computer.] Charlie: Okay. Abbey: Ready? Charlie: Yea.

Behavioral markers show that Abbey had significantly lower inchargeness compared to Charlie and Will throughout the "moving forward" storyline. Charlie and Will shared the power in driving the group activity: they alternately initiated topics and suggested ideas and only addressed their questions and answers toward each other. Meanwhile, Abbey engaged with very few turns of speech and actions, and most of those were taking up her peers' bids. We contend that Abbey's reduced inchargeness in this storyline was connected to her low relative on–task expertise. This gap in on-task expertise set Charlie and Will at a higher positioning than Abbey, where they were more authorized to carry out most of the communication acts that moved the lab forward, whereas Abbey played a minimum and passive contributive role.

3.4.3 Contrasting narrative in the "conventional group work" storyline

Abbey's lack of on-task expertise in the "catching up" and "moving forward" storylines contributed to her lower inchargeness in those storylines compared to her peers. In contrast, on the first day of the LoM lab, they worked together and had similar on–task expertise as the lab was equally new to all of them. We found one storyline of "conventional group work" where they positioned themselves as having equal authority to participate.

In contrast to the XRD lab, where Abbey rarely interacted with the instructors or contributed to on–task topics, Abbey was an equal participant in LoM: she independently invited the teaching assistant to check the setup, rather than waiting for Charlie or Will to do so. Throughout this storyline, Charlie, Will, and Abbey all engaged in various on–task activities. Abbey comfortably contributed to the group's progression: she brought up concerns, shared related experiences, gave on-task suggestions, and followed up on–task discussions by sequentially asking and answering her peers. Although Charlie and Will still made more speech turns, more often initiated topics, and sometimes didn't explicitly address their speech to her, Abbey certainly made more successful bids to drive the group activity and the relevance of her bids to the ongoing tasks helped her bids to be taken up more frequently compared to the XRD lab. For example, when Will and Charlie proposed to start running the experiment with high voltage, Abbey interrupted that plan with a suggestion that the group ensure the setup safety first. They then all followed up to explore each other's ideas on the need of checking with the instructors for safety.

These behavioral markers infer that Abbey still had less inchargeness than Charlie and Will in this storyline. However, the gap in inchargeness was much smaller during the LoM lab than on the second day of the XRD lab. Abbey's equal on–task expertise with others put her in a position where she was able to make more on–task relevant bids that her peers would consider. This contrasting case supports our claim that lower on–task expertise decreases inchargeness as the "conventional group work" storyline diverges into the "catching up" and "moving forward" storylines.

3.5 Conclusion

From the perspective of Positioning Theory, we defined the "catching up" and "moving forward" storylines that are tightly tied to the gap in the students' on–task expertise. The students shift back and forth between these two storylines, which properly expand the lab period interaction. Analyzing behavioral markers in these storylines, especially the types of discourse and the way each student contributes to the conversations, we find that Abbey has much lower inchargeness relative to her peers in driving group activities. In contrast, the gap in inchargeness is significantly smaller when all group members' have similar on–task expertise. We contend that one's smaller on–task expertise leads to reduced inchargeness, which may subsequently reduce opportunities for participation and therefore for learning.

Our work investigates inchargeness with a focus on on–task expertise to unpack the richness of group dynamics in laboratories. We also recognize that other factors are likely exist that cause uneven distributions of inchargeness in collaborative groups. More work should be done to learn the impacts of on–task expertise (due to missing a class, joining new groups, etc.) and other factors that influence group dynamics.

Chapter 4

Summary and future work

In chapter 2, I am interested in the phenomenon where students associate positive and negative signs with polysemous meanings. I use the mechanism of conceptual blending theory to show how different blends can be constructed from the same input spaces. Each of the blends accounts for a meaning that student can tag on the signs. From the lens of conceptual blending theory, this phenomenon is due to the selective selection of inputs from each space for blending. We contend that negative and positive signs can be ascribe with polysemous meanings, causing troubles when students solving physics problems.

This result is in consensus with current literature: students' struggles in problem solving may not be merely due to their mathematical skills. Rather, successful problem solving requires students to be able to understand and navigate the physical meanings of mathematical representation in that context. Yet, the model we constructed contributes a relatively new lens to the way conceptual blending theory has been used in physics education research: same input spaces can produce different blends, which causes students trouble as they need to choose the appropriate blends.

Additionally, research using conceptual blending often focus on individual moments where students construct a new meaning or make sense of an idea. My analysis, on the other hand, offers a way to characterize students blending between math and physics over the entire course of their problem solving. This approach aligns with some researchers' epistemological belief which appreciates students' fruitful chain of thoughts, although they often emerge from dense and messy problem solving processes.

This work contributes a relatively new aspect to our knowledge of physics students' understanding and reasoning. Yet, the further application of this work can remain questioned. This issue is, indeed, one of the concern of researchers using cognitive psychology theories in general and conceptual blending theory in particular. More work need to be done to shine light on the effective instructional implication from our growing understanding.

In chapter 3, we adopt the inchargeness framework and positioning theory to investigate students' group dynamics. As discussed in this chapter, many factors could influence students as they take up different positionings, which produces differing inchargeness and power dynamics. My study, however, is not a exhausted list of those influential factors. In fact, I only focus on one characteristics: each member's on-task expertise perceived by others in the group.

This finding is neither surprising: members with higher perceived on-task expertise often have more inchargeness, and thus learn more. However, upper-division physics laboratory is still a largely new landscape, where the characteristics and dynamics of interaction is still under exploration. The dynamics I describe in this work can be thought-provoking to lab instructors. How should we group students? What can we attend to in order to notice the group dynamics? How could we support low perceived on-task expertise members in a group? These practical questions along with other factors such as inter-sectional identity (gender, race, socioeconomic class, etc.) are interesting extension of the current work.

Another direction for this work is deepening the interaction of the same group and extending research to other groups to search for the complex relationship between group dynamics, equity, and individual identity development. Previous research has discovered how interaction with instructors and peers can impact students identification as physics people, which in turns affect their participation in those interactions. Using our available longitudinal data, it can be interesting to observe how students set up and navigate inter-personal relationship with different groups of peers and their changes in engagement with physics over time.

Taking a step back from these two studies, they are both important aspects of student professional development. These two aspects of development are inevitably entangle and influential each other. Students' individual success in their courses may lead to their comfort with identifying themselves as physics people and impact their relationship with other peers. On the other side of the coin, a students who view themselves as a physics person in interaction with other peers might gain learning opportunities which extend their confidence and ability beyond group setting or in individual work as well.

That means it would be greatly beneficial to cross-analyze the interview data presented in the chapter 2 and 3. The two studies share a large portion of students who participated in several interviews, classroom observation, and oral exams, giving us the opportunities to study these students' professional development more holistically. Unfortunately, this great opportunity is beyond the scope of the dissertation. But I hope the ideas provoke interests in future education research dissertation projects to discover the fuller picture of students professional development.

Part II

Faculty long-term professional development

Chapter 5

Review of related literature and studies for part II

5.1 Introduction

Education continuously changes with respect to major economic and societal shifts. There is a wave of reforming the educational system with the ultimate goals of increasing students' capacities to succeed in constantly evolving situations. Reformed movement in STEM education, such as PER, focused less on policy, but more directly on changing faculty teaching practice[(66)]. PER has been creating a large reservoir of research-based instructional strategies (RBIS) and disseminating these materials to faculty. Examples of some successful RBISs include Tutorials in Introductory Physics[(67;68)], Peer Instruction[(69;70)], RealTime Physics[(71)], along with their guides for classroom implementation[(67;72;73)]. A more holistic review of PER products in reformed movements can be found in the Resource Letter by Meltzer and Thornton[(74)].

Strubbe et al.[(75)] has termed this research paradigm as teaching-method-centered paradigm. This paradigm has been successful in bridging the gap between research in education and faculty teaching practice: more college physics faculty are aware of and using RBIS over time and RBIS are used more often in physics classrooms compared to other disciplines such as biology or chemistry[76;77]. However, RBIS are only, at best, marginally integrated in classroom practice[78]. Surveys of faculty in physics[76] reveal that less than half of the respondents report some use of RBIS and they often use them with significant modification, which risks the intended efficacy of RBIS[79;78;80]. Moreover, a large portion of instructors who adopted these methods discontinued their use[76].

Although education researchers have put a lot of time and effort into devising and disseminating RBIS through publication, conference talks, professional development programs, etc., the insubstantial impact of RBIS on changing classroom practice suggests that we need to reconsider the approach of teaching-method-centered paradigm and address other challenges that impede instructors' processes of incorporating RBIS[81]. An array of work has done surveys, interviews, and classroom observations to identify barriers to instructors' adoption and continuing use of RBIS, including individual and structural factors[76;77;81;82;83;84].

Common individual factors are limited training in the use of reformed teaching strategies, lack of resources, uncertainty with the practice, and pedagogical preference[76;85]. Instructors report greater barriers coming from structural factors, such as department norms, expectation for content coverage, time constraint, class size, absence of institutional support[66;77;86]. Additionally, many faculty members may struggle with professional identity that is set up by their departmental norms, where being regarded as a successful researcher holds higher status than being an effective teacher, especially at research-oriented institutions[84]. Although research in this strand acknowledges the various barriers against faculty implementation of RBIS and encourages researchers to further consider faculty individual situations when disseminate RBIS, they often dismiss faculty's ability and competence to navigate through their situation and overcome personal challenges.

Concurrently, researchers have deepened in the nature of the teaching-method-centered paradigm and addressed issues around this approach[75;87]. Henderson and Dancy[87] propose an adoption-invention continuum to describe the interaction between instructors and researchers. They found the divergence between instructors' and researchers' viewpoints of the reformed education approach regardless of their shared goal for better teaching practice. Although instructors are convinced and believe in the effect of RBIS, some of them tend to reinvent the materials and/or invent their own materials. Meanwhile, researchers expect instructors to adopt or adapt these materials with minimal modification. Additionally, dissemination of educational products under teaching-method-centered paradigm rests primarily on researchers' negative view of faculty as having traditional conceptions about teaching and being reluctant to change[87;75]. This negative view of faculty eventually holds little validity and productivity in bringing together educational research and teaching practice[75;88;2].

The two streams of mentioned research have reached the same conclusion: researchers need to do more work to understand faculty situational and structural conditions and work with faculty to integrate new research-based ideas into their teaching practice[86;78;89;2]. Previous work started with observing faculty's process of change, focusing on how faculty make decisions to implement a particular teaching innovation. Most of these studies are conducted over a short-term period during which faculty decide and try RBIS. The findings often provide little new information, that faculty's discontinuance of RBIS or partial incorporation of RBIS is due to various internal and external constraints[77;85;79;90;86].

In this work, I conduct a qualitative longitudinal investigation of faculty processes of change and emphasize faculty's ability to understand their situation, develop experiences, and overcome the encountered constraints over their long-term career. Taking the asset-based agentic view of faculty proposed by Strubbe et al.[75], I believe and show that faculty have fruitful and productive resources around teaching that are compatible with education research. We observe that faculty continuously incorporate new ideas from educational research through various avenues, which may or may not include specific RBIS, to make meaningful decisions that best fit their teaching practices. I focus on factors that are most influential to faculty in their long-term processes of change. The outcomes of this study contribute to the literature of faculty professional development a rich description of tracking faculty growth over time. More work is needed for generalizable results, yet our case studies with faculty from various backgrounds reveal the commons that can imply further insights for research and practice for sustainable, long-term change in faculty's classroom practice.

In the next section, I introduce and explore in depth some theoretical background that influences our choice of theory and focus of analysis. These literature include the asset-based agentic view of faculty[75], adult learning theories, and some models of change process[2;91]. I introduce the framework I use to guide this study – the Reasoned Action Approach – and its application in study around professional development in the next chapter (chapter 6 . The rest of part II focuses on the three case studies of three faculty members on their long-term processes of change and the insights these case studies offer.

5.2 Literature and theory background

5.2.1 Asset-based agentic paradigm

Strubbe et al.[75] address substantial limitations of the teaching-method-centered paradigm around viewing faculty and disseminating PER products. According to Strubbe et al.[75], teaching-method-centered paradigm primarily builds on the premise that using RBIS with greater extent of fidelity yields better teaching outcomes than any other interactive ways of teaching. This premise dismisses faculty's roles and ability around their own teaching. The teaching-method-centered paradigm faces the challenges in validating RBIS's value, as there are various extents to which faculty commit to the principles of RBIS other than intended by the developers. Relying on this premise, research under the teaching-method-centered paradigm inappropriately assess faculty's improvement and success in their teaching practice through their awareness and exercise of RBIS.

Noticing the importance of faculty's unique contexts that in many ways affect their integration of RBIS, other work under teaching-method-centered paradigm explicitly encourages faculty to borrow RBIS principles and customize RBIS pieces to better fit their situations[87;92;93]. Despite this positive effort, Strubbe et al.[75] point out that the teaching-method-centered paradigm still does not account for good teaching that is not grounded on RBIS and disregards faculty's other values and expertise. In contrast, Strubbe et al.[75] propose an alternative model called asset-based agentic paradigm which emphasizes good teaching practices that, although align with educational research, may not fall under specific available RBIS. Building on the frameworks of How Learning Works[94], Self Determination Theory[95], and Bandura[96]'s work on agency, the asset-based agentic paradigm characterizes that faculty have productive resources and agency around their teaching – the features that are often missed in the teaching-method-centered paradigm. The asset-based view emphasizes a wide variety of teaching principles (expanded on Ambrose et al.[94]) that are more likely to align with faculty's self-described practice. At the same time, the agentic view recognizes that faculty certainly have self-efficacy and motivations to improve their teaching – which guide them to plan, reflect, and make intentional decisions regarding their teaching[96;95]. The asset-based agentic paradigm therefore, offers an approach that can address issues around the teaching-method-centered paradigm that many PER studies have been implicitly and explicitly accumulating.

I situate this study in the asset-based agentic paradigm, where I consider the professional development of faculty as trajectories where faculty exercise their agency to make changes in their teaching practice. These changes include implementation of RBIS in any form along the adaptation-invention continuum[87], but do not exclude development of other ideas and practices. This includes, but is not limited to, using external resources from YouTube, materials designed by faculty colleagues, or revising and inventing materials inspired by research-based ideas. We believe that using an asset-based agentic view of faculty can elicit a fuller picture of productive and thoughtful faculty. This study aims to reflect a more holistic and realistic interaction among individual faculty members, educational research and their institutions, giving direction for further professional development activities.

5.2.2 Adult learning theories and teachers' professional learning

Professional development is generally defined as a process in which teachers bring about changes in their classroom practice with the ending result as improvement in the students' learning[2]. Although research often critically links teacher professional development and student learning outcomes, perspectives of professional development that are more faculty-centered have become popular[75;2]. One common approach considers faculty change in belief, attitude, practice, and knowledge as an important impact of faculty professional development. This approach connects faculty professional development with a broader context of professional learning, especially highlighting the aspects of lifelong and continuing learning[2;97;98;99].

Elmore and McLaughlin[88] emphasize that "the problem of promoting change in teachers' practices is a problem of promoting learning in adults". While identifying multiple perspectives of "teacher change", Clarke and Hollingsworth[100] advocate for the identification of "[teacher] change as growth or learning". Under this perspective, change is associated with learning – it is a natural and inevitable outcome as faculty engage in their professional activities. Aligning with the asset-based agentic paradigm[75], this approach moves away from a deficit model of faculty. Meanwhile, other approaches that narrowly focus on changing teachers by changing their well-established practices and knowledge, such as adopting RBIS, often misses the key elements of productive and sustained learning. In this work, I use the term professional development to refer to faculty change which is embedded in various professional learning activities, such as professional development programs and job-embedded activities[101].

Considerable research has been done in adult learning theories and given suggestion to adult professional development, specifically teacher professional development. Trotter[102] reviews a list of research around adult learning theories, including age and stage theories, cognitive development theories, and functional theory. Altogether, the work in adult learning theories emphasizes the roles of learner's experience and autonomy in the process of learning and changing. Adult learners have a need to be self-directed in their learning - they prefer to plan their own development path and choose to learn topics that are interesting and relevant to their existing experiences and situations. Strongly aligning with the asset-based agentic paradigm[75], research from adult learning theories advocate that professional development programs need to attend to faculty's intrinsic goals towards teaching, respect faculty's experience, and allow faculty latitude to form their own professional development.

Adult learning theories add an important factor to the discussion around faculty development that change, associating with learning, is a lifelong process. I found that it is meaningful to situate our investigation of faculty professional development or faculty processes of change through the lens of professional learning, just as Guskey [2] emphasized that "change is primarily an experientially based learning process for teachers". We think that faculty development, therefore, should not be evaluated through a single event of implementing specific new instructional techniques. Rather, faculty development should continue to be followed up in the long term, where faculty motivations and beliefs for further learning and change are important outcomes. Research from adult learning theories also address other critical elements of the learning process including communities of practice [103;104], motivation [105], and reflection [106;107]. These elements are also present and essential in many models of change, which I discuss in the next subsection (5.2.3).

5.2.3 Models of change

Understanding the faculty process of change is important in studying their professional development. Guskey [2] points out that professional development programs often fail not only because they do not consider faculty's motivation to engage in professional development, but also because they do not address the process by which teachers make changes. Research around professional development has created several models to operationalize faculty's decision-making process, addressing how they decide to execute instructional changes in their classroom, such as adopting or inventing new instructional techniques. In this subsection, I want to review two models: a model of teacher change by Guskey [2] and the innovation-decision process by Rogers [91]. While the former one is popular in various fields from medical education to science education, the latter is one of the most popular models used by physics education research to disseminate RBIS [78].

A model of teacher change

Guskey [2] proposes a model to characterize the process that teachers decide to adopt a new teaching method (Figure 5.1). According to this model, a teacher experiences a change in their beliefs and attitudes toward a new method only after trying the method in their

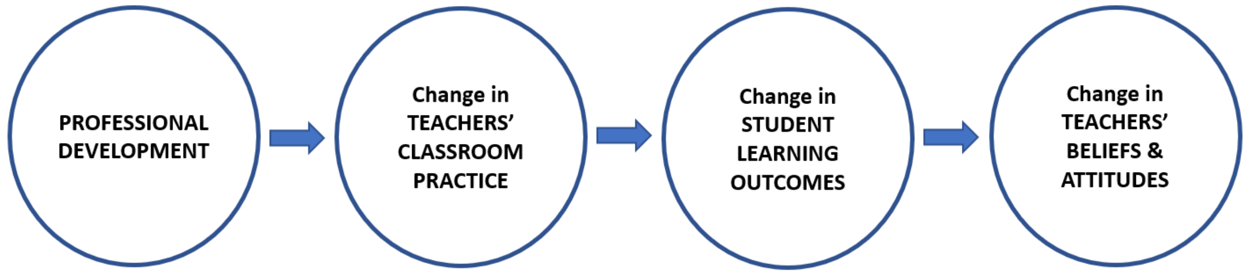

Figure 5.1: *A model of teacher change*[2]

classroom and seeing the positive effect of the method on their student learning outcomes. Crucially, it is not the professional development that causes the change in teachers, but rather the evidence of their own successful implementation that shifts the teachers' belief and attitude. Vice versa, when a teacher tries to bring in a new method, but it lacks the evidence of student improvement, they are unlikely to gain positive beliefs and attitudes towards the new method and further changes are unlikely.

Professional development program developers and researchers often put their main effort in changing faculty ideas and beliefs about teaching first. This intention is based on the presumption that once faculty gain new beliefs and attitudes, they will commit to and adopt research-based materials, which eventually improve students' learning. In contrast, Guskey[2] emphasizes that significant change in teachers' beliefs and attitudes should be considered as the ending stage in the process of change. The change in beliefs and attitudes facilitates and guarantees a meaningful and long-lasting change in teachers' practice. This model aligns with findings from observation of faculty's instructional reform, that change in beliefs and attitudes are not necessarily followed by long-term change in practice. Rather, faculty are often found to quit the RBIS use and return to their prior ways of teaching after trying RBIS unsuccessfully[76].

Guskey[2]'s model of teacher change offers a strong emphasis on connecting faculty professional development with adult learning theories, where faculty's decision of adopting new RBIS are strongly influenced by their individual experience of learning about and using new RBIS. However, the model tends to describe the faculty process of change as strictly linear.

Continuing expanding on Guskey[2]'s work, Clarke and Hollingsworth[100] proposed a cyclic model with flexible entry points. They also added the dynamics of reflection and enactment to connect the stages of change. Still, these models may appear to oversimplify the complex process of change, where situational and structural factors are not explicitly included. Moreover, the models do not specifically include changes that are inspired by faculty career practice and are outside of professional development programs. Guskey[2]'s model also suggests some level of fidelity needed to exercise during the transition between professional development and change in teachers' classroom practice. These implications oppose some of the core ideas in the asset-based agentic paradigm that guides our work.

Innovation-decision process

Considerable research, particularly in PER, has approached faculty change using Rogers' model of innovation-decision process[91] [77;78;82]. Innovation-decision process operationalizes faculty decision-making process to adopt innovation through five stages (Figure 5.2): Knowledge, Persuasion, Decision, Implementation, Confirmation. During the Knowledge stage, faculty gain "awareness" knowledge (knowing an innovative strategy exists), "how-to" knowledge (knowing how to use the strategy), and principles knowledge (understanding critical elements of the strategy as intended by the developers). During the Persuasion stage, faculty make conscious consideration of the benefit and applicability of the innovative strategies. This consideration forms certain beliefs and attitudes towards the innovation, which imply the decision and the action they make to implement the innovation in the Decision stage and Implementation stage, respectively. In the Confirmation stage, faculty members evaluate the success of their implementation to decide to continue using the innovative strategy.

Essentially, Rogers[91]'s innovation-decision process differs from Guskey[2]'s model for teacher change in where faculty's change in beliefs and attitudes towards the innovation would occur. Rogers[91] suggests that faculty shift their beliefs right after gaining the knowledge of the new methods and before implementing them. Guskey[2]'s model, on the other

Figure 5.2: *Innovation-decision process (as presented in Dancy et al.*[3]*'s work)*

hand, argues that change in beliefs and attitudes only occur after trying the new method and directly precedes the decision of continuing use. Research using the innovation-adoption process finds that faculty are generally convinced of the value of innovative strategies such as RBIS[82]. However, it is subtle and unclear in the study if faculty are convinced of a specific RBIS before using them.

Crucially, the innovation-decision model takes into account factors that impact the stages in the process of making decisions such as individual factors, contextual influences, and communication channels that are only implicitly implied in Guskey's model of teacher change[2]. The influences of those factors are evident in numerous studies around faculty professional development, especially around the barriers and challenges faculty members face when adopting and adapting new RBIS[77;82;83;84;81;76]. However, research has also addressed some limitations of the model in light of faculty-centered movement. For example, when qualitatively conducting a change process of a faculty member, Henderson[85] notices that the model presumes innovation to come from external resources and does not consider invention by the faculty member. Moreover, while Rogers' model proposes innovation decisions are based on significant knowledge of the innovation, Henderson[85] found that the faculty member did not seek extensive information about the innovation before use. Instead, faculty often make significant changes of materials, even risking the critical elements of the innovation as developers intended. These findings are consistent with other large-scale results[3;78;76].

This work does not attempt to argue for the superiority of one model of change over the other. Instead, I learn from the merits and limitations of these models when searching for the framework and analyzing our data. Although the two models do not completely overlap in many aspects, they collectively imply important things about faculty professional development: change is a gradual and difficult process, which involves a great amount of time and effort. Faculty change process needs to be framed around the core idea that "teachers are learners", which are influenced by their personal and structural factors, and the communities within which they learn and change. Both models emphasize faculty reflection on the experience with implementing new strategies to make informed decisions to endure or reject the change.

5.2.4 Our approach to studying faculty change

I situate this study at the intersection of the three mentioned literature: asset-based agentic paradigm, adult learning theories, and models of change. From the asset-based agentic paradigm, I decide to approach faculty experiences of professional development from the faculty-centered point of view. This analysis includes faculty's various teaching practices that are often disregarded by the teaching-method-centered paradigm and pay special attention to faculty's agency when making changes in their practice. From the adult learning theories, I want to situate faculty professional development within faculty professional learning that continuously occurs through formal and informal professional activities. I think that learning is an essential step of professional development as faculty continuously reflect and build new knowledge on their existing understanding. The role of learning in adult learning theories are emphasized in models of change, where learning is a first step of many change models. Adult learning theories also address that learning for adults is lifelong, from which I believe in the merits of investigating the long-term processes of changes. I focus on new things faculty have learned after rounds of reflecting upon experiences and consider their growing knowledge as a positive outcome of professional development. I also look at how models of change emphasize the nature of making decisions in professional development contexts, from which I get multiple ideas about the critical stages and elements of the faculty's process in making decisions and other influential factors along that process.

In this work, I do not argue that these models are either mutually exclusive or inclusive. Although they share similar contexts where studies in each realm have been carried out, they also focus on making relatively different arguments. Neither, I do not argue that they are the only avenues to address positive views around faculty practice. However, in this work, I find the three streams of research offer productive perspectives and directions to address the question: ***What are factors influencing faculty members' long-term professional development, specifically, their trajectories of change?***

Chapter 6

Case studies of faculty on-going professional development

6.1 Theoretical framework

6.1.1 The Reasoned Action Approach

In light of the reviewed literature, we take up the Reasoned Action Approach (RAA) developed by Fishbein and Ajzen[4] to help address faculty long-term professional development. The RAA is developed overtime on their original models – the theory of reasoned action and the theory of planned behavior, aiming to predict and change human behaviors. The RAA proposes that one's behavior is directly determined by their intention. Their intention is determined by the three immediate determinants: the attitude toward behavior, the perceived norm, and the perceived behavioral control (Figure 6.1).

In RAA, the person's attitude toward behaviors is composed of instrumental aspect (the person perceives the positive or negative consequences of performing the concerning behavior) and experiential aspect (the person perceives positive or negative experiences of performing the concerning behavior). Perceived norm considers injunctive norm (the person perceives what should or ought to be done as expected by their relevant and significant

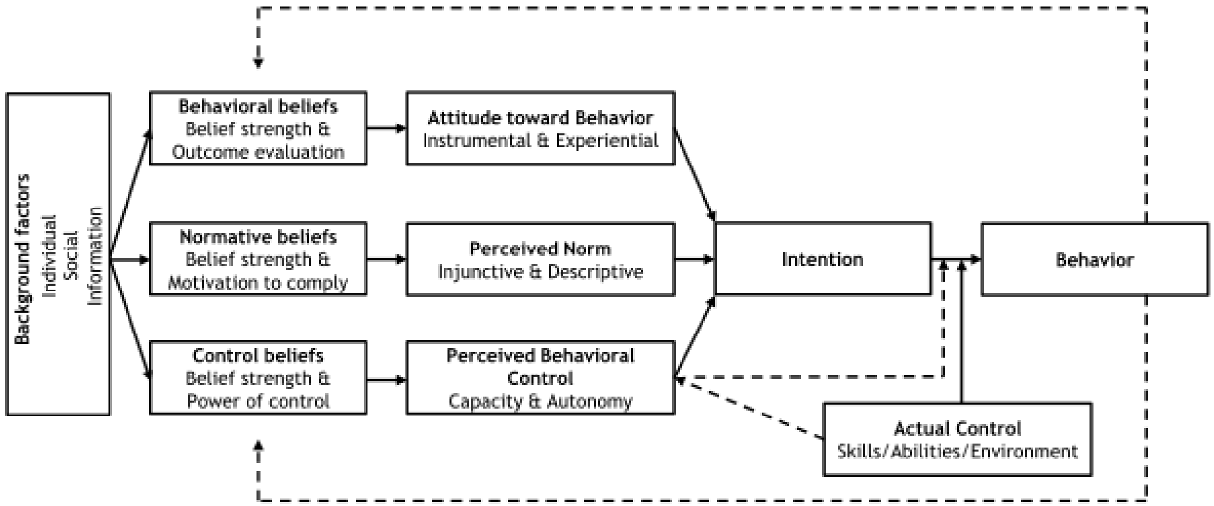

Figure 6.1: *The Reasoned Action Approach*[4] *(graphical presentation designed by Gjalt-Jorn Peters*[5]

relationships) and descriptive norm (the person considers if their fellows are or are not performing the concerning behavior). Perceived behavioral control is the person's perceptions of their self-efficacy and their control over performing the concerning behavior, i.e, their autonomy. The person's perceived behavioral control does not only indirectly influence behavior through intention, but can also directly influence behavior (Figure 6.1). Examples of intention determinants in the context of faculty professional development can be found in Table 6.1.

In the RAA, these three intention determinants are constructed from the person's beliefs towards the behavior, respectively, behavioral belief, normative belief, control belief. These beliefs are constructed from the individual background. The eventual behavior can also feedback into their background to further influence future intentions and behaviors. Additionally, there are actual controls which are the person's actual skills and abilities, and/or the environmental support or barriers, etc. that are beyond the person's perception before forming the intentions. The actual control can influence the process of turning intentions into actual behaviors, such as unexpected external barriers causing actions to differ from intention. But once the actual control is registered, they can also feed back into the perceived behavioral control, which adjusts intention and behaviors appropriately.

Table 6.1: *Examples of the RAA codes in faculty professional development context*

Intention determinants		**Examples**
Attitude	Instrumental	I've always been seeking material that the students can afford and I chose this book because it's cheap.
	Experimental	I have good experiences using a similar book in my other courses and I chose this one because I know it would work.
Perceived norm	Injunctive	Our department has the expectation of us to engage students in class, so I want to try something like active-learning.
	Descriptive	Everyone is trying to become better at teaching, so I don't want to be the only one that sucks.
Perceived behavioral control	Capacity	I cannot grade twenty individual reports, so I decided for my students to do group presentations.
	Autonomy	I think I have enough experience teaching this course to stand up for my decision to change the topics covered in the course.

According to the RAA, the more favorable the attitude and perceived norm and the greater the perceived behavioral control, the stronger the person's intention is and the more likely the person is to perform the concerning behaviors. The RAA and its relative models have been in popular use in research around health behaviors, political choices and other societal actions. In education research, the RAA and its relatives have been applied to investigate teachers' decision to integrate new instructional strategies[108;109], to evaluate professional development workshops[110], and students' enrollment choice[111], etc.

I recruit the Reasoned Action Approach (RAA) because of several reasons. First, the RAA is an integrative model of change that operationalizes human's process of making decisions and actions of change. Compared to other models of change that we discussed in the previous sections, the RAA does not offer a chain of stages that faculty go through when they make changes. Rather, the RAA focuses on identifying and addressing factors shaping faculty's intentions and actions. In this case, we are primarily concerned with influential factors and do not argue for the steps of changes. Therefore, the RAA is a suitable framework for our focus. Secondly, the RAA well captures important factors influencing changes that other models often omit or imply implicitly. Many factors addressed in research around faculty change including individual background, different attitudes and motivations, agency, structural and situational influences, etc. are embedded in this model. Additionally, the RAA also discusses the mechanism by which these influential factors interact with each other and with the individuals in terms of their weight towards making decisions and actions. Thirdly, the RAA offers an explicit way to discuss the cycle of change, where the outcomes of initial actions continuously feed back into the process of change. As we want to address faculty long-term professional development, the model offer tools to address faculty's reflection on their experiences to make future changes.

6.1.2 Our application of the Reasoned Action Approach

The analysis using the RAA is sensitive to the level of generality of which we define the concerning behavior. In the RAA, one behavior is usually identified by four components: action, target, context, and time. For example, we can define the concerning faculty's behavior as "collaborating with fellow teachers to revise Introductory Physics teaching materials throughout the semester". In this case, the action is "making changes", the target is "the Introductory Physics teaching materials", the context is within the "collaboration with the colleagues", and the time to consider changes is "throughout the semester". This definition promotes our focus on a specific change and influences and do not consider other factors that are outside of the defined scope. For example, we may not consider how the same collaborations have helped faculty members change their teaching in other courses concurrently, or how they would plan to revise their teaching in the Introductory Physics in the following academic years.

From our data, we observe that faculty members often teach some set of courses repeatedly over the years. They are also assigned a few new courses additionally. To include the faculty's wide-range professional activities and situations over a long time span, we decided to keep the concerning behavior's definition as general as possible – "making changes in teaching practice over time". In this case, the action of "making changes" on the target of "teaching practice" is considered at any time over their teaching career. Meanwhile, the context is implicitly defined as within the situation where they exercise their teaching, including the courses and the students, the departments, the colleges and the institutions, etc. With this level of generality, we have the opportunities to study a holistic process of change, identifying various factors that impact faculty's intention and action of changes in their long-term career.

6.2 Methodology

6.2.1 Data collection

We recruit interviewees from a wide range of backgrounds. This intentional decision reflects upon our understanding that different faculty, specifically at different types of institutions and at different stages in their teaching career, may have radically different experiences at professional development. To date, we have conducted longitudinal interviews with a total of 8 faculty members, each faculty member has been interviewed four times since 2018. These interviews were part of a larger study in which we interviewed twenty-three faculty members from diverse backgrounds to study their professional development. The results of these studies can be found elsewhere[75;6;112]. In this work, I focus our analysis on three case studies of three participants: Ogilthorpe – a junior tenure-track physics professor at a state university, Khan – a senior instructor at state university astronomy and physics department, Shorb – a junior tenure-track professor at an astronomy and physics department. All names are pseudonyms that are chosen by the participants. I intentionally choose to focus on these case studies as the variation in their experience has shown us both interesting contrast and meaningful generalization.

We designed a semi structured interview protocol in order to gain information and perspectives of individual interviewees regarding their professional development. Two members of the research team (Linda Strubbe and Adrian Madsen) conducted interviews over Zoom with each faculty member, with all interviews about one-hour long. In each interview, we explicitly framed the interview to gain an understanding of the interviewee's teaching and how they made changes in their teaching. In the first interviews conducted in Fall 2018, we started the conversation by asking them about their roles at their current departments, the courses they were teaching, and letting them choose one specific course they would like to discuss in depth about. We then explored their teaching practices, the interview protocol includes: "If I walked into your class last week, what would I see?", "Is there anything new you're trying in your teaching this term?", "How did you learn to teach like this", "How do you know it's working?", "What resources or supports do you draw on to help you with your teaching?", "What are some aspects of how you're teaching this course that you are finding challenging?", "Looking ahead, are there things you're thinking of changing about your teaching for next semester?". In followed-up interviews, we focus more on the interviewees's updates on new changes, reflection of previous changes, and discuss with them more about their self-efficacy and teaching philosophy. There is an exception to the last interviews we conduct with our faculty participants in Spring 2020. We changed part of our interviews to explore the faculty's shift in their teaching in response to the ongoing pandemic. This change is huge and important. Yet, we will only focus on their experiences before the pandemic shift in this work.

Faculty may have broad interpretations of the names of RBIS and may become sensitive when being asked about RBISs. Therefore, we avoid mentioning names of RBIS. Similarly, in exploring the factors that strongly influence faculty professional development, we asked open questions and did not specifically refer to any resources we found impactful in this study. Rather, all of these claims and results emerged naturally and generalized from the participants' narratives we collected. We manage follow-up questions to explore the process in which they transfer from getting to know about new ideas, to deciding to try on new ideas, and to reflecting on those changes. We asked the faculty their demographic information at the end of the interviews so that their identity did not impact their answers as it is not our focus in this study.

6.2.2 Analysis method

This work uses the mixed method of ethnography and case-study. I first start with conducting case studies of faculty members, in which I develop an in-depth description of each participant using analysis from multiple interviews with them. I summarize the process of change over the faculty members' career as described by them. Although the participants are suggested to choose one course that they would like to focus on, the interviews also revealed their past experiences, which helps us record their process of change. I pay special attention to the faculty's description of why they reached the decision of making specific changes in their class and the factors they found impactful when executing and reflecting on those changes. The case studies provide us with a rich understanding of each faculty member within their own situational conditions[113]. We then carry out a cross-analysis between these cases to look for similarities and differences across the faculty's experiences with change. The case studies is face-validity checked regularly with the two members who conducted the interviews.

With ethnography, my goal is to explore the working culture of faculty, in which they continue to develop their teaching practice. Longitudinal interviews with faculty allow us to create a connection with faculty, immerse in their experiences, and share the languages faculty use to describe their teaching practice, which may not necessarily be similar to the way education researchers and developers talk about teaching. Using ethnography, I aim to develop emergent themes about their on-going change experiences through their own perspectives[113]. The set of interviews is designed with the focus on reflection of the information around teaching that faculty share. This interview format provides rich data through which we can triangulate information and interpret faculty's experiences appropriately. All the research team members have followed up with the interviews in many ways and offer expertise to generate common themes about the faculty.

Once we found the emergent themes across the three cases, I re-analyzed the initial case studies, focusing on connecting to the theory we use – the RAA and looking for specific quotes to illustrate the faculty participants' experience regarding the emergent themes. The language the participants used in the interviews helped us identify influential factors and the extent to which these factors have influenced them in making decisions about their teaching. My goal is not only to record influential factors that our faculty interviewees mentioned. Using the RAA, I want to further address in what way the factors have influenced them. The RAA argue for multiple paths: influences can impact positive or negative attitude towards change, positive or negative perceived norm of change, and positive or negative behavioral control to make change. I also collect factors that faculty find as external barriers and challenges (or actual controls), and see how the faculty overcome or reflect on them.

6.3 Result

In this study, I present the case studies of three faculty members from different backgrounds regarding their professional development. From our analysis, we found three important themes around their processes of change. First, these faculty mentioned disciplinary professional development programs as having great long-term impact on their process of changes. Second, the long-term relationships with disciplinary colleagues supports the faculty to change, maintain and appreciate the changes. Lastly, faculty often refers to external challenges and barriers to help them structure their changes and creativity.

The ideas of the first two claims we made have been mentioned in literature in different ways. However, in this work, I want to clarify the influence dynamics from the RAA approach. Especially, we want to highlight the disciplinarity element I found from our data, which is relatively new from previous studies. The third argument adds in the literature around faculty examples of faculty owning agency and fruitful resources to make changes in their teaching, which aligns with the asset-based agentic paradigm[(75)]. This result is new, as literature often discusses how external barriers challenge faculty's changes: either make their changes less productive and/or prevent them from changing. Our study of these faculty's long-term processes of change reflects their trajectories of learning and expanding on their teaching experiences, rather than focusing on tracking faculty's implementation of a specific RBIS.

6.3.1 Prof. Ogilthorpe case study

Prof. Ogilthorpe is an assistant professor at a small physics department, where his role comprised "60 teaching, 20 service, 20 research". At the time we first interviewed him, i.e, Fall 2018, he was in his fourth year at his department and he did not have teaching experience other than being a teaching assistant during graduate school. Prof. Ogilthorpe described his department as teaching-focused and very teaching supportive, where teaching was much more important than publishing research papers. Regarding teaching, he was often assigned to teach two sessions of Physics 1 – an introductory mechanics course every semester. Additionally, he also taught upper-division Classical Mechanics in spring semesters and upper-division Applied Solid State Physics in fall semesters. During our first interview, Prof. Ogilthorpe decided to tell us more about the upper-division Applied Solid State Physics course that he had been teaching since 2015.

In the first interview, when being asked about his teaching philosophy and how it evolved over time, Prof. Ogilthorpe expressed that engaging students was always important to him. "I wanted to be more than just someone reading a textbook and lecturing concepts." – said Prof. Ogilthorpe. This teaching philosophy strongly connected to his experiences back in college and grad school as having both "bad teachers" and "good teachers". His teaching philosophy remained the same over years, yet he has learned a lot more about how to better engage students in his class – "I'd say a lot of the details of how I think it's best to do that have evolved. Just as I've learned more about different pedagogical techniques [...]". This change is especially evident in how his teaching in the course Applied Solid State Physics develops overtime. Based on his description of changes occurring in this course, I summarize his experiences in Table 6.2.

Additionally, he also changed his teaching in his other courses, i.e. upper-division Classical Mechanics and Physics 1. However, among all those courses, he found Applied Solid State Physics was especially challenging for several reasons: little teaching materials, difference in the students' physics background, little consensus on covered topics, abstract content, etc. As he tried to get better at teaching Applied Solid State Physics, this course stood out as a

Table 6.2: *Changes occurred in Prof. Ogilthorpe's Applied Solid State Physics teaching*

Time	Main experience	How it worked	Other events and changes
Fall 2015	"A lot of lecture", "I didn't really try anything creative [...]"	"Horrible"	First time teaching this course
Fall 2016	Just-in-Time Teaching and some other things	"It didn't work very well"	Going to New Faculty Workshop (NFW)
Fall 2017	Pre-lecture questions, explicit learning outcomes, worksheets, documenting students' misunderstandings, students' presentations	"It seemed to really work"	Small class size (around 10), participating in Faculty Online Learning Community (FOCL), having course releases
Fall 2018	Pre-lecture questions, worksheets, term paper with peer-review	Pre-lecture questions did not work as great as in Fall 2017	Larger enrollment (around 25)
Fall 2019	Pre-lecture questions, slight adjustments in worksheets, spending more class time for lecture and conceptual discussions, change the distribution of homework	Overall things worked great, pre-lecture questions worked with mixed result	Research lab preparing and running

representation for his evolving teaching in both creating the course materials and adapting teaching methods. I will discuss in details three aspects around his evolving teaching in this course that we found significant.

Disciplinary professional development

During the second time he taught Applied Solid State Physics (Fall 2016), Prof. Ogilthorpe went to the New Faculty Workshop (NFW) and started participating in a one-year long Faculty Online Learning Community (FOLC). During NFW, he gained awareness and knowledge about various pedagogical strategies to teach. In FOLC, he was paired with a faculty fellow from another institute, who was also teaching Applied Solid State Physics, to redesign their teaching in this particular course. In the later interview (Spring 2020), Prof. Ogilthorpe described that they were the only "real" professional development that he participated in. Throughout the four interviews, he reflected consistently on how these two disciplinary professional development programs have strongly impacted what and how his teaching had changed since 2015.

When reflecting on NFW three years after his participation (Fall 2019), he said that although he already committed to active learning pedagogies, he did not really know how to integrate them at that time. NFW had broadened his view of what those pedagogies are and better ways to use them.

> "But I think I had a poor understanding because I didn't do any research, you know, of the depth and detail of different active engagement pedagogy. So like, going there and seeing all the different techniques and all that, and even the ones that I had heard of, [. . .] learning more about how much research and how much was known about better ways to implement them, and that was kind of eye opening. And it was like, [. . .] I heard of things, I'm going to try and do that. But really, I had no idea how to do it. [. . .] It was just really education. So it made me a lot more confident [. . .]."

This is a specific example of how Prof. Ogilthorpe gained new ideas to try and adapt from NFW. Right after coming back from NFW, Prof. Ogilthorpe implemented Just-in-Time Teaching that he just learned about at NFW. Using Just-in-Time Teaching, he started moving away from only lectures. He had his students reading the textbook, answering questions, submitting their responses electronically the night before the class. He then held an in-class discussion around some anonymous responses he chose. He admitted that it was difficult to make changes in the middle of the semester and it was hard for him to facilitate discussions and engage his students in this term (Fall 2016). However, in the next year, Prof. Ogilthorpe changed Just-in-Time Teaching into what he called pre-lecture questions. He posed the questions prior to the class, had his students bring their responses to the class, and had an open discussion, which resulted in better student engagement. Not only did

Prof. Ogilthorpe gain ideas to implement in the course of Applied Solid State at the time, he also gained a library of teaching strategies that inspired him to make changes further in the future. He elaborated this NFW's benefit as below.

> "[...] I definitely heard lots of discussion and ya know, I don't think I would've had the idea, had I not been involved there. So like, there were a lot of useful discussions, like I remember there being a lot of stuff in labs and different things that just haven't, I haven't done those styles of courses. But, I'm sure when the time comes, I'm sure I'll have ideas, and have had ideas that are from that."

It is evident that NFW had a long term impact on the way Prof. Ogiilthorpe decided to make specific changes in his teaching. Largely, participating in NFW has clearly broadened his library of ideas which directly increased his self-efficacy in making specific changes in his teaching. When telling us about NFW experience, Prof. Ogilthorpe recalled many people who ran the sessions he attended and often referred to them as smart, dedicated PER people. His beliefs in the NFW's invited speakers and organizers built in his interest and attitudes towards trying their ideas, such as feeling curious how peer-review would work in class (experimental aspect of attitude toward adapting the strategies) and believing in the positive students' outcomes of using a specific method (instrumental aspect of attitude toward adapting an behavior). NFW therefore, had influenced his intention and action to make first changes in his class and continued feeding back into his teaching development years after.

FOLC started right after NFW and lasted a year long afterwards, during which he worked in a close collaboration with his FOLC fellow and engaged in other forms of group discussion. Prof. Ogilthorpe and his peer had worked over the year of 2017 to revise their teaching in the course of Applied Solid State: setting up learning goals, writing worksheets, learning how to implement PhET interactive simulations, etc. Prof. Ogilthorpe attributed a lot of changes he made in this course to his FOLC collaboration.

> "I was fortunate enough to meet a professor at Cal State San Bernardino, at the NFW, who is in the exact same position I'm in. [...] We're in the FOLC

together as well. So, we paired up a lot and I know we've both used like those activity worksheets, like I've run them by her, and she's sent me something that she's working on."

"[. . .] every other week having to talk just in general kind of forced me to actually do it. [Participating in FOLC] prevented me from kicking the can down the road. [. . .] I think the FOLC kept me on top of actually doing it."

Prof. Ogilthorpe found that FOLC offered him the community where he met and worked with other faculty in similar situations. FOLC was powerful in boosting his intention and action of change by influencing his perceived descriptive norm, i.e., seeing what and how other faculty like him made changes in their practices. This influence did not only hold him accountable, but also comforted him for the teaching decision that he was making. When we interviewed him in Spring 2019, he shared with us that he still chimed in the FOLC discussion board although he was no longer in his FOLC collaboration. He found it comforting to know that his ideas on the course's grade distribution resonated with some other faculty. In summary, Prof. Orgilthope found a lot of support he needed to make changes from the disciplinary professional development he participated in. He described both NFW and FOLC as "extremely useful". I find that the disciplinary professional development strengthens his intention and supports his action of change via two main paths: increasing his perceived capacity in making those changes and his perception of descriptive norms around those changes. The effects of these influences are also long-lasting. Additionally, participation in those programs enhances his attitude and interests towards using specific techniques.

In contrast, Prof. Ogilthorpe showed his lack of interest in multidisciplinary professional programs offered on his local campus. It is not because he thought they were unhelpful. Rather, he thought the multidisciplinary resources were not relevant to his needs in teaching, and therefore, not as valuable to him as talking to his departmental colleagues. Combining his time constraints, he decided not to attend those workshops.

"We have a campus faculty workshop thing. So there's constantly, like every semester you get an email or two, about like, oh we're having a workshop on like flipping classrooms, or doing things like this, lots of support."

"No, [I don't attend those workshops]. Like they're university level. So, a lot of them are not as directly applicable and this is where I feel like the content specific advice as well. I can get just by walking up the hall and harassing my colleagues, it's probably as much, or more valued than [...] I get at one of those. So, with time constraints, I normally don't dedicate it."

Unlike disciplinary professional development, multidisciplinary counterparts had little influence on his action and intention of improving his teaching in his class. His quotes implied that he viewed these programs as the manifestation of the university's culture around teaching value. This culture, along with his department environment, had helped enhance his perception of injunctive norm (what is value in the institution). However, as he was looking for content-specific change, these programs did not have a positive impact on his descriptive norm (feeling irrelevant to what others are doing). In his perspective, they were unlikely to help boost his skills (perceived capacity) to make changes, as opposed to NFW and FOLC, for instance.

Disciplinary relationship

Prof. Ogilthorpe described his department as teaching-focused. There were only six faculty members in the department, two senior members were identified as PER. Throughout the four interviews, Prof. Ogilthorpe highlighted his relationship with his local colleagues as encouraging him to make changes in his teaching from various approaches. Significantly, he mentioned his departmental colleges as part of the department culture of valuing teaching. Situated in this culture, he was motivated to continuously get better at teaching because it was not only expected of him, but it was also what others in his department were doing.

"But I think the environment here, like having colleagues who are very supportive [and] innovative. Like being surrounded by colleagues who value teaching so

> much, and clearly do the same thing in retention tenure promotion. Not that that's the ultimate motivator. But, just there seems to be a strong culture here to try to do the best in classes for the students [...]. It kind of motivates you to want to do well as well. You don't want to be the only one that sucks."

When he was asked about other resources around teaching that he looked into, Prof. Ogilthorpe mentioned specific relationships with his senior colleagues. They were the ones who gave him support around his teaching such as encouraging him to participate in NFW. He often looked for them to get specific on-time feedback and advice. As mentioned previously, he found the conversations with his colleague more helpful and relevant to his needs and problems.

> "So I have a lot of peer conversations I guess, about different techniques. And it's not just them too, our department is extremely student centered. [...] I lean on them a lot basically every time it feels like things aren't going well or could be going better."
>
> "[They] are my go-to Google for teaching advice."

I found that the long-term relationships Prof. Ogilthorpe had with his departmental colleagues significantly influenced his continuous process of change. Over the years, Prof. Ogilthorpe had continued forming intentions and enacting actions of change as change was valued and practiced by his departmental colleagues. That means his disciplinary relationships positively impact his perception of both injunctive and descriptive norms. This effect strongly connects to instrumental aspects of his attitude toward change, i.e., better teaching is rewarded with tenure promotion, for instance. The way Prof. Ogilthorpe described his relationship with the department and the colleagues also expresses his freedom in making changes in his courses, showing positive effect on perceived control toward forming intention and action of change.

Challenges

I found from Prof. Ogilthorpe's interviews that he took on challenges and difficulties to structure his creativity and changes. For him, the challenges were very content-specific and course-specific. Tracking his changes over time, we see that he reflected on the actual controls (challenges and external barriers) to better determine his perceived behavioral control (what can he do – his capacity) in order to determine the sequential action of changes. For example, Prof. Ogilthorpe shared that he never wanted to lecture and always wanted to do active learning. Yet when he started teaching the Applied Solid State Physics course, he ended up lecturing a lot because the course was very difficult to teach for several reasons. There was little material about teaching Applied Solid State. Therefore, he decided to use his course release and his time during the FOLC to redesign this course. Another example of how Prof. Ogilthorpe flexibly navigated changes was when he switched from having his students doing presentations to writing term papers and peer review. He made this decision in response to realization of his actual control: He could read twenty-five reports, but could not hold twenty-five presentations. In summary, the actual control was continuously determined overtime via his informal reflection and was used to feed back into Prof. Ogilthorpe's perceived control, which helped him make informed decisions of changes in the classroom.

6.3.2 Prof. Khan case study

Prof. Khan is a senior lecturer at the Physics and Astronomy department in a state university with around 15 years of teaching experiences at her department at the time we first interviewed her. Beside her role as lecturer, professor Khan is also the director of the Supplemental Instruction (SI) program since 2016, where her job is mainly hiring and training undergrad students to become learning assistants (LA) for the SI program. As senior faculty with special roles, professor Khan has been trying to make changes both in her departmental teaching and institutional student training. Although our work focuses on faculty development in teaching, we notice that her experience with the SI program frequently mapped to her experience of change in her teaching. Based on her narratives over the interviews, I summarize her main experiences over years as in Table 6.3.

Prof. Khan was often assigned to teach low-division large-enrollment introductory courses. Being a lecturer, she did not get to know her teaching assignment ahead of time. Therefore, she usually did not have enough time to prepare for the course she would teach. In 2007, she attended a professional development workshop called Cosmo in the Classroom run by the Center for Astronomy Education. In this conference she learned a lot about different instructional strategies and principles, all which became the core of her teaching philosophy. Among them, student's active practice and instructor's feedback were key elements. With experiences working with diverse students, she had always been mindful about her students' needs and seeking materials that were affordable and best fitted their programs. In terms of teaching, a lot had changed since she started her career. Her teaching philosophy had an underlined role in her decision-making process. In contrast to the case of Prof. Ogilthorpe, I found that Prof. Khan often made only one big change at a time.

Disciplinary professional development

Our first interview with Prof. Khan was in Fall 2018, when she was teaching Physics 101 (introductory physics for non-physics major) and using Ranking Tasks (RTs) for the first time. When we asked her about resources that inform her teaching overall and her decision to use RTs, one of the standout influences was from the disciplinary professional development she attended back in 2007. Prof. Khan emphasized that the Cosmo in the Classroom conference had shaped her belief of teaching and teaching philosophy, which became the underline for many of her teaching decisions later on. Prof. Khan elaborated her experiences with the disciplinary professional development as below.

> "I don't think I would've found the ranking tasks if I wasn't so used to using the lecture tutorials. And, I found out a lot about those by attending the old Cosmos in the Classroom conference [. . .], that was where I learned a lot about how to try to predict what students are gonna get wrong ahead of time, how to write good multiple choice questions, how to do Think-Pair-Share with the

Table 6.3: *Prof. Khan's trajectory of change*

Time	Main experience	How it worked
2006	Graduating with master degree from the same department, having teaching experience as a graduate teaching assistant	N/A
2007	Attending the Cosmos in the Classroom conference, learning about Lecture Tutorials (LTs) and other instructional strategies (Think-Pair-Share, ABCD cards, student misconception, etc.)	N/A
2006 – 2012	Teaching introductory astronomy using LTs	Working nicely
2012	First time teaching Physics 101, trying to adopt her teaching methods in introductory astronomy for this course and create worksheets similar to LTs	Creating worksheets took a lot of time, she returned to mostly lecturing
2015	Teaching Physics 101 again with mostly lectures	N/A
2016	Becoming director for Supplemental Instruction (SI) program. Teaching Physics 111 for the first time with her own materials	Having time constraints to prepare materials
Fall 2018	Teaching Physics 101 using Ranking Tasks (RTs) and trying new grading system called Gradescope	RTs have similar structures to LTs and she was happy to use them
Spring 2019	Choosing to teach Physics 111 adopting a colleague's curriculum, first time teaching smaller class size (around 70)	It was hard but it worked better than expected
Fall 2019	Teaching Physics 101 using RTs, switching completely to the Gradescope, writing her own homework assignment. Going to the winter conference of American Association of Physics Teachers (AAPT) and trying grading on a 4.0 scale.	Everything worked pretty well

> voting cards in a big lecture hall, how to implement the lecture tutorials in a big lecture hall."

It is evident that the Cosmo in the Classroom provided her pedagogical knowledge that she had been using to transform her teaching practice in courses beyond introductory astronomy. This professional development had boosted her self-efficacy, believing in her ability and decision to integrate these strategies in her class. More importantly, Prof. Khan mentioned how participating in this professional development gave her insights of what other astronomy faculty thought about and taught introductory astronomy, which eventually empowered her attitude of change towards student-centered teaching. In other words, the disciplinary professional development had strongly impacted her teaching practice by induced a positive perceived norm around teaching astronomy and a positive attitude towards specific ways to teach.

> "And, attending Cosmos in the Classroom, and seeing presentations, and doing workshops with the Center for Astronomy Education folks, it was eye opening because they were taking science for the masses seriously. And, there was never a sense of weeding out or gate keeping. [...] They were very, very clear that anybody can understand basic science concepts. There was this wonderful emphasis, also, on mathematical literacy for everybody. And, that was incredibly, incredibly powerful for me to hear when I was a brand new faculty person. And, it's definitely influenced how I think about the students in my class [...]. The service courses, they mean a lot to me. And, that's one of the reasons why I feel like it's important for me to think about how they're practicing, and show them how you actually do science problems, instead of just giving them this tour through the topics without letting them sit and hang out there [...]. It definitely influenced my ideas about how people learn [...]. I didn't right away ascribe to a constructivist belief about how people form knowledge. But, it definitely paved the way for me to get there much faster and more easily in my teaching career."

Prof. Khan became the first person in her department exclusively using the Lecture

Tutorials (LTs) to teach in introductory astronomy. From there, she partially influenced the department's integration of active learning. The experience following her participation in the Cosmo in the Classroom helped her gain autonomy around her decision of changing her courses to better fit with her students' needs.

> "So, nobody was going to say, 'Boo', if I cut out topics in that class. And so, then, when I started using those same techniques when I was teaching other physics courses, I was like, 'Hey, I'm not gonna fundamentally change my teaching methods because I'm doing this other subject.' I felt like I had a stronger place to argue from when, say, I would decide to focus more on certain topics than on others in our physics for chemistry and biology majors class [. . .]. So, I felt like I had a much more grounded teaching philosophy because I had had that experience."

When asking about other changes she made in other courses over time, Prof. Khan continued to express her desire to have similar materials as the LTs she learned from the Cosmo in the Classroom conference. For instance, she decided to write her own worksheets for Physics 101 in 2012 to make it as similar to the LT as it could. Similarly, she used the RTs in Physics 101 in Fall 2018 due to the similarity between RTs and LTs. In Spring 2019, she decided to adopt her colleagues curriculum, partially because she found it similar to her teaching philosophy: some parts of the curriculum included RTs as well. These examples show a long-lasting impact of the disciplinary professional development on Prof. Khan. Later in the Fall 2019, Prof. Khan went to another small disciplinary conference, AAPT winter meeting, and learned more about grading on scale of 4. She was instantly receptive to this idea as it well resonated with her teaching philosophy. She started shifting to this grading style at the end of the semester.

On the other hand, Prof. Khan also highlighted her engagement in other interdisciplinary and multidisciplinary professional development on campus such as the Center for Excellence in Teaching and Learning (in 2017) and a social justice group called the Faculty Agents of Change. She emphasized these programs had influenced her awareness of student diversity and her thinking about good teaching – "good teaching looks very similar at a fundamental level no matter what you're trying to teach". Although she said that they had helped her become a better teacher as she understood her student better, it was not clear how these programs directly informed her teaching practice. It is likely that the multidisciplinary professional development resources strengthen her belief about students' need and success. This belief sequentially strengthens her attitude toward changes she made to make her class more inclusive and student-centered. For her, these changes are instrumentally rewarded with her students' success in their major.

Disciplinary relationship

Being around her department for a very long time, her relationship with the department and the colleagues provided her support to make changes in her teaching. From her stories of change, I found that Prof. Khan had a strong sense of autonomy around her teaching. This autonomy is not only internally supported by her belief in her capacity, but also externally supported by her departments. Prof. Khan described her department as "receptive" to her integration of LTs and active learning although she was the first one doing that. She also often referred to her departmental chair giving her freedom to make changes and even encouraged her to make big changes if she would have liked.

Another significant example of her long-term disciplinary relationship is with her colleagues whose curriculum she adopted. From time to time, Prof. Khan had a strong preference in the way she taught, which was influenced by her teaching philosophy. Prof. Khan had tried to create her own materials to best fit with her teaching preference. Therefore, it is prominent seeing Prof. Khan adopted her colleague's curriculum when she taught Physics 111 (introductory physics for physics major) in Spring 2019. Prof. Khan emphasized her choice of adopting her colleague's materials partially because it shared the underlying teaching philosophy, and she had full access to details of how her colleague taught this course before. Having this trusted relationship with her colleagues strongly boosted Prof. Khan's attitude toward adopting new materials from both instrumental and experimental aspects.

She believed that using the materials with the same underlying philosophy would be good for students. Additionally, well organized materials would save her time creating her own materials, resulting in more time to prepare and smoother class. Having a close colleague that she trusted and knew that she could reach out to also enhanced her capacity in trying the new curriculum.

Along with participating in multi-disciplinary and interdisciplinary professional development programs, Professor Khan also built relationships with faculty members from other departments. Because her students were not physics majors, these relationships had helped her understand her students' needs in her course in order to be able to succeed later in their majors.

> "I also think a lot about what students need by having conversations with other faculty who are outside of my department. So, I'm part of a couple of reading groups. One is focused on social justice and institutional change. And, I meet with them every other week. And, we talk about, 'What do our science major students need? And, what sorts of experiences do we want students in our college to have around science?' So, that informs a large amount of my teaching."

Additionally, Prof. Khan connected with the biology education research group and math education research group. The conversations she had with these faculty outside of physics helped her think of ways to teach her non-physics students with minimal math background. Many of these thoughts integrated into her jobs as the SI program director. However, it is not clear how they directly influenced her teaching practice as it applied to her SI program.

> "I also get to pass a lot of that on to the SI student leaders. So, I'm thinking a lot about that as well. What sorts of techniques, or practice problems resources, or learning activities, or guiding principles, can I fold into training next year for my SI facilitators."

Similarly to multidisciplinary professional development, the interdisciplinary relationships she had built were very important to her. The resources she sought out in these relationships well resonated with her philosophy and her impression of the Cosmo in the Classroom community. It is likely that her relationships with colleagues outside of the physics department enhanced her capacity of changing towards student-centered teaching. This capacity is likely to help her form the intention and action of tailoring the course curriculum to better serve her diverse students.

Challenges

Professor Khan has encountered many difficulties throughout her teaching career. Being a lecturer, she usually knew of her teaching assignment very late and often did not have enough time to prepare her courses. When teaching lower-division courses, she often had non-science and non-physics major students, who tentatively had misconceptions about the course content and outcome. She often taught large enrollment courses, adding challenges to active learning implementation. These external factors pose challenges in her teaching, yet they did not prevent her from making changes, but rather guided her to make appropriate changes in her capacity.

Prof. Khan has a great power in self-efficacy awareness, continuing reflecting and determining her needs in teaching in response to her changing situation. In order to best support her non-physics students, she decided to cut irrelevant topics out of the course. Not getting to know the teaching assignment ahead of time is very challenging. Yet, this actual control fed back to her perceived capacity, guiding her to other kinds of change that were easier for her to control (such as using Ranking Task, trying new grading style and system, etc.). When using RTs and having more group work time, she had to slow down the pace of the course. That did not stop her from integrating those approaches. Rather, she decided to allot less time on less important topics. As a lecturer, professor Khan also felt that there was too little support for professional development. In response, she voluntarily trained undergraduate students, who were SI program facilitators, so that she could have them as learning assistants in her class. She emphasized that having the learning assistants in her class made her much more comfortable with making changes.

One prominent example of her elaborating on external barriers to re-define her capacity and structure change, is in Spring 2019 when she adopted her colleague's curriculum. This was her voluntary choice and elaborate decision of change after considering barrier factors: her role as SI program director would occupy more time, she did not teach the course for a while, and last time she wrote her own materials which was very challenging. These challenges all strongly influenced professor Khan's decision to adopt her colleague's curriculum.

6.3.3 Prof. Shorb case study

Prof. Shorb is an assistant professor at an physics and astronomy department, he was in his first year when we first interviewed him in Fall 2018. He had a lot of teaching experiences (around 10 years) starting as a graduate teaching assistant for the Paradigms in Physics. His experience with the Paradigms led him to different teaching positions afterwards. He also taught at a community college and a high school in the past. Prof. Shorb described his current institute and department as teaching-focused, where his role is primarily teaching with a research component. He described himself as an experimentalist, doing research on biomedical optics.

Prof. Shorb had been mostly teaching college physics over ten years. Within the current department, he was often assigned to teach college physics and upper-division optics labs. He shared that moving to a new institute and being in a new position really motivated him to change things up. Throughout the interviews, Prof. reflected on several changes he had made over his career teaching, focusing on making the class more interactive and engaging. Initially, most of the changes he made were inspired by his collective experiences with various methods in the past. During Fall 2018, he went to New Faculty Workshop (NFW) and integrated more new ideas into his teaching philosophy and teaching practice. Based on his sharing, I summarize his teaching experience career in Table 6.4.

Table 6.4: *Prof. Shorb's trajectory of change*

Time	Main experience	How it worked	Other events and changes
Prior to 2017	Engaging in Paradigms in Physics program as a student and later as a teaching assistant, teaching at community college and another college	N/A	N/A
2017	Teaching highschool biology and physics, using Mastering Biology for teaching biology	N/A	N/A
Fall 2018	Teaching college physics sequence (part 1), initially using group work with white boards, Mastering Physics, using more interactive tutorials as pre-lecture questions, integrating ABCD cards and open-ended intro lab from NFW. Teaching upper-division optics lab.	Students were more prepared going to class and more engaging, they loved ACBD cards	First year in the professorship at the department, going to NFW in mid-semester and AAPT winter meeting at the end of the semester
Spring 2019	Teaching the physics college sequence (part 2), trying more open-ended, less-structured lab instruction, creating some ABCD cards questions, continuing pre-lecture questions and Mastering Physics learning modules, trying kinesthetic group exam. Teaching physics for biology major	"It was going really well, I felt pretty successful with it."	Receiving new grant the optics lab equipment, running research lab and having new undergrad mentees
Fall 2019	Teaching colleague physics sequence (part 1), and teaching upper-division Electrical Lab, focusing on refining the ideas from NFW (ABCS cards) and kinesthetic learning.	N/A	N/A

Disciplinary professional development

In the first interview, when being asked about influences on his teaching, Prof. Shorb emphasized his experience with the Paradigms program both as a student and a teaching assistant. He started as an English and philosophy major and there was a lot of interaction in those classrooms. In contrast, he found science class was heavily lectured until he participated in the Paradigms in Physics, which included lots of active learning structures.

> "I think that along with really being a part of the paradigms as a student and as a TA has been huge in influencing. [They] always said that you teach how you're taught, and I think in my case that's probably true."

Paradigms in Physics is considered as his first professional development, which maintained its positive impact on his attitude of change toward active learning and boosted his self-efficacy in how to teach active learning. The long-term influence is evident when he referred to many of the Paradigms-based strategies as his "wheelhouse" or "comfort zone". Throughout the interviews, Prof. Shorb highlighted that active learning had become central to his teaching philosophy. This philosophy underlined many of his pedagogical decisions, including kinesthetics learning (learning physics with bodily experiences), white board group work, using Mastering and learning modules, etc. In our third interviews, when he found it challenging to integrate new ideas, he shared that he moved back to using the Paradigms materials.

Around October 2018, Prof. Shorb went to the New Faculty Workshop (NFW). From his sharing, we found that NFW had a great impact on updating and expanding his teaching philosophy and practice. There were many teaching strategies that inspired him bringing changes into his current practice: gaming principles became a new central idea that guiding his teaching, ABCD cards activity were increasingly integrated in his class, reforming introductory laboratories inspired him to further think about lab instruction. I found that he was very receptive to those ideas because they shared his goal to make the classroom more engaging. Using ABCD cards is an example of his change under the influences of this disciplinary professional development. He expressed that initially he did not like using

ABCD cards for several reasons: he did not like the restrictive structure of ABCD cards compared to white boards, and he thought that ABCD cards were only used around conceptual questions. However, having the interaction with the developers at NFW, he learned more about ways to use ABCD cards to support problem solving. He then immediately tried ABCD cards in his college physics class Fall 2018 using NFW materials and enjoyed using them. He stopped using them as he ran out of the material for the second semester (Spring 2019). However, we found his strong intention to invest time and create similar questions for later years. Additionally, during NFW, he learned about other faculty doing open-ended labs, turning introductory labs more exploratory than descriptive. This idea was striking to him as it resonated with his goals of active learning and his unfavorable experience of teaching labs. He right away tried the idea with some adjustment into his labs (Fall 2018) and increasingly thinking about lab instructions in later semesters.

> "I think that's what was appealing, and I think if I invest more time to do that, [. . .] I think that would probably make a difference. I think that should help and it seemed like that was working well for them. So I'd like to do more of that. The goal is to get them thinking, to get them learning the material."

I found that two disciplinary professional development programs – Paradigms in Physics and NFW – had significant, but different influences on Prof. Shorb teaching practice. The Paradigms, as an early-career professional development, had largely informed his teaching philosophy, shaped his attitude toward active learning and increased his capacity in enacting active learning. I found that NFW, on the other hand, brought him new ideas about active learning to try out in his class. The NFW was very receptive to him for two main reasons. He found this professional development promoted his attitude towards active learning, which had been formed by the Paradigms. Additionally, the NFW provided him the encouraging norms of what others had been trying, inspiring him to try what has been working for them and sharing back.

Prof. Shorb also participated in the multidisciplinary professional development with the Center for Teaching and Learning Excellence on his campus, where he was encouraged to develop a very different set of skills, i.e. writing grants. Prof. Shorb shared that he got some grants to develop curriculum for one of his labs and buy the laboratory equipment in the future as well. Although he mentioned participating in their workshops, we did not see specific examples of this experience impacted his changes in the classroom. It is likely that these supports are favorable external factors that would increase his perceived capacity in teaching these labs in the future.

> "We have a department on campus that is all about helping faculty across the departments to kind of be empowered for engaging students and doing active learning and pulling technology into the classroom, and a lot of the stuff that's been going on in PER for years, they've got this department that does a lot of that. They've been a resource that I've pulled on a little bit. They have workshops all the time and I've gone to a couple of those and I'll go to a few more and they're actually, I got a grant to help pay for my travel to this conference through them, so that's good support. Yeah, that's another resource that I pulled from."

Disciplinary relationship

Prof. Shorb is a special case compared to the previous cases. While Prof. Ogithorpe and Prof. Khan had started their professional career at their departments and stayed there for a period of time by the first interview, Prof. Shorb had been at his department for two months when we first interviewed him. In terms of disciplinary relationships, there were two relationships that he specifically mentioned.

Prof. Shorb often mentioned his colleagues when talking about the departmental culture and support. Prof. Shorb shared that they valued teaching a lot and he believed that it was one of the main reasons they asked him to join them. He depicted his departmental colleagues as helpful resources who also had lots of teaching experiences and was very supportive to his transition. They assigned him to teach college physics because he had lots of experience there. His chair shared her lab instruction materials with him, which he adapted to use in his lab. He said that there was a good amount of collaboration within the department around teaching, especially highlighting the autonomy this departmental culture supported:

> "I think [collaboration] is there for what you need when you need it, if you need it or want it. I think we all teach different courses so we all spend time preparing our own curriculum, but when we have questions we ask or we talk."

Specifically, for the courses that he taught, he expressed he had a lot of flexibility in changing the course. In his second interview, when he was sharing about changing up his lab using an ideas he learned about during NFW, he emphasized his supportive colleagues as giving him freedom to change, highlighting his department chair was also considering these changes:

> "And I think I have the [autonomy] here [...]. I have the ability to do that for my courses, I think and I would have the support of the faculty. There's only three or four of us. And they've been looking more at that stuff, too, the other faculty here. [...] I know the chair was thinking to go into that because she was thinking of that same type of thing. So I think there's enough commitment in the department that if I wanted to do that, nobody would tell me I haven't [covered enough labs]. I think they'd be good with that."

I noticed that Prof. Shorb received different influences from the two disciplinary relationships he mentioned. When Prof. Shorb mentioned departmental colleagues, I found that their most significant influence was on his perceived autonomy to make changes in his class. He also perceived the positive effect from the departmental norm, such as his teaching is valued and other faculty are interested in changing as well. However, this norm was often embedded in the autonomy he gained towards making change. On the other hand, Prof. Shorb highlighted the relevance and resonance in his long-term friendship. Although we could not explore further, his quotes suggest this long-term disciplinary relationship offered him reflection on his capacity, bouncing off teaching ideas that support and sustain changes he made in this career.

Challenges

During his time at the current position, Prof. Shorb experiences challenges, many of them could be traced back to him being new to the position. Time constraint was the most mentioned barrier to Prof. Shorb. During our first interview, he expressed that although he had more time to integrate new active learning in his class, he found time constraints were challenging especially when he taught the first semester. Despite having had lots of experiences teaching college physics in the past, his current departmental schedule for the course differed from other institutions he was at. In order to help him keep track of the schedule, he made elaborate plans on the calendar at the beginning of the semester to make sure he could cover the required topics. Additionally, he tried to be more mindful about balancing interactive activities and lecturing, preparing for flexible changes so that he could cover the topics required.

Another challenge he encountered was of students' resistance. After coming back from NFW, Prof. Shorb made instructional changes in his labs, turning them less directed and more open-ended. However, he then noticed that the students were bothered with the new structure and did not enjoy it much. Instead of completely rejecting the ideas due to this barrier, Prof. Shorb reflected on his ways of integrating the original ideas and planned accordingly what he should do for his next integration. I found that challenges played an important role in structuring the plan for future intention and action of change. This example shows the process in which actual control feeds back to his perceived control in making future changes.

6.4 Discussion – Comparison across three case studies

Across three cases, we found that disciplinary professional developments play a significant role in shaping the faculty's teaching philosophy and instructional preference, specifically with Prof. Khan and Prof. Shorb. The Cosmo in the Classroom conference and the Paradigms in Physics had strong influence on Prof. Khan and Prof. Shorb, respectively.

Not only did they gain positive attitudes towards learning and teaching, but they also received specific instructional tools which improve their capacity in their teaching. Although Prof. Khan and Prof. Shorb received additional support from multidisciplinary and interdisciplinary relationships to maintain their change process, the ways they continue reflecting on their disciplinary professional development programs years later demonstrate the immense influence of disciplinarity.

Additionally, both Prof. Ogilthorpe and Prof. Khan mention that the positive influences of their disciplinary professional development on their perception of teaching norms. Prof. Khan, who usually teaches large introductory lectures for non-science and non-physics majors, was empowered by the norm of other faculty in the Cosmo in the Classroom conference defining these courses. Differing from Porf. Khan, Prof. Ogilthorpe had the opportunity to engage in a year-long disciplinary professional development (FOLC). His experiences in FOLC strongly connect to his productivity in improvement. FOLC did not only boost his capacity or self-efficacy in making changes, but also encourage him to keep up with changes from seeing what other peers were doing. The most distinguishing difference between them is, while Prof. Ogilthorpe finds multi-disciplinary PD offer little value compared to disciplinary PD, Prof. Khan finds it is influential to attend multi-disciplinary PD and have the relationship with other faculty from other departments. Most likely it is because Prof. Khan was seeking changes in both her teaching and her role as SI program direction.

When discussing collegial relationships, all three faculty members highlight the influences of their departmental colleagues on their autonomy to make changes. Oftentimes, the positive influences on autonomy strongly resonate with the innovative norm of the department, such as in the case of Prof. Ogilthorpe. In Prof. Khan's and Prof. Shorb's situations, the correlation between innovative departmental norm and faculty autonomy is less evident. However, having the support from departmental colleagues on their own autonomy plays an important role for them to continue trying new things into their teaching practice. More regularly, we found the three faculty referred to their disciplinary colleagues as reliable and highly relevant resources to their day-to-day teaching.

Although the three faculty experience professional development programs and relation-

Table 6.5: *Comparison of experiences of change across the three case studies*

	Prof. Ogilthorpe	**Prof. Khan**	**Prof. Shorb**
Position	Junior assistant professor, teaching and doing research, 5 years of teaching experience	Senior lecturer, teaching and directing the Supplemental Instruction program, 15 years of teaching experience	Junior assistant professor, teaching and doing research, 12 years of teaching experience
Main disciplinary PD experience	New Faculty Workshop and Faculty Online Learning Community	Cosmo in the Classroom conference	Paradigms in Physics and New Faculty Workshop
Main influences of disciplinary PD	Increase attitude, perceived norm, and perceived capacity	Increase attitude, perceived norm, and perceived capacity	Increase attitude and perceived capacity
Main interdisciplinary/ multidisciplinary PD	N/A	Center for Excellence in Teaching and Learning, Faculty Agents of Change, and Seminars from math and biology departments	Center for Teaching and Learning Excellence
Main influences of interdisciplinary/ multidisciplinary PD	N/A	Feed into SI training program, increase understanding of student diversity	Getting grants for laboratory teaching
Main influences of disciplinary relationship	Positively impact perceived norm, autonomy	Positively impact autonomy, perceived capacity	Positively impact autonomy
Challenges	Course content difficulties promoted material creation	Time constraint lead to adoption of new techniques and materials	Time constraint helps guide organizing and refinement of teaching strategies

ships in different ways, the effect of disciplinarity embedded in these activities stays consistent. Using the Reasoned Action Approach (RAA), we found the directiveness of disciplinarity's influences on faulty professional development compared to multidisciplinary and interdisciplinary counterparts. Through the lens of the RAA, faculty perceived greater influences from disciplinary professional development programs and relationships via combinations of various paths: gaining positive attitude towards change, being encouraged by the perceived norm of faculty change, and increasing the self-efficacy and autonomy in making changes. Significantly, our qualitative analysis of the longitudinal interviews reveal the long-lasting effect of these disciplinary experiences. The findings suggest disciplinarity elements of professional activities do not only support faculty making changes, but also sustaining and appreciating changes for longer run of their career.

Across three cases, our longitudinal analysis also reveals faculty's ability and agency around facing challenges and barriers to their process of change. Other change models and literature discuss barriers and challenges as one of main factors that hinder faculty's change. However, we found that faculty have accumulated their awareness of their situational challenges and their strategic knowledge to flexibly make changes accordingly. Moreover, we see that faculty continue to reflect on their experiences, especially challenging experiences, to gain perception of their efficacy and ability. Challenges and barriers are mostly inevitable. Yet, instead of refusing change, we find that faculty usually base on the situational barriers to structure their change process. The Reasoned Action Approach lens suggests that faculty refine their capacity based on these actual controls, and reflect on their experience of change to continue their on-going change towards improvement.

Chapter 7

Summary and future work

In this work, we study longitudinal interviews with faculty with an attempt to characterize their on-going professional development and the influential factors on that process. While research under the teaching-method-centered paradigm is often based on the premise that faculty are satisfied with their traditional teaching and reluctant to change, we found noticeably different experiences. We found that faculty engage in on-going processes of change throughout their career. Faculty change is a natural consequence as faculty continue their professional learning and practice. Faculty are not completely satisfied with their teaching, but rather they determine that there is often more room to grow in their teaching. We also found that faculty have a strong positive attitude towards active learning and innovative teaching. Additionally, they have been actively applying and trying various resources and teaching strategies to better engage their students in the class.

Through participation in professional development programs and job-embedded professional activities, faculty continue to update their awareness of various teaching resources, including RBIS, online contents, materials created by colleagues, etc. We noticed that faculty usually carry deeper thoughts of teaching and learning such as class assessment, learning material affordability and accessibility, student group work, etc. They also adapt and invent new resources more often than adopting RBIS with fidelity. Significantly, we found they have a strong active learning philosophy underlying their decision of using specific materials and inventing their own materials. When looking at faculty professional development from the teaching-method-centered paradigm, these elements of faculty's agency and experiential knowledge are often dismissed. For example, Prof. Ogilthorpe adopted the Just-in-Time Teaching and revised it into what he called pre-lecture questions which work better for his students. Prof. Khan adapts her colleague curriculum because it shares the philosophy of active-learning and the format of Ranking Tasks and Lecture Tutorials with the content fitting better with her students. Prof. Shorb, on the other hand, adopted ABCD cards, yet eventually invented his own questions because he could not find the developers' further resources. These are all productive innovations that would be missed under the lens of teaching-method-centered paradigm.

Our interviews with the three faculty members from various backgrounds show that faculty engage in the on-going processes of change that are beyond the consideration of the traditional view of faculty. Faculty professional development should not be narrowly defined with implementing research-based materials and evaluated by only the learning outcomes of students. Rather, it should be considered as a career-long process during which faculty build on their knowledge and develop new skills in various professional areas with multiple experiential inputs. For example, Prof. Shorbs shares how his investment in writing grant practice gives him further support in teaching development. Prof. Khan gains new insights from other group activities and from her position of training learning assistants to support her changes. In later interviews, Prof. Ogilthorpe describes how his teaching has fed into his mentoring practice and overall profession. It is realistic that faculty have multiple roles and engage in multiple tasks that interact, influence, and entangle with each other. Therefore, it is important for researchers and developers to consider faculty long-term professional development to better understand and support them.

In this study, we found that the Reasoned Action Approach (RAA) is a productive framework to investigate the process in which faculty form their intentions of change and enact their actions. Not only does the RAA allow space for reflection and expanding on faculty existing experiences, but it also is inclusive to various decisions of change that faculty make in their professions compared to other change models. Using the RAA, we find the significant influence of disciplinary relationships and disciplinary professional development on faculty long-term processes of change. Specifically, we found that faculty often refer to professional development programs that they participated in their early career, which maintains a powerful experience and resources over later years after their participation. The qualitative analysis with RAA further provides new insights on how faculty manage external barriers and continues to make changes accordingly to their situation and capacity. We found that faculty deliberately navigate between their contexts and use their existing experiences to make meaningful decisions about teaching. The barrier may challenge faculty to commit to research-based materials. Yet, faculty still find various ways to overcome the barriers and continue making changes in multiple ways.

When studying faculty professional development situated in their changes trajectories, we found interesting elements of their development. While literature often addresses how professional development is impactful in disseminateing research-based teaching strategies, little work has been done on faculty's deliberate decisions of adopting partial or fully new strategies. This work contributes the voice to the perspective of asset-based agentic faculty, which suggests that further professional development needs to be more faculty-centered. Researchers, instead of training faculty how to use specific materials, need to listen to faculty's stories and support them in choosing materials that fit best to their needs. Faculty do care a lot about their students and their teaching, and can make meaningful decisions for their students, which ultimately reforms their classroom towards a productive student-centered approach.

In terms of the methodology of the study, we found that tracking faculty via interviews over a long period of time offers faculty opportunities to explicitly and consciously reflect on their teaching practice. Our study participants shared how they found the interviews helpful, supportive of their informal reflection, and thought provoking. According to Mezirow[(106)] and Schon[(107)], critical reflection supports oneself to assess their own ideas, beliefs, and challenges, even the long-held ones, leading to significant personal transformations. We personally notice our interview participants gain more confidence and productive ideas of self and accumulate more innovative intentions in their practice. We suggest that the field of PER needs to conduct more longitudinal studies of faculty learning and professional development to gain deeper understanding and knowledge of faculty before continuing disseminating more research-based teaching methods to them.

There are several future trajectories of this work that would be beneficial and contributive to this field of study. First, we can proceed similar qualitative research on a larger available data set, seeking for more contrasting cases and generalizable results. Secondly, the fourth set of of interviews was conducted in the middle of the Spring 2020, when institutions started their sudden transition to online teaching due to the contemporary pandemic. This period is a very challenging time to faculty where they were also given little supports and preparation. Continuing the longitudinal interviews with these faculty and conducting studies on this data will provide greater insights into faculty's holistic and practical picture of professional development. Lastly, developers and researchers can use the findings of this study to feed back into their theoretical models of change and renew the design of professional developments, so that they are more faculty-centered and collaborative with faculty.

Part III

Personas as a design tool for educational design

Chapter 8

Review of related literature and studies for part III

8.1 Introduction – user-centered design and educational design

Education is increasingly described as a design task which includes but is not limited to pedagogical design such as curriculum design, assessment design, and classroom layout. As the field of education research has rapidly brought multiple insights into learning, teaching, and professional development, design remains an important step to bring these ideas to life and bridge the gap between research and practice. This perspective of educators as designers requires researchers to provide educators with appropriate design knowledge, tools, and strategies.

Effective design puts an emphasis on exploring user perspective and experience. The term “user” refers to anyone that the product or the service is designed for. In a university context, the “user” could be faculty, students, academic staff, administrators, etc. With the development of technology and design in educational contexts, some strategies and procedures from those fields are now in use of several areas of educational design. The focus of this part is the application of a user-centered design tool called personas from the interface design context to education. Personas enable designers to center the needs of users by providing evidence-based, relatable, person-like constructs to design for. In this chapter, I will briefly discuss the user-centered design framework and some approaches and analytical tools under the user-centered design umbrella, including personas (Figure 8.1). We argue for the implementation of personas in educational context to approach design problems based around user needs and goals.

User-centered design as a design approach has been widely adopted in human-computer interface design as an attempt to develop programs or products that are shaped by the end users(114). Even though it is still common for designers to pretend to be users and imagine the product features that they think users would like, designers still differ from real users in their technical skills, knowledge, expertise, and goal in usage. Furthermore, designers and product builders face tension between the ease of coding and design issues and the product's power and usability. Consequently, in designer-centered or technology-focused design, many products turn out to poorly serve the needs of real users, because they are based on the designers' perspectives and experiences and not the users. In recent decades, user-centered design has emerged to promote product usability as well as user satisfaction.

User-centered design focuses on understanding the whole user experience with products via the user's characteristics, tasks, and environments. This understanding allows designers to prioritize various types of users and create products that fulfill those diverse requirements and expectations. One of the key principles in building a user-centered design is organizing the products around the users' goals, tasks, and abilities, as well as the way users process information and make decisions(115). The focus on different characteristics leads to different approaches and analytical tools, which vary in how and when to involve users in the design process.

I would like to compare some of the most common user-centered approaches, highlighting different aspects of users that they focus on. Emotional design(114) and empathic design(116) are two approaches to user-centered design that focus on users' emotional state. Meanwhile, activity-centered design (ACD) attempts to understand users by focusing primarily

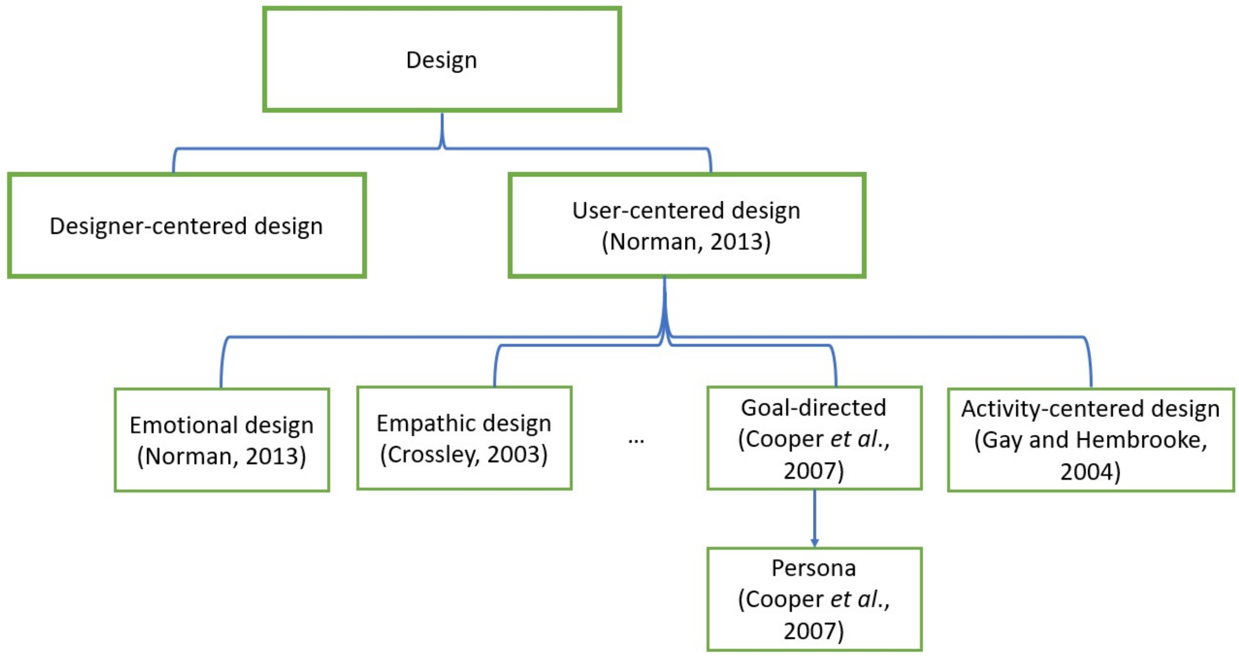

Figure 8.1: *Persona under User–Centered Design guidelines*

on understanding the activities that people perform with given sets of tools which in turn influences the design of those tools. Even though ACD properly addresses human behavior, it does not really address *why* a user is performing an activity or a task, which is often viewed as a drawback of this approach[117].

Instead of focusing on users' activity, Cooper[118] proposes a design approach called goal-directed design, which prompts designers to focus on people's goals and attitudes in the early stage of the design process to devise design solutions that users find useful, powerful, and pleasurable. Cooper also devised personas as an analytic tool to support the goal-directed approach by providing a language to represent and discuss the rich and dynamic-behavior of users. The method of using personas to represent potential users as life-like characters has become standard practice for user experience designers[119].

In educational contexts, we understand that users are heterogeneous and they often do not share the expertise of designers. Furthermore, they might not be intrinsically motivated toward the activity we propose[120]. This context raises the need to employ a method of design which enables the designers to empathize with and understand the users' goals and motivation, for which the user-centered design process coupled with the method of personas can be helpful. This method has previously been used in limited ways in educational contexts including library research[121] and faculty professional development[122]. However, persona use is still scarce in education.

In this part of the dissertation, I discuss personas via two examples of educational problems of practice: faculty professional development[112] and undergraduate student research engagement[123]. The details can be found in chapter 9 and chapter 10 respectively. The method of personas is useful outside of these contexts as well. For example, an instructor might create a set of personas to describe a variety of learners in order to help set up and run a course that best meets those learners' needs. A curriculum designer could also develop personas of faculty who are potential implementers of the materials that they are developing, so that they can ensure the materials meet the faculty needs. Or a department could consider building and using personas of teaching assistants and learning assistants to appropriately design more personalized training programs for them.

Even though the procedure and technique of generating personas can be found in other design instructions, the difference between interface and educational design requires designers to make adjustments when employing personas in educational contexts. With this study, I hope to offer the science and the art of generating and using personas in exemplary design problems that educators may find relatable, useful, and applicable for their own design problems. We propose a method of creating personas largely based on the method commonly used in interface design, but with new modifications that involves completing a phenomenographic analysis as part of the process.

8.2 Overview of personas

8.2.1 How personas serve design

Originating from the goal-directed perspective, personas are life-like characters that are driven by potential or real users' personal goals and embody their experiences when using products[118;124]. Personas are not a description of individuals or average information of specific groups of users. They are combined patterns of users' behavior and motivations, where the rich information of an amalgamation of users is synthesized into a set of user archetypes or personas[122]. These personas have some fictional details added, such as name, images, and background information, to make them more concrete and life-like.

Even though personas are not real people, they represent real users throughout the design process. Just like scientists build models to represent and simplify physical systems for further focusing investigation and exploration, a set of personas is a powerful tool to represent and communicate users' rich and complicated behavior, motivations, and attitudes. The key strengths of personas are encapsulating the critical characteristics of users into human-like constructs in such a way that designers and stakeholders can understand, remember, and relate to while leaving out details about individual users that are idiosyncratic and irrelevant to the design problem[125].

Personas work because people can predict another person's behavior by understanding their mental state[119;126]. We use our partial knowledge and experience to draw inferences, make predictions, and form expectations. When fully engaged with personas, designers can effortlessly project them into new situations and extrapolate how different contexts could affect their behaviors. For example, designers can easily engage and empathize with a specific persona in a statement "Diego prefers to use resources from his own department because he is trying to enculturate into his new departmental practices." In contrast, it can be difficult to engage with and act on a statistical statement such as "only 30% of the interviewed faculty with access to departmental resources look for resources from elsewhere". Building personas pushes designers to engage with and think from the users' perspectives, treat them as real, and prioritize their needs over the ease of the design process. Personas therefore can help with bolstering the usability of the products.

Personas also help designers to draw focus on a specific range of users and to promote communication and consensus among designers and stakeholders[118;117;119;127;128]. One design cannot satisfy all users, and personas, no matter how carefully conceived, will not perfectly cover all conceivable users. Instead, building personas helps us explicitly discuss who is being designed for and target specific features, rather than creating every possible feature and ending up with usability problems[126;124]. The art of persona creation also lies in its ability to push designers to be aware of and put aside their biases and stereotypes. Designers can purposefully craft personas that celebrate the diversity of users and potential users, instead of only representing the small set of users represented in their data. For example, if you interviewed more men than women, you could still represent an equal number of men and women in your persona set[129].

Personas, as user archetypes, are an especially powerful way to represent research subjects with a marginal risk of exposing their identities. Classic research methodologies, such as phenomenology and ethnography, face a much higher risk of exposing identities when presenting and reporting confidential individuals' rich and accurate details to stakeholders. Classically, we can increase the size of the anonymity set, either by sampling more people or by removing some identifiers. However, personas present a different path, which is well-suited for many different kinds of problems that classical solutions are not as good at. In this work, I propose using phenomenographic study to craft personas, which I argue makes the experience feel relatable and representable to users, while still protecting their identities.

8.2.2 How personas fit into design flow

In a user-centered design process, crafting personas is usually one of the first tasks after collecting user data. Personas, as a user research and analysis tool, support and cooperate with other design tools such as *scenarios* and *user cases*. A scenario is a story with a plot and a sequence of actions and events built around actors — personas — who have distinctive goals. In the perspective that users' goals drive their behavior, designers figure out each personas' actions in specific scenarios, which are goals that users might have when interacting with the product, coupled to actions that they would take to achieve their goals.

Further, designers often use persona-based scenarios to write out user cases, which describe the flow of tasks that the user would take to accomplish a specific goal with their product. The scenarios and user cases address *pain points* that would interfere with a persona accomlishing a specific goal or task[122]. Some designers create these scenarios and user-cases with a generic user in mind. But we find it much more rich, data-grounded, and productive to choose a persona and use its specific details to shape the steps of the scenario. Using personas to shape scenarios means the scenarios are personalized for specific types of users, and better reflect the specific users' experience. In return, these persona-based scenarios and user cases clarify and give life to our personas, leading towards meaningful design solutions[(126)].

Creating and using personas can feel much intuitive and overwhelming. In chapter 9, I go in details on our proposed methodology of generating and using personas, giving step-by-step example of building faculty personas. I am not arguing for one right way to design personas. Rather, I want to provide researchers and educators with the knowledge of persona design so that they would be comfortable in trying and designing better user-centered programs.

Chapter 9

Crafting personas methodology – Example from faculty personas for PhysPort's redesign

9.1 Personas versus phenomenology case study and phenomenography

In this chapter, I present our methodology of creating persona based on phenomenographic results. Personas address different questions than traditionally asked in education research and therefore might or might not be useful in all cases. Both phenomenology and phenomenography are commonly used methodologies in physics education. Yet, these terminologies may sound confusing. I will ground the persona methodology first on the discussion of comparing persona with those methodologies – phenomenography and phenomenology. As I aim this work to education audiences, it is meaningful to illuminate the differences among them to help you decide if personas are a potential method for your research and design problem before addressing *how* to build them.

Phenomenologic case studies[130] explore rich details of small numbers of anonymous individuals with a focus on the nature of their experience (Table 9.1). Phenomenology qualitatively describes individuals' experiences and phenomena. In presenting rich details about individuals, there is a risk of revealing the participants' identity even if those identities are anonymous, because the uniqueness of the individual creates an anonymity set too small to protect their identity. For example, in a case study of a "female physics faculty member", readers from her department can probably identify her. On the other hand, personas are synthesized from real people's behavior constructs and do not represent any one individual. Therefore, personas are great at protecting participants' identities.

Phenomenologic case studies are valuable in deeply understanding individuals, but it is difficult for designers to use these descriptions of individuals to solve design problems. Many of the details are specific to an individual and don't generalize to other similar users. If designers base their designs on case studies of individuals, they will likely end up with a product that only meets the needs of those individuals. Personas are built from larger collections of participants, leaving out idiosyncratic details of individuals, which leads to design solutions that are more broadly useful.

On the other hand, phenomenography investigates a variety of qualitatively different ways that people experience some activities or artifacts[131] (Table 9.1). Phenomenographic studies collect ideas about the experiences of a large number of participants; the results of this method are lists of categories within broader themes describing the participants' experiences. For example, you might have a list of the various motivations your users discussed in interviews and a list of the various attitudes they described.

Phenomenography describes the variation in interview participants' experiences around different themes, but does not track the experiences of individual users across themes. For example, phenomenography may present a list of results about participants' motivations and another list about their challenges, but it doesn't connect an individual user's motivations to their challenges. This disconnect means that it cannot serve the design process, whereby motivations and challenges must be linked at the individual level. However, phenomenography can be used as the basis to create personas. This idea will be further explained in the next section.

Table 9.1: *Phenomenology, phenomenography, and persona in comparison*

	Phenomenology	**Phenomenography**	**Persona**
Characteristic features	Study an individual's human experience, focusing on the nature of the phenomenon	Studying the qualitatively different ways people experience a phenomenon	Building goal-driven semi-fictitious user archetypes from amalgamation of real users
Exemplary research question	How does an instructor notice and flip a student's frame of reasoning?	How do faculty approach changes in teaching?	Who are the users of PhysPort and how are they using the resources there?
Data collection	Many possible sources (observation, interview, human artifact with the focus on the phenomenon, i.e. experience)	Semi-structured interviews with focused questions	Many possible sources (interview, survey, site log, etc. with the focus on users' goals, attitude, and interaction with the designed product)
Expected outcomes	A rich, complete, and accurate qualitative description or interpretation of an individual's experience	An emerged list of themes and categories of descriptive ways in which many participants experience something	A set of personas (including name, pictures, goal-directed description)
Evaluation method	Thickness of description, participation validation, triangulated description	Seeking for saturation of themes and variation within themes	Seeking for the set of personas that expand the user sample
Weakness	Generalization issue due to dependence on the participant's point of view and articulate skills. Overfitting the data.	Emergent themes dependent on interplay between the researchers and research	Sensitive to users' changeable goals, sensitive to design questions and contexts. May miss out atypical users because it does not seek saturation in sampling data.
Iconic citation	Polkinghorne(132)	Marton(131)	Cooper et al.(117)

9.2 Personas built on the results of phenomenography

The methods for building personas vary from quantitative methods based on user surveys or site logs[129] to qualitative methods based on in-depth user interviews and observation[117]. Although there is no clear consensus on the optimal method to build personas, some designers[117] argue that qualitative data, specifically ethnographic interviews, is a cheap and effective way to deeply understand users.

Although these methods have worked well within their contexts, they become difficult to apply to qualitative data that is common in educational contexts. Cooper et al.[117] represents variables (such as attitude, aptitude, challenges, etc.) on separate axes. On each axis he plots users in relation to each other, looking for emergent behavioral patterns across all axes. For example, Cooper et al.[117] maps user behavior from service-oriented to price-oriented, giving each user a single value along this axis. However, for some qualitative data, the categories within each theme can be characteristically different without an inherent ordering. For example, categories in the theme of motivation for change can include solving big problems in the department, becoming a better teacher, or having fun with teaching. Moreover, one person can be present in multiple categories within one theme; one faculty can have multiple motivations. Using phenomenographic analysis, which we propose, can avoid this complication.

I argue that persona generation should be based on phenomenographic studies for two reasons. First, a phenomenography develops a list of short, concise, and significant variations among users' experiences. Building personas from phenomenographic data makes it easier to make sure our cast of personas fully accounts for the significant variation in experiences, which could be easily washed out in other qualitative methods. Our personas, therefore, better reflect the important features of real people. Building personas from phenomenographic results can be more time consuming than building personas from raw interview data because it involves extra analysis to generate the phenomenography. However, spending more time with the data during the phenomenographic study helps researchers turn their visceral feelings into data-grounded decisions.

One might argue that there is no better way to fully reflect real people than directly describing them. However, that is not the purpose of personas. Personas are user archetypes: we want them to be as human-like as possible, but we also need to foreground the features which are salient to our design problem. Therefore, working from a phenomenographic study helps us avoid drowning in details that do not help solve the design problem. These superfluous details tend to draw our focus away from the design itself and toward the description and narrative of real stories or real people instead. I suggest that an effective first step in building a set of personas is phenomenographic study. In the next sections, I will introduce the an example set of personas for faculty professional development website design, including how we used phenomenography to generate these personas.

9.3 Example personas: faculty personas for PhysPort's redesign

To help ground our discussion about building personas, I introduce here a set of personas to give readers a sense of what personas are and what kinds of details they contain. This set of personas is built for website-based design – PhysPort – that supports faculty professional development (Figure 9.1)[(112)]. In general, we construct each persona with a name and pictures, details on their goals, a description, and key quotes.

9.4 Methodology

I present our methodology of building personas step by step via an example process of building faculty personas to address a design problem of a faculty professional development website – PhysPort. In general, we start with articulating the design problem and collecting user data. Next, we carry out a phenomenographic study where we assemble categories of user experience and features. Then we construct personas by synthesizing the categories into human-constructs and check the personas' validity.

	Name of Persona	Key Quote	Description	Key Goals
	Claude the cautious implementer	“I ought to move away from pure lecture, but I'm nervous about trying new things."	New to teaching, wants to get it right. Thinks he should try some new active learning strategies, but is worried that some are too radical or won’t help	Get good teaching evaluations from students and colleagues.
	Diego the departmental participant	“What is the best way to use the departmental ways of teaching and resources?”	Belongs to a department with a culture and set of practices around teaching; wants to learn to fit into that culture.	Adopt the practices that are sanctioned by his department.
	Suki the satisfied incrementalist	“I’m happy with how things are going in my classes, but I will tweak and improve where I see it necessary.”	Generally satisfied with how her class is going. Makes changes if she notices students didn't learn something well in the past, but not anything too instructor intensive.	Efficiently address specific issues with teaching as they arise.
	Imani the intuitive explorer	“Teaching well feels good. If it's fun for us, we're learning more.”	Wants teaching to feel good and be fun; gets bored so she likes to try new things. Teaching is more enjoyable when her students are learning.	Make teaching enjoyable and satisfying for herself and her students.
	Sameer the student-focused improver	“I want to maximize students learning in my classes”	Continuously improving his teaching; very thoughtful; wants to optimize his classes for the students.	Provide a high quality educational experience for his students, addressing many aspects of their development.
	Charlotte the change agent	“My department has a big problem, and I’m going to solve it”	Highly experienced educator; strong internal motivation to enact change. Notices a big problem in her department and brings together resources to solve it.	Bring about large-scale change to address a pressing problem.

Figure 9.1: *Faculty personas*

I also briefly discuss how we are going to use the personas for future design. Designing, including building personas, is an iterative process. I hope to provide educational designers with the underpinnings of the process, so that they are confident in developing useful and reliable sets of personas.

9.4.1 Articulate design problem

At the beginning of any design, it is very important for the group of stakeholders, researchers, and designers to discuss and specify a design problem that aligns with the ultimate mission of the organization. A clearly defined design problem helps clarify and guide user research, including choosing users to study as well as design research methodologies.

PhysPort (http://physport.org) is a website that supports physics faculty in implementing research-based teaching and assessment in their classes[133;134]. PhysPort was created piecemeal, as various pieces of the site were funded, and now the PhysPort team is redesigning the site to make it more coherent whole as well as more usable for its intended audience, college physics faculty. The design problem for the PhysPort redesign is: How can physics faculty find what they need on PhysPort to try out new things in their teaching? The PhysPort team uses personas to understand and prioritize potential users, and then to create scenarios that meet the needs of those users.

Clearly articulating the design problem helps us determine the range of users whose data we want to collect. For example, experienced faculty seeking new resources have radically different goals and decision-making processes from new faculty seeking materials for their first time. Effective design trajectories for these two types of users are different. Therefore, in this case, we focus on faculty that have been making or attempting to make changes in their teaching, rather than those who are teaching for the very first time.

9.4.2 Collect user data

There are several data collecting methodologies. Whereas interviews and surveys are better at clarifying user goals, motivations, and attitudes, other methodologies such as site log analysis or eye tracking can reveal users' actual behavior and interaction with the product[(129)]. To support user-centered design with a better understanding of and empathy for users, designers should interact with users during data collection, instead of just relying on quantitative survey or site log analysis data or watching an interview someone else did with the users.

In this case, the whole PhysPort team collectively design interview protocol. Then, two members in PhysPort team, Adrian Madsen and Linda Strubbe, collected qualitative interviews with 23 physics faculty (7 women / 16 men) from diverse US university contexts to build faculty goal-directed personas.

The interviews focused on how physics faculty approach changes to their teaching; a secondary aim was to develop personas of potential PhysPort users. We conducted phenomenographic semi-structured interviews remotely using video and audio; each lasted for about 1 hour. During each interview, we asked the participant to describe their instructional practices: how they approach their teaching; what kinds of changes they were making to their teaching this term; their motivation to make changes; their assessment practices around the change; resources that they use; how they use those resources; and challenges they experienced with their teaching. We also asked about their background, departmental culture, and how they collaborate with others around teaching.

After each interview, the two members who participated in the interview individually wrote down the key points they noticed and discussed these. After several of these discussions, we updated the interview protocol to probe themes around motivation and development of teaching practices more carefully for subsequent interviews. Each interview was video recorded and transcribed for analysis using a professional transcription service. After completion, the video and transcripts of the interviews became the focus of our phenomenographic analysis.

9.4.3 Assemble phenomenographic categories

Before building personas, we carry out a phenomenographic study that aims at exploring and assembling a variety of human experiences. The creativity of the work of phenomenographic study lies in the focused and principled noticing of this emergent information. The process of generating a phenomenographic study starts with identifying emergent themes. We acknowledge that these themes are directly and indirectly predetermined by our goal of the design. We initially use our judgement to decide what types of information about users is important enough to characterize users and users' interaction with our design. We base on this judgement call to design our semi-structured interview protocols.

After collecting the data, we examine the set of interviews to refine and finalize the list of themes such that they are also commonly important from interviewees' experiences and perspectives. Semi–structured interviews allow us to explore further users' complex and personalized experiences, therefore giving us more information to ground our choice of emergent themes. When these themes are identified, researchers carry out iterative analyses, going back to the data and re-examining each real person in order to probe the full breadth

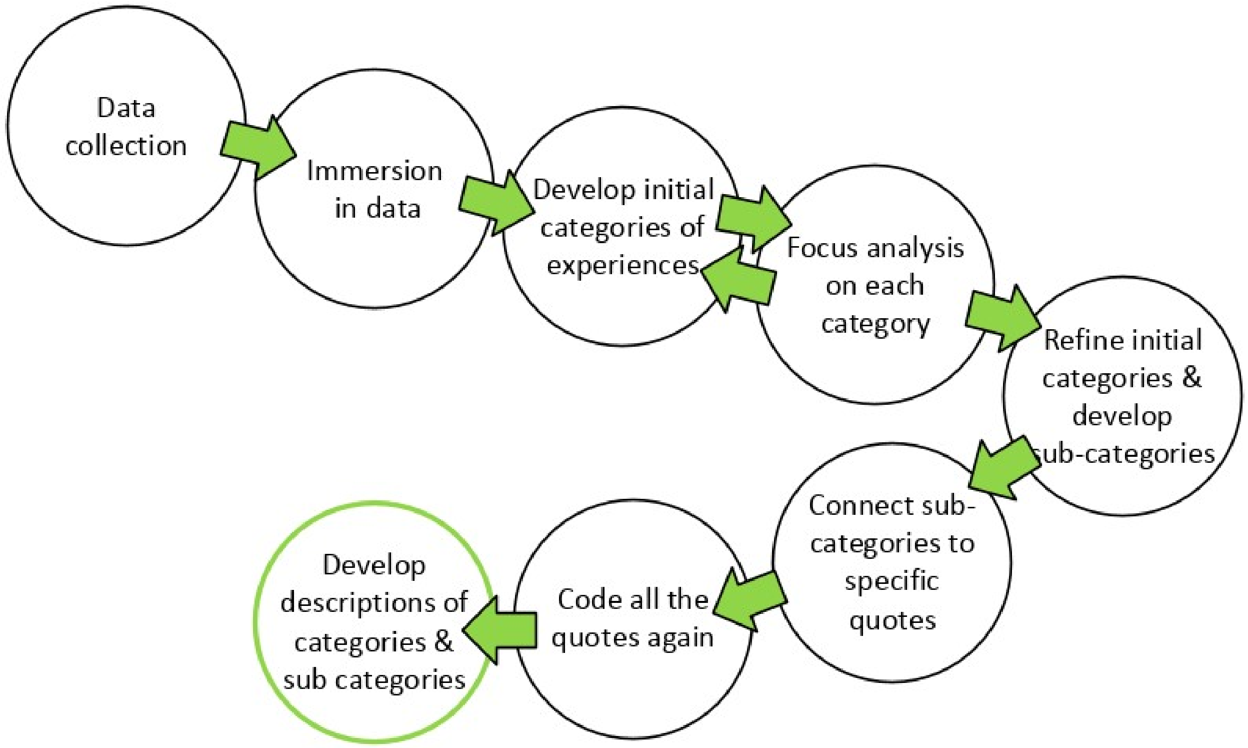

Figure 9.2: *Phenomenographic study generation*[6]

of each theme. Figure 9.2 describes in detail this process[6]

For example, when investigating faculty approaches to change, our emergent themes included: motivations for trying a new idea, attitudes toward change, types of ideas to implement, how they know if the new idea is working, and what resources faculty use to find new ideas. These themes are varied among all the interviewees. For example, in the theme of motivation for changing, we found our interviewees' motivation included wanting to benefit their students; wanting to integrate with their departmental culture; and wanting a more enjoyable teaching experience. Motivation for teaching and making changes has a huge influence on other behaviors, which is consistent with motivation theories[105] and the goal-directed perspective of personas[124]. Once we have the phenomenographic results as themes and sub-categories describing each theme, we can start creating personas.

Table 9.2: *Illustrative table to create personas*

<table>
<tr><th>Persona</th><th>Theme 1
(goal and motivation)</th><th>Theme 2
(attitudes)</th><th>Theme 3
(challenges)</th><th>Theme 4
(needs)</th></tr>
<tr><td>Persona 1</td><td rowspan="3">Variation
within
theme</td><td></td><td></td><td></td></tr>
<tr><td>Persona 2</td><td></td><td></td><td></td></tr>
<tr><td>Persona 3</td><td></td><td></td><td></td></tr>
<tr><td>Persona 4</td><td colspan="4">A good and plausible mix of traits, ideas, and needs</td></tr>
</table>

9.4.4 Build personas

The process of building personas is composed of two stages. The first stage is developing the personas using the phenomenographic themes and the variations within those themes. The second stage is making the personas feel alive with person-like features. When embodying phenomenographic categories into personas, the creative task is to make sure the themes and the vast variations within those themes are distributed throughout the cast of personas such that they emerge as plausible mixes of traits. One conducive format is a tabular form as shown in Table 9.2.

We sketch out personas by filling in their characteristics using the categories found in the phenomenographic study. We prioritize goals and motivations by filling in the column of "Goal and motivation" first, as very different goals and motivations result in vastly different personas. Therefore, the goal and motivation of each persona will help us set a tone for their characters later. Further, starting with the goals and motivations helps ensure your personas will reflect your users' perspectives and not a researchers' perspective.

We continue by filling in other characteristics for each persona according to their goals, and in relation to other characteristics, as shown in Table 9.2. At the same time, it is important to constantly compare with other personas when filling in their characteristics, making sure that the personas are distinctive from each other and represent different types of users. Creating personas is a creative art requiring constant comparison. Working and discussing with collaborators who are familiar with your data will help you with face validity: Does this persona feel real? Are they coherent? Do they align well with the data? Since phenomenography describes the variation in the data, but does not tell you how results in different categories connect to individual users, checking the face validity of the personas with a team member deeply familiar with the interview data is a vital part of this process.

Crucially, we do two processes simultaneously to build meaningful contexts where personas feel more human-like: we synthesize across phenomenographic categories at the same time as we elaborate on these categories using ideas and language from the interview participants. For example, one category in the goal and motivation theme could be decontextualized as "changing to adapt to departmental and practical considerations". We can enrich this category as if it was said by a specific plausible person. The Diego persona could say: "My department has a culture and a set of practices around teaching, and I want to do it, and there is an expectation that I do it too." This elaboration makes the personas life-like, relatable, and understandable, so that we as designers can easily make sense of those personas' characteristics.

We do not create personas that mimic individual real people, but instead we build coherent and plausible human constructs that correspond to our understanding of faculty. We are flexible in distributing characteristics to personas, in abandoning implausible personas, and in changing and revising our choices until the personas as a set are a coherent and plausible representation of our data.

For example, in this work, we eventually finalized the set of faculty personas to 6 personas that fully represent the diversity of faculty we interviewed (Figure 9.1). During this iterative design process, we started with Charlotte as part of Sameer for their similar goal to change to help students. However, as we elaborated and reflected on the persona's characteristics with our interview data, we decided to separate them to distinguish Charlotte's motivation for large-scale change and Sameer's motivation for smaller-scale change. Charlotte and Sameer's stories corresponding to their new and subtly different motivations makes their distinction more plausible (Table 9.3). In our experience, it is difficult to get to know and work with more than 6 personas, and so we aim to develop 4–6 personas to describe a set of data.

The second stage in crafting personas is adding details to make the personas feel more like real people. This includes names with short descriptive nicknames, ages, profile pictures, background, short quotes, etc. Adding these details makes it easier for a design team to

Table 9.3: *Example of PhysPort personas representing variation in physics faculty around their motivations and attitudes for making changes to their teaching*

Persona	**Motivation for trying new things**	**Attitude towards change**	**Type of things to try**	**How they know if it works**	**Resources**
 Sameer	I care a lot about student learning and development including students' skills, content knowledge, affect, identity, etc. Keeping my students engaged will support their learning.	I want to be continually improving my teaching and I'm really thoughtful about my class. I will try things that take me a lot of time and are hard for me, if I think that they will benefit students.	I want to add a new teaching method to my toolbox of things that I already do. I'm open to new big ideas. I want to broaden my perspective on important issues that influence my students/ classroom.	My students learn more and are more engaged and it shows in my student evaluations, research-based assessment scores, and exams. Evidence is important!	Everything, everywhere
 Charlotte	I see a big problem in my department: Drop/ Fail/ Withdrawal rates, graduation rates, major conversions, learning gains in intro, etc. I want to fix it.	This needs to be done. It's hard work and it's important. I need to build support in my department to do this, possibly via research results or funding possibilities.	Let's make big pedagogical or programmatic changes that involve multiple faculty or courses.	My problem is better.	I looked in the literature to find the most effective solution to my problem. Both pedagogical articles and physics education research ones. I also ask experts to help.

remember and refer to each persona, as well as treat them like real people. You can use photos of real people or create avatar-like pictures of people (as used in Figure 9.1 and Figure 10.1). You should carefully consider the benefits and drawbacks of each representation based on your intent. For example, while photos of real people make personas feel more real and memorable, they often cost more to achieve. Moreover, their bodily expressions and appearances may influence designers' personal emotions and bias towards the users whom those personas represent.

The creative art in this stage lies in how to portray plausible personas and simultaneously avoid stereotypes that one might have. For example, you can choose portraits which represent a diversity of users and backgrounds, which may help your design team think more inclusively about the people they are designing for. Similarly, when naming the PhysPort personas, we sought to present a diverse set of physics faculty personas to illustrate that all kinds of people can be physics faculty. Each persona's name also alliterates with their epithet, making the personas even more memorable. We sought to avoid gender or ethnic stereotypes when assigning identities to different personas; however, we tried to match names with gender and racial characteristics in the portraits. We shared our named personas and descriptions with colleagues and community members, renaming personas when they pointed out issues that could lead to confusion or bias.

When we finished infusing themes into personas and making them human-like, we wrote a descriptive paragraph for each persona, a narrative that linked their characteristics to get a full portrait of a human. We designed persona cards so that personas are better assimilated and communicated with the design team, including stakeholders. We present here the 6 faculty personas (Figure 9.1) as well as an example persona card of Claude (Figure 9.3).

9.4.5 Check the personas

Checking the personas is an important step to scientifically ensure their validity and reliability for further deliberate design. In this case, we need to check our personas' validity by going back and forth between the sets of personas, the real data, and the phenomeno-

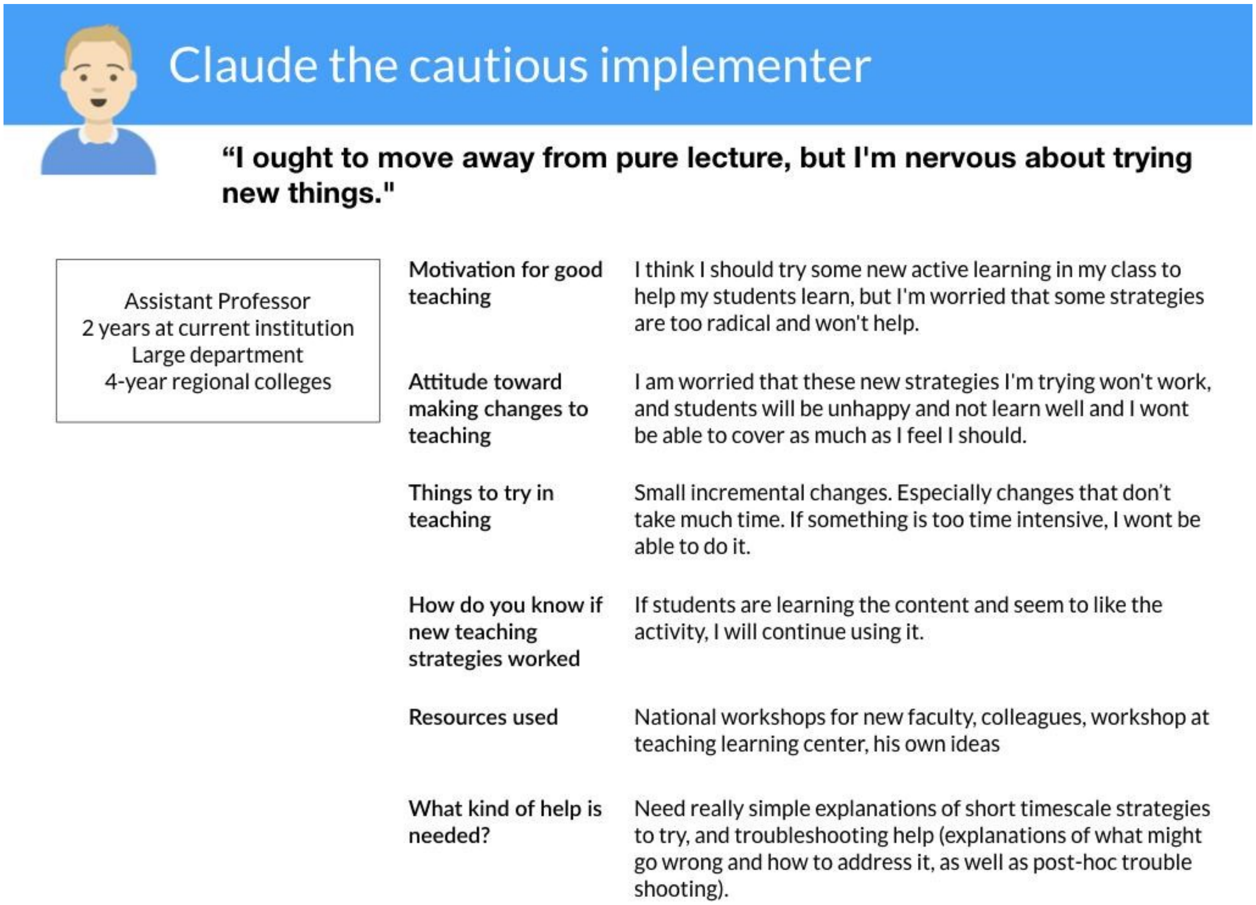

Figure 9.3: *Claude persona card*

graphic analysis. A valid set of personas is one that covers the whole data set, where every real person from the data is primarily represented by one persona while having a reflection in least one or a few other personas. For example, the set of 6 faculty personas represent the sample of 23 faculty interviewees as shown in Table 9.4. In this case, Interviewee 1 is primarily described by the persona Claude (with main motivation, attitude, and behaviors) and secondarily described by the persona Suki (with minor experiences).

This quality of personas is extremely important for us to effectively represent our interviewed faculty without revealing their individual identities. What is more, we hope that a design solution that is devised mainly with one persona in mind could also benefit other users who have this as their secondary persona. During this process, we are more concerned with creating personas that are distinct from each other and which completely describe the

Table 9.4: *Personas well cover the characteristics of real users from the interview data. Each user is represented by a primary persona and also be represented by a secondary or tertiary personas*

	Claude	**Diego**	**Suki**	**Imani**	**Sameer**	**Charlotte**
Interviewee 1	Primary		Secondary			
Interviewee 2		Primary			Secondary	
Interviewee 3		Secondary	Primary	Tertiary		
Interviewee 4	Secondary			Primary		
Interviewee 5		Primary		Secondary		
...						
Interviewee 22	Tertiary				Primary	Secondary
Interviewee 23			Secondary			Primary

set of potential users than we are with the weight of each persona in the interview data.

Before we discuss using personas to solve PhysPort design problems, I want to address a common concern of designers using personas: losing too many details from our real users at the end of the creation cycle (Figure 9.4). When conducting phenomenographic analysis, we gain insight into abstractions of individuals' experiences, but we lose some details that do not fit into our emergent themes. Our goal for the design intentionally influences the themes we decide to prioritize and the details we decide to ignore. From a large group of real stories, a list of important details gets extracted out and synthesized into a much smaller set of personas, and we lose the direct link to individuals. When infusing the variation within themes into our cast of relatable personas, we again use our design sense to judge whether a mix of traits is plausible and hence, we perhaps lose some variation as well. When mapping back to the data, we revive the connection between personas and real people, which is more representative, but might not be as descriptive, because of the connection to individuals we have broken in the previous step.

In concerns of losing details when building personas, I think it is inevitable. Not all details carry equal weight and it is often practical to lose idiosyncratic details that are irrelevant to the design goals. Different methodologies represent the data for differently meaningful purposes. When transferring the information from one methodological representation to

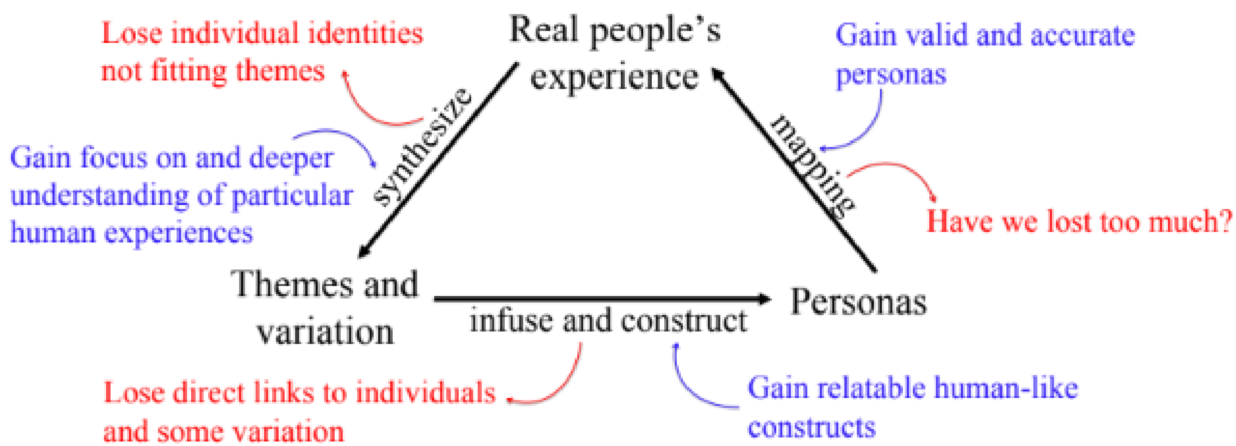

Figure 9.4: *The persona methodology cycle diagram shows the relationships between the three parts of the persona development cycle, and how information is gained or lost when moving between stages 9.4.2 – 9.4.5*

another, it is important to ensure that we capture details that are deeply connected to our design goals. In many cases, this process may allow some personas to be too disconnected from representing our real users. Adjusting one persona in a set might impact others' uniqueness. Therefore, revising personas might entail adjusting the whole set of personas, and designers might need to iterate the whole cycle several times in order to achieve a representative set of personas. This is a common situation and we suggest giving each new iteration of personas new personal information, including new names and images, so that earlier draft personas do not affect your process of constructing new ones.

9.4.6 Solve the PhysPort design problem

To use personas in the PhysPort redesign process, we order the personas in design priority. Designers often identify the design priority based on an evaluation of how important serving each persona is to achieving the goals of design to. Design priority guides designers to decide which users' needs should be met first. This may be related to the relative number of potential users associated with each persona, but there may also be cases in which a persona is very important even if that persona doesn't represent many users. For example, a persona might represent the small number of users who are likely to contribute content to the website, which is important to the project's goal of building the website's resources.

After we have a clear idea of our priorities, we will brainstorm a large number of scenarios that our top prioritized personas would do as a part of teaching their physics courses. For example, we could write out the steps Claude the cautious implementer would take when revising a lab activity or planning a new course from scratch, and how he would use online resources (including PhysPort) to help him in this process. Each scenario is written for a particular persona, though similar scenarios featuring different personas are possible. Next, we would prioritize the scenarios by project goals. From there, we would create a workflow for each high-priority scenario, sketching out the steps of the scenario step by step. Using workflows, we would then design wireframes, which are the actual design of the actual screens. The final step of the design process is to test the wireframes by asking potential users to achieve the goal of the scenario using the wireframes.

9.5 Implication

Educational design is an important part of the process of evidence–based education reform, bridging the gap between educational practice and educational research results. Addressing educational design problems requires educators to further take the roles of researcher and designers. In this work, we introduce a design tool – personas – from human-computer interface design that supports user-centered design. User-centered design is increasingly assimilated within designer community as a perspective that promotes the usability and productivity of the designed product. We adopt user-centered design as well as personas, arguing for their power in helping us addressing our problems of practice – a very different work from phenomenologic case study and phenomenographic study.

Personas are motive-driven user models. Building personas helps us focus on why and how our users use our products so that we can design the ones that they need. Personas are a great model to represent our research participants, not only covering large data sets in smaller numbers of relatable human-like constructs, but also protecting participants' identity in communication with other designers and stakeholders. Discussing design features for 6 personas is certainly more effective than for 23 different real interviewed faculty.

Personas are great at protecting study participants' identity thanks to the blended construct of characteristics from many different real people and fictitious details. In this cases of building personas of PhysPort users from various institutions in the U.S., participant's identity is less likely to be of a concern. However, when studies and personas of participants are presented within their own institution, there is a need to reduce the risk of revealing their identity. Chapter 10 will discuss in greater length an example of building personas of undergraduate student researchers to build better research, where personas can offer great protection of their identity.

Designing is a deliberate work involving both art and science. The heart of this paper lies in our attempt to clarify this design strategy in both its art and science parts. Even though there are many guidelines for building personas available in interaction design, differences in the nature and approach of education and interaction design make it difficult for educational designers to follow without certain adjustments. This could contribute to why the use of this powerful tool is still scarce in education. Therefore, we hope to provide the step-by-step instruction of building validated and reliable set of personas via two problem designs of faculty professional development and student research engagement that educators could find helpful and supportive.

Because personas are built upon users' motivation or goals, which varies with the product, personas are not complete or generic, but rather directly dependent on the context and the problem designs. Therefore, for a similar problem design, we would expect a different set of personas. Even though in design it is common that different design teams sometimes find the same set of personas useful, I recommend that using personas from different contexts requires careful consideration and adjustment.

Chapter 10

Undergraduate researcher personas

10.1 Introduction

In chapter 9, I have presented the idea of personas and a methodology we proposed to build personas. With the kind of qualitative data we often acquire in educational contexts. I argue that building personas from phenomenographic results can help us produce effective personas. Personas are traditionally used for website-based design. Yet, in this chapter, I argue and provide an example that persona can benefit for non-website-based design in educational contexts as well. I take on a design problem of designing undergraduate research programs that are student-centered using personas. I briefly present the stages of building undergraduate researcher personas and discuss how could these personas help us build more attractive research programs for undergraduate students.

Authentic undergraduate research activities have a great impact on students' comprehensive development that neither lab courses nor other activities have been able to offer [135;136]. Faculty-mentored, hands-on research programs offer a community of practice that supports science students' cognitive and personal growth, as well as the development of their professional identity [137]. Moreover, undergraduate research experiences also positively influence underrepresented students' retention, persistence, and pursuit of science career pathways [138]. Researchers have developed a huge body of work investigating undergraduate research experiences in STEM fields. In this work, we are seeking to solve the narrower problem of using student interviews to guide the design of undergraduate research programs.

Despite various attempts to include more students in undergraduate research [139], faculty still often report obstacles, including difficulties in pitching their research program to a wide variety of students. Although psychologists have shown the critical influence of motivation on students' attitudes and behaviors, little discussion has explicitly included the diversity of student motivations into designing research programs. As many of the tasks we want students to perform, including research practices, might not be inherently interesting to all students [105], we need to account for the diversity of motivators when designing research programs. I argue that persona methodology can help within this educational context.

We repurposed existing interview data with undergraduate physics students to build personas of students participating in undergraduate research. Personas are life-like archetypes that stress users' diverse goals and motivations and embrace their corresponding needs and challenges. I use Self-Determination Theory to thoroughly describe the motivations that student personas have with regards to their research experiences. I claim that a set of memorable, sensible, and relatable personas can help facilitate student-centered discussions among faculty and departments with the goal of designing research programs that better fit students' goals and needs. For this design problem, I focus on building personas of students who are sufficiently motivated to engage in research, either intrinsically or extrinsically. I did not build personas of students who lack motivation to engage in research since it is not our goal to move students from unmotivated to motivated. Designing a complete research program with the constructed set of personas is also beyond the scope of this work.

10.2 Personas and Self-Determination Theory

The persona approach is consistent with Self-Determination Theory (SDT) [105], which emphasizes the critical role of motivation in energizing one's behavior and development. Although other classic perspectives view motivation as a continuous spectrum from low to high, SDT characterizes extrinsic and intrinsic motivations along axes of competence, autonomy, and relatedness. Your action is intrinsically motivated if you find the activity inherently enjoyable and satisfying. Conversely, your action is extrinsically motivated if you perform the action to gain separable outcomes, such as reaping instrumental rewards or avoiding sanctions. Each type of motivation yields different experiences and attitudes toward an activity.

SDT suggests intrinsic motivation results in high–quality learning and creativity. However, extrinsic motivation is not always distasteful. For example, students can perform extrinsically motivated actions with resentment and disinterest or, alternatively, with willingness and inner acceptance of the activity's value [105]. One can also become more intrinsically motivated by internalizing and integrating extrinsic regulations in such a way that their innate needs of competence, autonomy, and relatedness are satisfied.

In this context, Deci and Ryan's definition of autonomy concerns the sense of volition and self–endorsement, that means doing research on students' own will, stemming from their interest and integrated value. Competence refers to feeling effective in interacting with the research and experiencing opportunities to exercise and express their capacity. Relatedness, meanwhile, refers to feeling connected to others in the research group and belonging to the research community [140].

Researchers have taken up SDT in various fields, particularly education, to study social and environmental factors that facilitate rather than diminish one's motivations for learning [141], researching [142], or teaching [143]. In this work, I drew on SDT to identify the various kinds of motivation students might have to engage in scientific research, as well as to predict students' corresponding behaviors and experiences when building their personas.

10.3 Context and methodology

The data are drawn from semi-structured interviews with 2nd- and 3rd-year physics students at Kansas State University that was collected for a series of studies on students' identity formation, epistemological sophistication, and metacognition [144;137]. Paul Irving and Eleanor Sayre conducted interviews with 21 students (18 male); 9 of them (8 male) joined research groups either before or during their interview sets. The gender ratio is typical in our department. The interview protocol explored students' interest and experience in physics, their perception of physicists, their self-perception and physics identity, and their professional career plans. I found this set of data well suited for our focus, and therefore I repurposed it to build student personas that address our design problem. I discuss some of the constraints from using this data set in later sections.

Our physics department offers undergraduate research opportunities in two forms: voluntary assistantships with or without stipends during the academic year and the NSF-funded summer Research Experience for Undergraduates program. Students make their own decisions to engage in research taken outside of class work; this makes their motivation towards research activity worthwhile for deeper investigation. Here, I purposefully built student personas from the 9 students with research experience. I argue that these students were sincerely motivated to involve themselves in research. Therefore, their motivations and experiences with research produce a reliable primitive set of personas.

Previously, the interview data had been phenomenographically[(131)] analyzed[(144;137)]; I drew on and extended the results of that analysis as I searched for information related to students' various research motivations and experiences. Building personas from phenomenographic study is a new approach as present in depth in chapter 9. After watching 5 interviews, I found emergent themes of college majors and minors; disciplinary experiences and motivations; physics identity; and career plans and awareness of other physics-major jobs. Then, the whole set of interviews was repeatedly analyzed to explore the variations within each theme.

For example, I found three distinct motivations for students engaged in research from the interview data, aligned with the autonomy, competence, and relatedness dimensions from SDT. In this context, autonomy concerns students' sense of volition and self-endorsement that stems from students' interests and integrated values. Competence refers to students feeling effective in interacting with the research and experiencing opportunities to exercise and express their capacity. Relatedness refers to students' feelings of connection with others in the research group and of belonging to the research community.

A set of personas is valid and useful when each student participant is primarily represented by one persona (with major goals, challenges, and core details) and secondarily represented by a few other personas (with minor motives and details). Personas are goal-driven models, so we prioritized motivations and goals when making them. I created a spreadsheet with a column of 3 different motives that potentially make up 3 personas. Each motivation set a tone that guided us to fill in each persona with characteristic variation from every phenomenographic theme. During this process, we made constant comparisons among the personas and the data to assure that these personas are distinct and meaningful, and collectively embody the phenomenographic results. After having sketches of the personas, we fleshed them out with names and short descriptive quotes and construed their potential actions and challenges. I then revised and validated the set of personas by matching back to the data before discussing the work with other researchers for peer review.

10.4 Student personas

Although all students in our dataset expressed an inherent interest in physics, they had little idea about what research is like or what it entails before their involvement in research[(144)], i.e. they were extrinsically motivated towards research activity. We constructed 3 personas – Maria, Ashley, Louis (Figure 10.1) – whose motivations to do research are at various levels of autonomy, relatedness, and competence.

Of all the personas, Maria has the most diverse interests, which includes physics and physics research. Maria-type students are likely to have double majors or multiple minors, one of which is physics. She thinks physics research is somewhat important to physicists; therefore, she wants to try it out. Multiple interests also mean that she is open to many options and may have trouble deciding which option to try. This could be an obstacle to her committing to a research experience, regardless of her interest in physics. Maria is concerned with how research activity fits her broader interests and values, and she spends time weighing physics research with other options, ranging from research in other disciplines to non-academic activities. She is most attracted to research that is fun, where she can learn

Persona	Key Quote	Description	Challenges
 Maria	"I want to see what it's like."	Has many academic and non-academic interests. Open to many future career options. Research is somewhat important to scientist. Engage in research for self-competence and exploration experience.	Self and time commitment
 Ashley	"I want to work with these people."	Ambivalent physics background who do not commit to physics until having a great physics class or mentors. Career plan undetermined and open, but she has some role models. Field commitment is significant to scientists. Join research group for learning with the people she likes.	Struggles with self-efficacy and belonging feeling
 Louis	"I want to go to grad school."	An aspiring scientist who is determined on Research – Grad School – Professional career path. Research is significant to scientists. Engage in research to learn research skills, look for research of interest, and get competent for grad school.	Frustration with research activity or disappointment with self-efficacy

Figure 10.1: *Undergraduate researcher personas*

interesting things, and which does not require too much commitment.

Ashley stands out as a persona with a strong sense of relatedness, who is extrinsically motivated by the social influence of research activity. Ashley-type students might have had unfavorable experiences in other departments, or they might not have committed to physics until meeting a welcoming mentor or taking a great physics class. She participates in research for the fulfillment of relatedness needs, on the scope of either working with a direct mentor or with the physics community. Ashley tends to desire approval from her advisor and research colleagues as rewards and has not integrated extrinsic motivation yet. Therefore, Ashley might later encounter competence demotivators, which likely diminishes feelings of relatedness, i.e. feeling left behind, feeling incompetent at doing research.

Louis is extrinsically motivated by competence need – gaining experience useful for the future, exercising capacities, seeking for optimal challenges, and extending skills. Louis-type students are pretty determined on the path of Research -– Grad School -– Professional Career; he sees research as a necessary step to pursue post-graduate studies. Louis-like

Table 10.1: *Persona grid*

Real people vs Personas	**Louis**	**Maria**	**Ashley**
Will, Oliver, Ryan, Charlie	dominant	echo	
Ed	echo	dominant	
Sam	echo		dominant
Sally		echo	dominant
Jack	dominant		echo
Matt	dominant		

students do not necessarily have a specific research interest yet, but they are not hesitant to consider themselves as aspiring physicists, to approach research mentors, and engage in research early in their undergraduate program.

Ideally, the set of personas fully covers the aspects of students' experiences that are important to the design problem as shown in Table 10.1. I only present here one brief excerpt to illustrate the persona of Maria. For example, a student named Ed (pseudonym) is slightly represented by Louis for planning to become an academic professional, but he is dominantly represented by Maria for his struggles with choosing between interests in physics and chemistry, as well as allocating time for another non-academic activity as well as for language courses. "I couldn't pick between either of [physics and chemistry]. They're both a lot of fun. . . Well. . . there is a possibility that A, I just won't ever decide. I'll be dabbling in everything forever. Or B, after trying different things, I'll find one that I specifically enjoy more than others."

10.5 Discussion

We generated three personas of undergraduate researchers driven by various goals and motivations, which are differentiated by SDT. Personas are powerful because they encapsulate students' rich and relevant information in sensible and memorable forms. Using such a set of personas would not only help researchers, faculty, and departments to sympathize with and understand the richness of student variation, but would also create a space for effective communication among them without revealing students' identity. These plausible and relatable personas can help to bolster student-centered research design as well as optimize research program designs that fit real students as opposed to our biased perceptions of students. When we understand students' motivations as represented through personas, we can properly predict their experience in undergraduate research, and design motivators and pedagogical advising practices that increase students' individual interest, satisfaction, and retention in research. In other words, personas can point the way to a successful pitch for research programs to diverse students while saving faculty time and effort.

For example, in our context, Louis is excited for research experience regardless of being paid or not. Louis-type students may just need information such as faculty project details and contacts, and faculty do not need to make an extended effort to include them. For Maria-type students, however, it is important to advertise the research in such a way that highlights its interesting aspects, promotes tips for self and time management, and encourages her to check it out. Ashley needs close contact and collaboration with research peers and seniors; their faculty mentor should provide them with supportive collaboration.

Notably, the frequency of persona appearance in data is not the most important factor to validate personas. Rather, it is how personas are distinct from each other and collectively expand the data set. In our data, we find more Louis-like students than Maria and Ashley-like ones. However, we predict that we would find more Maria and Ashley-like students if we expanded the sample data. Also, the interview protocol on this data did not purposefully explore students' family or financial backgrounds, and we expect these aspects might play a role in additional personas. For example, an additional persona might represent non-traditional students -– who are age 25 or older, and who prioritize the need to earn money when making decisions about their academic activities(145). This persona might be interested in physics research as providing part-time jobs or better future jobs, but they might also weigh the value of research opportunities against other internship opportunities as well as against non-academic jobs.

10.6 Conclusion

Personas represent real users throughout the design process. Carefully crafted personas help designers put aside their biases and stereotypes of users and instead pay attention to whom the products are designed for and why or how those products will be used. By thinking about users first and foremost, designers can avoid urges to jump into fascinating design ideas that oftentimes are appealing to the designers, but are not meaningful to the user [124]. Personas are powerful because they seem like real humans with realistic characteristics and stories; this evokes designers' empathy for real users and thereby, promotes user-centered design. Although the persona methodology has been mostly used in website design, much of the work of building personas has benefits beyond that field [122;112]. I aim this work toward building personas of undergraduate researchers, so that we gain a better understanding and representation of those researchers and subsequently support future design of student-centered research programs.

Personas are also great at protecting study participants' identity thanks to the blended construct of characteristics from many different real people and fictitious details. Using personas has benefits beyond website design. In this chapter, I described an example of building personas of undergrad researchers. These personas provide faculty with a coherent understanding of undergrad research students without exposing the identities of particular students in the department. The personas can be used to develop a research program well-matched to undergraduates' motivations.

Furthermore, personas can be powerful research tools, especially when researchers study critical and sensitive issues. For example, building personas of students who decide to stay in or withdraw from physics programs due to racist and sexist academic environments will bring data-driven insights into the open discussion of these issues without risking student participants' anonymity. This is because each persona is an amalgamation of the characteristics of several people, not a single person as in a case study. Further, we can create the details of the persona so the people participating in discussions of sensitive issues using the personas don't inaccurately assume they represent a certain real student.

I also want to emphasize that personas are context and design-problem sensitive. I recognize that our data, even though it is characteristic for our institution, is limited and not representative for other contexts. In other words, while our persona set is suited to serve our institutional design problem, it may not be fully applicable and helpful in other contexts. I encourage departments and researchers to carefully justify any personas according to their targeted data. In addition, I advocate for the incorporation of personas methodology in educational research contexts for the advantage of strongly protecting participants' identity when research is presented to and discussed within departments.

Chapter 11

Summary and future work

Since its first introduction by Cooper [118], the method of personas has gained attention from and been used by program developers in fields beyond human-computer interface. Many practical design guidelines for generating personas are available with examples mostly taken from business, marketing, and website design. Many of these examples usually works with different kinds of data that we usually collect in educational contexts, where the data is often more qualitative and less quantifiable. It is not yet clear how to build effective personas with this type of data.

Persona use is scarce in education, regardless of its promising features. In this part of my dissertation, along with arguing for the power of persona for educational design, I endeavor to clarify this methodology with examples from educational contexts. Through these examples, I hope to justify the method of translating the user data in to personas and design solutions, keeping personas detailed enough so that we have the user focus, but general enough so that the number of personas needed to describe your data is not overwhelming.

One key component of the persona method I proposed is conducting a phenomenographic study and using the phenomenographic categories and variation for crafting personas. I argue that the process involving a phenomenographic study helps produce effective sets of personas. Phenomenography aims at abstracting the important information of real users. Therefore, doing phenomenographic study helps extracting out the hierarchical list of concise and significant variations of users' experience. Building personas starting from this list helps us avoid the overwhelming data of users, which usually includes superfluous data and tends to distract us from the important details, as well as the design itself. Furthermore, this process helps us avoid creating personas as exact description of individual real users, which tends to occur when we skip the phenomenography and start from raw user data.

One major common criticism towards persona as a methodology is that it can strongly involves designers' intuition or designer common sense in the process of building and using personas[(124)]. I agree that it is unavoidable to employ our own gut feelings during the research or design process. We use our understanding and knowledge of generic user experience to devise the interview protocol. We then use the our understanding and experience to interpret interview data and conduct phenomenographic study, deciding which details are important to include and which are to be set aside. We use our intuition to arrange abstract details of real user into persona constructs, deciding if the persona feels rational. We also use our knowledge and empathy to create persona representations and elaborate their stories and challenges.

Designers and researchers using their common sense or intuition is eventually inevitable and must be acknowledged. However, I argue the significance of this study is not to construct a methodology to eliminate designer intuition and common sense. Rather, I aim to trace out the methodology for ourselves to be aware of where and how we are using our intuition and common sense. It is only in the case we are aware of our intuition and gut feeling that we can make our intuition more knowledge-based and data-grounded, using them in a more meaningful and productive way.

In chapter 9 and chapter 10, I propose a methodology to building personas and present the process where we build 2 sets of personas: faculty and undergraduate student researchers. Although other researchers and education designers may find those set of personas useful to their design problems, I strongly encourage them to carefully examine the difference between our design mission, design questions, and available data. Personas are sensitive to the design questions. For example, the research team who cares about students future job preparation may find the set of undergraduate researcher persona relatable. But we need to carefully consider the differences to decide the extend to which of these personas can be useful.

Compared to the discussion of building the personas, less has been elaborated on the process of using personas and revising them. I acknowledge that design is a revolving process – users can change overtime and personas will evolve and need updating. My work is an introduction and overview of personas as a potential methodology in education. Much research needs to be done around the practice of using personas in educational contexts for us to gain more experiences and insights of personas and its use in education.

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