High School Physics Students', High School Physics Teachers', and University Physics Professors' Conceptions about What it Means to Understand Physics: A Phenomenographic Study

by

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Abstract

There is limited literature about what it means to understand physics. Previous research has focused on university physics students' understanding of physics concepts, but no research to date has examined variations across populations of what it means to understand physics. This study begins to fill this gap in the literature by describing high school physics students', high school physics teachers', and university physics professors' conceptions of what it means to understand physics. Therefore, the conceptions being explored in this study are the conceptions of what it means to understand physics itself.

Seventy-three participants (twenty-two students, twenty-three teachers, and twenty-eight professors) from one province in Canada were interviewed and their experiences and conceptions of what it means to understand physics were explored utilizing a phenomenographic approach. The result is a description of students', teachers', and professors' conceptions for the phenomenon, what it means to understand physics, and the qualitatively different ways the phenomenon was experienced.

Five categories of description emerged from the analysis: (1) feelings, (2) achievement, (3) communication, (4) making meaning, and (5) application. Twenty-two distinct subcategories of description emerged and represent the variation in what it means to understand physics between the students, teachers, and professors. The study found that as the level of the participant's physics expertise increased from novice to expert, the number of conceptions of what it means to understand physics also increased.

Four of the five categories of description: 'feelings', 'achievement', 'communication', and 'making meaning' were not found in the current literature of individuals' conceptions of understanding physics and some of the variations in the subcategories may reflect the varying

extent of the participants' physics expertise and experiences. The participants shared that they experienced an emotional response to what it means to understand physics and a key finding is that the physics professors conceptualized what it means to understand physics as a 'gut feeling' or a 'feeling of intuition'. The outcome space for this study is non-hierarchical, holistic, and represented by a circle, which means that each category of description is arranged on the same level as each other.

Preface

This dissertation is an original intellectual product of the author, Michael Paul Lukie. The research project, of which this dissertation is a part, received research ethics approval from the University of Alberta Research Ethics Board on May 24, 2016. Study ID: Pro00061042.

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Chapter 1 Introduction

1.1 Introduction to the Study

My study used phenomenography to determine the qualitatively different ways physics students, physics teachers, and physics professors conceptualized about what it means to understand physics. Students, teachers, and professors may have different conceptions about what understanding physics means and these variations in conceptions can have implications for teaching and learning physics.

According to Marton (1994), "phenomenography is the empirical study of the limited number of qualitatively different ways in which various phenomena in, and aspects of, the world around us are experienced, conceptualized, understood, perceived, and apprehended" (p. 4424). I examined the variations in the experiences of students, teachers, and professors for the phenomenon, what it means to understand physics. The variations in the experiences of the participants, or their 'conceptions', were characterized in terms of 'categories of description' and then these categories of description were presented in an 'outcome space' that describe how the categories of description are logically related to each other.

Accordingly, the purpose of my study was to investigate how physics students, physics teachers, and physics professors conceptualize about what it means to understand physics. By studying the variations in the conceptions about what it means to understand physics, the variations in these understandings between students, teachers, and professors can be identified, can be shared, and these might be used to raise awareness of them to ultimately improve student learning. There is limited scholarship about student, teacher, and professor conceptions of what it means to understand physics and this study begins to fill this gap in the literature.

The following sections describe: the background to the study, the purpose of the study, the significance of the study, the researcher's philosophical orientation, and the research questions.

1.2 The Background to the Study

Currently, I teach curriculum and instruction courses in physics, science, and mathematics in the Faculty of Education at the University of Winnipeg. Prior to 2016, I was a high school physics teacher and I taught for fourteen years in both public and private Manitoba high schools. My research, teaching, professional development, and personal interests are aimed at improving students' and pre-service teachers' conceptual understanding of physics, and in improving physics pedagogy across educational settings.

The concept of understanding has been associated with higher quality or in-depth learning (Hamer & van Rossum, 2017), and has been identified as one of six different possible conceptions of learning (Säljö, 1982; Marton et al., 1993) (see Table 1). Entwistle and Entwistle (1991) suggest that there is a distinction between whether learning is seen as "requiring the 'reproduction' of information presented, or the 'transformation' of that information in the process of coming to understand it for oneself" (p. 205).

Table 1

Categories Describing Conceptions of Learning, (Entwistle & Entwistle, 1991, p. 206)

A.	Increasing one's knowledge	
B.	Memorizing and reproducing	Reproducing
C.	Applying facts and procedures	
D.	Understanding	
E.	Seeing something in a different way	Transforming
F.	Changing as a person	

Although understanding subject material is associated with high quality learning or in-depth learning, a fundamental problem is that there is no commonly agreed upon definition of understanding, as noted some time ago by Nickerson (1985) and Ormell (1979). The word 'understanding' is a commonly taken for granted word within physics classrooms and classrooms in general and is used interchangeably with words such as 'information' and 'knowledge'. Nickerson (1985) writes that until an adequate definition of understanding is developed, it is difficult to have a methodology for determining "whether, or the degree to which, understanding has been attained" (p. 230).

The degree to which students have developed understanding in physics is difficult to determine. Students may appear to posses an understanding of physics concepts by performing well on assessments, but they may have simply memorized the problem solutions and/or algorithms, hence requiring no to limited conceptual understanding on their part. Ormell (1979) adds that an additional problem is that assessing for understanding has been conflated with assessing for knowledge in some classrooms.

Skemp (1976) suggests that it may be problematic when students consider that they come to understand a mathematics topic through the memorization of disconnected facts, while their teachers expect them to develop schemas to relate and connect these disconnected facts. Similarly, Newton et al. (1998) found variations between the conceptions of understanding science that university students and teachers held. Newton et al. (1998) speculated that, "when students' conceptions do not match those of their lecturers, there is a potential for difficulties in learning" (p. 45). These difficulties, Newton et al. argue, might arise when the lecturer values and expects conceptions of understanding science for which the student is not fully aware. Although variations between the students' and the lecturer's understanding of science can be present, students might find it “relatively easy to meet the lecturer’s expectations without understanding” (Newton et al., 1998, p. 55). Therefore, my study might shed light on how students’ conceptions of what it means to understand physics differ from those of their teachers as Newton et al. suggest.

My experience with what it means to understand physics is the result of having taken many university physics courses, having taught high school physics, and having taught pre-service physics teachers. I come to this study from my classroom experience where I have found that many students that I have taught claimed to understand physics via the memorization of formulas and the memorization of recipe like algorithms when solving problems. Van Heuvelen (1991) contends that physics students, “still use formula-centred problem-solving methods and their knowledge consists of a small number of facts and equations stored randomly in the mind” (p. 896), and I have recognized these issues with my students in my classroom experience. Hestenes (1998) writes about the Force Concept Inventory [FCI] and states that “for a typical University Physics course we found that nearly 80% of the students could state Newton’s Third Law at the beginning of the course, while FCI data showed that less than 15% of them fully understood it at the end.” (p. 465). Lawson and McDermott (1987) found that physics students who were studying motion, “were unable to relate the algebraic formalism they learned in class to the simple motion that they observed in the real world” (p. 811). The term ‘real world’ may be defined as “the realm of practical or actual experience, as opposed to the abstract, theoretical, or idealized sphere of the classroom, laboratory, etc.” (“Real World”, 2019) and I will use the term ‘real world’ throughout my dissertation in this context. Hounsell (1997) adds that:

> When the mastery of factual or procedural details (in many disciplines a vital cornerstone of understanding) becomes an end in itself, dislocated from meaning, then to have learnt is not to have partially understood but to have not understood at all. (p. 240)

These authors point to the potential issue that variations in the ways that students conceive of what it means to understand physics might be problematic since there is a "gap between reproduction and understanding" (Hounsel, 1997, p. 240). The significance of my study is the potential it has to identify the variations in the conceptions students, teachers, and professors have about what it means to understand physics.

1.3 The Purpose of the Study

The purpose of my study is to identify the conceptions that students, teachers, and professors have about what it means to understand physics and to investigate the variations between these groups in relation to these conceptions. By examining the conceptions students have about what it means to understand physics, classroom physics teachers might be informed about what students consider understanding physics to be. Dahlin (1999) states that it is important that a clearer view of how students "may conceptualize how understanding comes about since this may help us to construct their curriculum in ways which stimulate a 'deeper' approach to their subsequent studies" (p. 194). Furthermore, Dahlin adds that "by taking up for reflection and discussion the students' conceptions of understanding…we may hope to stimulate the development of motives and strategies for 'deep learning'" (p. 206).

The conceptions physics teachers have about what it means to understand physics may potentially be used to inform and modify both classroom practice and curricula. Teachers should know what conceptions students hold about what it means to understand physics because effective learning begins with where the learner is. By knowing about a students' conceptions, the teacher might move students from a novice type of conception of what it means to understand physics to more of an expert type of conception.

Physics professors are expert physics learners and by examining the conceptions that they have about what it means to understand physics, we might use their conceptions to inform classroom physics teachers and their practices and what they teach. Therefore, physics professors' conceptions of what it means to understand physics may be taught to physics teachers, who in turn can teach their students. The hope is to move towards improved physics learning since "we may consider as an indicator of degree of understanding the extent to which a student's understanding [of physics] corresponds to that of a physicist's" (Trowbridge & McDermott, 1980, p. 1020).

By asking the students, teachers, and professors what they consider it means to understand physics, each group is being provided with a backdrop for reflection about their thinking. Since "learners are always the key players in learning activities, we should be concerned about what they think, believe, and value about learning and understanding" (Berry & Sahlberg, 1996, p. 19). In reflecting about their conceptions, each group is being metacognitive. In being metacognitive, each group is stimulated at an epistemic level and this is something that may not have occurred otherwise.

Thomas and McRobbie (1999), Thomas (2017), and others found that in the case of high school chemistry students, a change in their conceptions of understanding of what it means to understand chemistry changed some students' behaviours although not universally. Based upon the outcome of my study, it may be possible to change some physics students' conceptions of what it means to understand physics and in turn their behaviors or approaches to learning by providing students with alternative views they might not know about.

1.4 The Significance of the Study

The significance of my phenomenographic study is its potential in beginning to fill the gap in the literature by examining the conceptions of what it means to understand physics. Phenomenographic studies have explored the nature of understanding as experienced by university students revising for degree examinations (Entwistle & Entwistle, 1991, 1992). There is currently no literature regarding high school students' conceptions of what it means to understand physics but there are studies that examined university "students' conceptions of understanding mechanics" (Waterhouse & Prosser, 2000, p. 4) and "upper-level physics students' conceptions of understanding" (Irving & Sayre, 2012, p. 198). Therefore, my study will begin to fill the gap in the literature by building upon the studies of Entwistle and Entwistle (1991, 1992), Waterhouse and Prosser (2000), and Irving and Sayre (2012).

Koponen et al., (2004) propose that, "in physics teacher education the challenge is to promote the development of the expertise needed in physics teachers" (p. 645). My study has the potential to promote expertise in physics teacher education by providing physics teachers and physics teacher educators with insights into professors' expert conceptions about what it means to understand physics. By providing teachers with professors' expert conceptions about what it means to understand physics, a reference point beyond the physics teachers' own conceptions might be established. This might potentially result in the teachers re-contextualizing what they are teaching students. Furthermore, my study has significance for physics education because my study will make students', teachers', and professors' conceptions of what it means to understand physics available for scrutiny, which will "enable viable conceptions of teaching and learning to be communicated intelligibly to students so that they might assess their plausibility and consider their potential viability and value" (Thomas, 2006, p. 106).

Many physics teachers are ‘out-of-field’ (Ingersoll, 1999; Ingersoll & Gruber, 1996) where an ‘out-of-field’ teacher is defined as “teachers teaching subjects for which they have little education or training” (Ingersoll, 1999, p. 26). I have observed this anecdotally during my fourteen years as a high school physics teacher. Consequently, many of these ‘out-of-field’ physics teachers may not have taken undergraduate or high school physics courses. These ‘out-of-field’ physics teachers may be considered novices (Dee-Lucus & Larkin 1986; Finegolf & Mass, 1985), thereby limiting how they conceive of what it means to understand physics. My study has the potential to provide ‘out-of-field’ physics teachers with conceptions of what it means to understand physics, such as those of expert physics professors, that the teachers might not have considered.

Bowden (2000b) reports that phenomenographic studies that question “students’ ways of understanding particular aspects of the world” (p. 59) around them are important because “having students question their own understanding has powerful potential for learning” (p. 60). My study was undertaken to listen to what students say it means to understand physics because as Bowden (2000b) contends, “good teachers do try to listen in order to discover students’ understanding” (p. 60) of phenomena and their experiences. When writing about what phenomenographic research offers teachers, Dall’Alba (2000) suggests that as students’ and teachers’ “understanding of the ideas we seek to develop” (p. 99) are identified, teachers can determine where both student and teacher understanding of these ideas can be developed. My study promotes good teaching by questioning and listening to students’, teachers’, and professors’ conceptions of what it means to understand physics.

As shared previously, literature about what it means to understand physics has not been previously published and has not focused on students’, teachers’, and professors’ conceptions about what it means to understand physics. What has been focused on is research about students' understanding of specific topics and concepts in physics. For example, students' understanding of Archimedes' principle (Heron et al., 2003), thermodynamics (Cochran & Heron, 2006), the role of models in physics instruction (Etkina et al., 2006), the role of experiments in physics instruction (Etkina et al., 2002), force (Brookes & Etkina, 2009), and peer instruction (Mazur, 1997; Crouch & Mazur, 2001). My study has an aspect of uniqueness about it because it examines three groups of participants with three different levels of physics expertise. Therefore, my study has the potential to develop a common language about physics that may be shared with each of these groups. Thomas and McRobbie (1999) suggests the following:

> If classrooms are to be sites for developing self-regulated learners based on constructivist principles then…the members of that community must share a common language that enables them to cultivate familiarity, custom or intimacy with regard to learning practices via their discourse. (p. 682)

By asking students, teachers, and professors about what their conceptions are of what it means to understand physics, my study has the potential to develop a 'common language' for the physics education community.

In summary, my study will begin to fill the gap in the literature about the conceptions of understanding physics and will add to the literature about what it means to understand physics from the perspectives of high school physics students, high school physics teachers, and university physics professors.

1.5 The Researcher's Philosophical Orientation

As a qualitative researcher, I identify with the interpretivist paradigm and both my ontological and epistemological views are influenced by interpretivism. In the following paragraphs, I describe the interpretivist paradigm and how this paradigm is consistent with the aims and goals of my phenomenographic study.

According to Scott and Usher (2000), interpretivist research "takes everyday experience and ordinary life as its subject-matter and asks how meaning is constructed and social interaction is negotiated in social practices" (p. 25). The ontology for the interpretivist paradigm, the nature of reality, is that reality is subjective and changing, and that there are multiple and diverse interpretations of reality (Bunniss & Kelly, 2010). The epistemology for the interpretivist paradigm, the nature of knowledge, is that knowledge is subjective, there is no one ultimate or correct way of knowing, and there is no one ultimate truth (Bunniss & Kelly, 2010). O'Donoghue (2007) adds that the basis for knowledge in the interpretivist paradigm is social interaction where "the researcher uses his or her skills as a social being to try to understand how others understand their world. Knowledge, in this view, is constructed by mutual negotiation and it is specific to the situation being investigated" (p. 10). For my study, the specific situation being investigated is what it means to understand physics and knowledge is being constructed by the social interaction between the researcher and the participants through an interview.

According to Green (2002, 2005), phenomenography "subscribes to an interpretivist stance" (p. 34) and is based upon the idea of multiple interpretations of reality. Therefore, my phenomenographic study is consistent with an interpretivist paradigm because multiple realities are constructed from the interpretations made by the interview participants as a consequence of their interactions within the world (Green, 2005). In general, interpretivism attempts to understand and describe the research participants' meanings and understandings of their social lifeworld (Koro-Ljungberg et al., 2009). In the case of my study, the meanings and understandings of interest are the variations in the conceptions participants experience about what it means to understand physics.

In summary, I am grounded in an interpretivist paradigm. My research is consistent with the ontological and epistemological underpinnings of interpretivism because I assume that reality is subjective and interpretations of reality are changing, knowledge is subjective, and there is no one way of knowing. I am using my skills as a researcher to try to understand how the participants understand their world, and I am specifically trying to understand what the participants conceive of what it means to understand physics.

1.6 The Research Questions

My study determined the variations in the qualitatively different ways high school physics students, high school physics teachers, and university physics professors conceptualized about what it means to understand physics. The following four questions were posed:

1) What are high school physics students' conceptions about what it means to understand physics?
2) What are high school physics teachers' conceptions about what it means to understand physics?
3) What are university physics professors' conceptions about what it means to understand physics?
4) What are the similarities and differences (variations) between the conceptions of these groups regarding what it means to understand physics?

In the following Chapter, the literature about understanding is reviewed to provide the reader the opportunity to contextualize previous literature that grounds my study.

Chapter 2 Literature Review

2.1 Introduction

For my study investigating what it means to understand physics, I drew upon a diverse body of literature ranging from philosophy to physics. This Chapter describes my search strategy, my categorization of the literature, and the contents of the literature.

To determine the state of both theory and research about understanding in general and in specific educational disciplines, I searched 'understanding' in a variety of combinations with other words and phrases, such as 'meaning of', 'philosophy', 'phenomenography', 'education', 'science', and 'physics' in EBSCO Information Services and Google Scholar. I read the title and abstract of each search result and if it met the criteria of examining understanding in general or it directly related to education and a given topic, I retrieved the full text of the scholarly works. From the literature that engaged in understanding, I grouped the literature into the following categories and subcategories:

1) Academic Conceptions of Understanding
    a) Philosophical Perspectives.
    b) Educational Psychology Perspectives.
    c) Mathematics and Science Education Perspectives.
2) Empirical Studies Investigating Conceptions of Understanding
    a) Non-phenomenographic Studies.
    b) Phenomenographic Studies.

The category, 'academic conceptions of understanding', consists of literature that examines theories and ideas about understanding in general from the academic disciplines of philosophy, educational psychology, and mathematics and science education. The category, ‘empirical studies investigating conceptions of understanding’, consists of literature utilizing qualitative research methodologies and is further categorized into non-phenomenographic studies and phenomenographic studies that examine understanding in general and understanding of specific topics. The following sections describe the literature in the categories and subcategories listed above. It is important to emphasize that my study examined the conceptions of what it means to understand physics as a field which has not been previously investigated. My original research presented in this dissertation is rooted in both the academic conceptions of understanding in general, and empirical studies that examine understanding in general and the understanding of specific topics. As I utilized phenomenography as my research methodology, the literature related to the analytical framework developed by Marton (1988) for analyzing the structure of phenomenographic conceptions is examined.

2.2 Academic Conceptions of Understanding

The following three sections examine literature about what it means to understand physics from a philosophical perspective, an educational psychology perspective, and a mathematics and science education perspective. This literature is based upon theories and ideas about understanding in general from the academic disciplines of philosophy, educational psychology, and mathematics and science education, but did not investigate or analyze data.

According to Gibbs (1992), understanding is a significant indicator of the quality of a student’s learning and Whitehead (1917) indicates that education should be useful and “it is useful, because understanding is useful” (p. 6). The significance of studying understanding, according to Nickerson (1985), is that “the concept of understanding is a fundamental one for education…and it deserves more attention than it has received” (p. 235).

In general, understanding is accepted to be an active process of meaning construction (Burns, Clift, & Duncan, 1991) and involves the interpretation of information based upon knowledge (Bransford, 1979; Schank & Abelson, 1977). Jenkins (1974) suggests that understanding is personal and depends on the context in which information is received and is based upon the context in which the knowledge is retrieved. Moreover, Hounsell (1997) asserts that "when something has been genuinely understood, it has been related by students to their prior knowledge and experience and it is perceived as helping them to make sense of the world around them" (p. 240). To achieve understanding, Schank (1982) and Ziff (1984) contend that an individual's background knowledge is important. However, of greater importance to achieving understanding is the way background knowledge is organized rather than how much background knowledge an individual possesses (Ziff, 1984).

Newton (2002) writes that "understanding is a powerful kind of knowing" (p. 2) but suggests that understanding is a finite achievement because the individual either understands or does not. A dictionary definition of understanding is provided by Merriam-Webster.com and 'understanding' is defined as "1.a mental grasp: comprehension, 2. a: the power of comprehending; *especially*: the capacity to apprehend general relations of particulars, 2.b: the power to make experience intelligible by applying concepts and categories" ("Understanding", 2019).

2.2.1 Philosophical Perspectives

This section examines literature based upon theories and ideas about understanding in general from the academic discipline of philosophy. The literature in this section examines the philosophical perspectives of the philosophers, Whitehead, Heidegger, Gadamer, and Malpas.

Whitehead (1938) describes a quest to “understand Understanding” (p. 58) and suggests that this quest is a hopeless task. The task is hopeless according to Whitehead (1938) because we can only “enlighten fragmentary aspects of intelligence” (p. 58) and “there is always an understanding beyond our area of comprehension” (p. 58). Whitehead (1938) explains that “understanding is never a completed static state of mind. It always bears the character of a process of penetration, incomplete and partial” (p. 60). Whitehead (1938) contends that in trying to understand “we realize ourselves as engaged in a process of penetration” (p. 43) and it is through this process of penetration that our self-knowledge is fuller and we have a sense of completion to the job of intelligence. Whitehead (1938) adds that understanding can be thought of as two different “modes of understanding” (p. 45) and these modes are ‘internal understanding’ and ‘external understanding’. Whitehead writes that ‘internal understanding’ is understanding where the thing to be understood is a composition of factors and how these factors interweave to form a whole while ‘external understanding’ is understanding where the thing to be understood can be considered “as a unity, whether or not it is capable of analysis” (p. 46). Bloom et al., (1981) agrees with Whitehead (1938) that defining understanding is a difficult task since “no one has ever seen understanding” (Bloom, et al., 1981, p. 20). Instead, only certain observable behavioral patterns are given the label of understanding by an observer. Therefore, it is difficult to both define and describe understanding since it is open to various interpretations due to the variability of what understanding is.

According to Heidegger (1962), the act of understanding is subjective and results in an individualized state-of-mind. Heidegger states that because we live in the world, we project understandings about the world, we have a history that affects our understanding about the world, and we have prejudgments and presuppositions about the world that additionally affects our understanding. Therefore, according to Heidegger, understanding is intertwined with both interpretation and application and cannot be separated from them.

Gadamer (2006) describes understanding in terms of Heidegger's hermeneutic circle where "constantly understanding understands itself" (p. 268). It is claimed that a circular process is involved with understanding because to understand means to continually correct and refine understanding (Gadamer, 2006). Gadamer (2006) explains that "in the circle is hidden a positive possibility of the most primordial kind of knowing" (p. 269). In describing Heidegger's hermeneutic circle, Gadamer (2006) writes that "what Heidegger is working out here is not primarily a prescription for the practice of understanding, but a description of the way interpretive understanding is achieved" (p. 269). In this way, understanding is seen as a recursive process where understanding is achieved through interpretation and by continually revisiting the interpretation in order to gain a deeper understanding (Gadamer, 2006). Understanding derived from the process of the 'Hermeneutic Circle' is then "generative recursion between the whole and the part" (Moules, 2002, p. 15) and continually revisiting the part to the whole.

According to Malpas (2018), Gadamer views understanding as a negotiation between two parties in a hermeneutical dialogue where the process of understanding is a matter of coming to an agreement about some given topic. The coming to an agreement about a given topic means establishing "a common framework or 'horizon' and Gadamer thus takes understanding to be a process of the 'fusion of horizons' (*Horizontverschmelzung*)" (p. 9). Therefore, all understanding involves a 'fusion of horizons' or a process of dialogue and mediation between what is familiar and unfamiliar. Malpas (2018) describes the 'fusion of horizons' as follows: "Inasmuch as understanding is taken to involve a 'fusion of horizons', then so it always involves the formation of a new context of meaning that enables integration of what is otherwise unfamiliar, strange or anomalous." (p. 9).

One might speculate that the 'fusion of horizons' might have value for my study because by providing students and teachers with the expert conceptions of what it means to understand physics from physics professors, the students' and teachers' familiar 'horizons' of what it means to understand physics may move toward the formation of new meanings with the integration of the professors' unfamiliar 'horizons' or expert conceptions about what it means to understand physics.

In summary, Whitehead (1938) suggests understanding consists of knowing a given concept and having comprehension about it. Heidegger (1962) describes an intertwined link between both interpretation and understanding, and Gadamer (2006) describes understanding in terms of Heidegger's 'Hermeneutic Circle' where it is constantly being refined and iteratively corrected. Finally, Gadamer (2006) and Malpas (2018) describe understanding as the 'fusion of horizons' or the taking of meaning from the unfamiliar and integrating it with what is familiar.

2.2.2 Educational Psychology Perspectives

This section examines literature based upon educational psychology perspectives about what understanding means in general. The authors' ideas and theories are grounded in the discipline of educational psychology.

Bloom and Krathwohl (1956) suggest that understanding is not well defined and refer to understanding as a common objective of educators. Although understanding is a common objective of educators, Bloom and Krathwohl indicate that teachers have different conceptions about what their students should understand. However, the teachers' different conceptions about what their students should understand is not the same as what their students should conceive of as understanding (Bloom and Krathwohl, 1956). Some teachers expect their students to ‘really understand’, some teachers would rather their students ‘internalize knowledge’, and other teachers would rather their students ‘grasp the core or essence’ of a topic (Bloom & Krathwohl, 1956). Bloom and Krathwohl (1956) pose an interesting question, “what does a student do who ‘really understands’ which he does not do when he does not understand?” (p. 1).

Bloom et al., (1981) contend that “the ability to understand instruction may be defined as the ability of the learner to understand the nature of the task to be learned and the procedures to be followed in learning it” (p. 56). Presumably, once a student can follow a procedure to understand instruction, the student is better suited to understand the content as well.

Anderson and Krathwohl (2001) describe understanding as the second cognitive process in the following cognitive processes: remember, understand, apply, analyze, evaluate, and create. The ‘understand’ cognitive process is described as the ability to “construct meaning from instructional messages, including oral, written, and graphic communication” (Anderson & Krathwohl, 2001, p. 31) and this cognitive process is further divided into: interpreting, exemplifying, classifying, summarizing, inferring, comparing, and explaining. Anderson and Krathwohl (2001) suggest that when students understand, they can “build connections between the ‘new’ knowledge to be gained and their prior knowledge” (p. 70). When students understand, they integrate incoming knowledge with their existing cognitive schemas and this cognitive schema may be defined as the organization of knowledge about a concept (Anderson & Krathwohl, 2001). Anderson and Krathwohl (2001) contend that since concepts are the building blocks for students’ frameworks and schemas, a students’ “conceptual knowledge provides a basis for understanding” (p. 70). Therefore, according to Anderson and Krathwohl, understanding refers to a student's ability to connect their prior knowledge with what is currently being learned and their ability to integrate this new knowledge into their existing cognitive framework.

According to Wiggins and McTighe (2005), understanding "involves meeting a challenge for thought" (p. 39) because when a mental problem is encountered, we use our judgment to "draw upon our repertoire of skill and knowledge to solve it" (p. 39). Wiggins and McTighe suggest that understanding involves the application of knowledge to new contexts but also describes it as a manifestation of insights. Wiggins and McTighe (2005) contend that "to understand is to make sense of what one knows, to be able to know why it's so, and to have the ability to use it in various situations and contexts" (p. 353).

Wiggins and McTighe (1998) write that when a student truly understands, the student can "explain, justify, generalize, predict, support, verify, prove, and substantiate" (p. 47) in order to demonstrate understanding. Six facets of understanding are presented by Wiggins and McTighe and these six facets describe understanding in the following way: (1) when one can explain, (2) when one can interpret, (3) when one can apply, (4) when one can have perspective, (5) when one can empathize, and (6) when one can have self-knowledge.

The first facet of understanding described by Wiggins and McTighe (1998) is, 'can explain', and describes the importance of explanation since it provides supported accounts of understanding through data, facts, and phenomenon. The second facet, 'can interpret', describes understanding as the ability to interpret and translate information by making it both personal and accessible through analogies, models, and images. The third facet, 'can apply', describes understanding as the ability to apply and adapt information to diverse new contexts. The fourth facet of understanding, 'have perspective', suggests that understanding is derived from critically seeing and hearing different points of view. The fifth facet of understanding, ‘can empathize’, involves understanding that is derived from finding value in what others may find different including the ability to perceive sensitively on the basis of direct or prior experience. Finally, the sixth facet of understanding described by Wiggins and McTighe, ‘have self-knowledge’, describes the state of understanding when there is the awareness that prejudices or habits of mind may impede understanding. In these six facets of understanding, Wiggins and McTighe view the facets of understanding as overlapping and integrated without a hierarchy.

Gardner (2011) describes understanding in a way similar to Wiggins and McTighe’s (1998, 2005) third facet of understanding, ‘can apply’, when he writes about endorsing an education for understanding. Gardner (2011) writes:

> By understanding, I mean simply a sufficient grasp of concepts, principles, or skills so that one can bring them to bear on new problems and situations, deciding in which ways one’s present competencies can suffice and in which ways one may require new skills or knowledge. (p. 19)

Gardner (2011) states that “understanding is not an acquisition that clicks into place at a certain developmental juncture” (p. 200) but that the “process of understanding involve sets of performances carrying out analyses, making fine judgment, undertaking syntheses, and creating products that embody principles or concepts central to a discipline” (p. 200). Gardner suggests that genuine understanding may be more likely to emerge if individuals possess several ways to represent the knowledge of a concept or skill and if individuals can readily move between these different forms of knowing. Therefore, Gardner is suggesting that understanding may be defined as the ability to apply and interpret knowledge in several different contexts or domains but is not something that occurs developmentally.

According to Nickerson (1985), the most important point about understanding "is that if one deeply understands a concept, principle or process, that understanding should be demonstrable in a variety of ways" (p. 230) and these ways may be considered behaviours. Some of these ways or behaviours include: the ability to communicate with people who are experts in a particular domain, the ability to consistently apply a principle in many different contexts, the ability to consistently perform a procedure or process to obtain a desired result, the ability to form analogies that experts in a particular domain would consider appropriate, and the ability to have the confidence that a principle or relationship is understood or seen (Nickerson, 1985). Nickerson adds that although a person can use a word appropriately for a given context, this does not mean that the person has understood the meaning of the word.

Ormell (1979) suggests that for an individual to achieve a 'clear' understanding about a topic, the individual must be aware of the "meaning of the message, policy or principle" (p. 34) for the given topic. To achieve a 'clear' understanding, Ormell (1979) suggests that understanding should involve a connection between the 'word' and the world. What Ormell has suggested might be potentially important for physics students' understanding of physics since many physics students do not make the connection between a physics concept learned in the classroom and its application in the real world.

In summary, understanding may be manifested in a number of ways and it is the application of knowledge to new contexts, represents the connection leaners make with the world (Nickerson, 1985; Ormell, 1979; Wiggins & McTighe, 2005), and is a common objective of educators (Bloom & Krathwohl, 1956). From the students' standpoint, understanding represents their ability to connect prior knowledge with what is being learned, and the ability to integrate this knowledge into their existing cognitive framework (Anderson & Krathwohl, 2001).

2.2.3 Mathematics and Science Education Perspectives

The literature in this section is based upon mathematics and science education perspectives about what understanding means in general and the authors' ideas and theories are grounded in the disciplines of mathematics and science education. The literature describes understanding in a number of different ways. For example, Newton (2002) describes descriptive, explanatory, and procedural understanding, Skemp (1976) describes relational and instrumental understanding, and Greeno and Riley (1987) describe theoretical and intrinsic understanding.

Newton (2002) writes about "some kinds of understanding in science" (p. 11) and include: (1) descriptive understanding, (2) explanatory understanding, and (3) procedural understanding. A student demonstrates 'descriptive understanding' when the student can describe understanding using "a mental picture and his or her own words to give a meaningful account of it" (Newton, 2002, p. 12). A student demonstrates 'explanatory understanding' if they have an "understanding of the situation and some relevant reason or causes for it" (Newton, 2002, p. 12). According to Newton, 'explanatory understanding' is especially important in science learning because students need to understand that science is more than simply naming and describing. Newton suggests that students should come to understand the importance and reasons for the naming taxonomies that are used in science rather than employing rote memorization without understanding. A student demonstrates 'procedural understanding' when the student can "grasp the way of doing something" (Newton, 2002, p. 13). Newton suggests that 'procedural understanding' can be broken down into 'descriptive procedural understanding' and 'explanatory procedural understanding'. The difference between 'descriptive procedural understanding' and 'explanatory procedural understanding' may be explained with the following example. A student demonstrates 'descriptive procedural understanding' when the student can describe how to use a thermometer while a student demonstrates ‘explanatory procedural understanding’ when the student can explain why a thermometer should be used in a specific way (Newton, 2002). Newton contends that the development of ‘explanatory understanding’ is especially important in scientific inquiry because it promotes a systematic process for the exploration and testing of scientific concepts.

Skemp (1976) writes about understanding mathematics and describes both ‘relational understanding’ and ‘instrumental understanding’. Relational understanding means “knowing both what to do and why” (Skemp, 1976, p. 2) where a student knows and can apply a mathematics rule while also being able to know why the rule works. Instrumental understanding means “rules without reasons” (Skemp 1976, p. 2) where a student simply knows and can apply a mathematics rule. The advantage of ‘relational understanding’ for students is its adaptability to new mathematical tasks. When students understand mathematics deeply, Skemp suggests that these students are more able to adapt their knowledge to problem types that do not follow a prescribed format or do not require a memorized rule. Skemp argues that a student who understands mathematics does not have to memorize as many rules since the student can see the interrelatedness of the mathematical concepts. According to Skemp, the advantage of ‘instrumental understanding’ is that it is usually easier for students to achieve since they can follow rote mathematical rules rather than understanding the underlying logical reasons for the mathematical rules being employed.

Skemp (1976) contends that there is a need for both ‘instrumental understanding’ and ‘relational understanding’. Students should memorize instrumentally and understand relationally because both instrumental and relational understanding provide students a much deeper and richer conceptual understanding of mathematics (Skemp, 1976). Futhermore, Skemp suggests that a disconnect between students and teachers occurs when students have an ‘instrumental’ form of understanding and simply memorize disconnected facts, while their teachers expect students to develop a ‘relational’ form of understanding and develop schemas to relate disconnected facts.

Greeno and Riley (1981) write about the processes of understanding that have “been developed in the context of studies of cognitive procedures relevant to school mathematics” (p. 289). According to Greeno and Riley, the question of understanding a cognitive procedure is whether the student performs the cognitive procedure with some knowledge about the procedure or whether the student’s performance is rote and mechanical. If the student performs the cognitive procedure with some knowledge about the procedure then Greeno and Riley call this ‘theoretical understanding’, but if the student’s performance is rote and mechanical then Greeno and Riley call this ‘intrinsic understanding’. Greeno and Riley clarify that ‘theoretical understanding’ “involve some general principle or structure that is related to the procedure” (p. 290) while ‘intrinsic understanding’ “involve factors that are included in the procedure itself” (p. 290). The ‘theoretical understanding’ proposed by Greeno and Riley is similar to Skemp’s (1976) ‘relational understanding’ where ‘relational understanding’ is “knowing both what to do and why” (p. 2) or performing a procedure with some knowledge. In addition, the ‘intrinsic understanding’ proposed by Greeno and Riley is similar to Skemp’s (1976) ‘instrumental understanding’ where ‘instrumental understanding’ involves “rules without reasons” (p. 2) or performing a procedure in a rote and mechanical way with no knowledge about how the procedure works.

In summary, the literature suggests that understanding refers to an individuals’ ability to build up a conceptual structure or schema for a given topic and the ability to apply this schema to a given situation to produce a solution (Skemp, 1976). Such understanding is referred to as 'relational' understanding or knowing 'what to do and why' (Skemp, 1976), 'explanatory' understanding (Newton, 2002), and 'theoretical' understanding (Greeno & Riley, 1987). Understanding may also be identified when an individual does not use a schema but simply memorizes facts and procedures to reach a certain goal. Such understanding is referred to as 'instrumental understanding' or 'rules without reasons' (Skemp, 1976), 'descriptive/procedural understanding' (Newton, 2002), and 'intrinsic understanding' (Greeno & Riley, 1987).

2.2.4 Summary

As I read the literature pertaining to academic conceptions of understanding it became clear that the authors' conceptions about understanding might be categorized as an intertwined ability, process, or product. Ability is defined as the possession of the means or skill to do something. Therefore, 'understanding as ability' means understanding as the possession of the means or skill to do something. A process is defined as a series of actions or steps taken in order to achieve a particular end. Therefore, 'understanding as process' means understanding as a series of actions or steps. A product is defined as the result of an action or process. Therefore, 'understanding as product' means understanding that is the result of an action or process. For example, Wiggins and McTighe (2005) proposed the following facets of understanding: (1) When one can explain, (2) When one can interpret, and (3) When one can apply. These three facets may be categorized as 'understanding as ability' since explain, interpret, and apply represent abilities.

The key findings of academic conceptions of understanding are found in Table 2. Table 2 includes the authors and the year of the publication, the authors' perspective of understanding, and the authors' conceptions of understanding. The conceptions of understanding include the authors' specific conceptions about understanding and includes a categorization of these conceptions as either an ability, process, or product, which are highlighted in italicized bold text. Table 2 has been organized in such a way to differentiate between three regions. These three regions are highlighted in bold text and correspond to the 'authors' philosophical perspective of understanding' for: (1) 'philosophical' literature, (2) 'educational psychology' literature, and (3) 'mathematics and science education' literature.

Table 2

Summary of Key Findings of Academic Conceptions of Understanding

Authors, Year	Authors' Perspective of Understanding	Conceptions of Understanding
Whitehead (1938)	**Philosophical** *Alfred North Whitehead (1861–1947)* British mathematician and philosopher whose work is associated with mathematical logic and the philosophy of science.	(1) Internal understanding: Understanding the thing to be understood as a composition of factors and how these factors interweave to form a whole. ***Understanding as process.*** (The process of a composition of factors.) ***Understanding as ability.*** **(**The ability to recognize how the factors interweave to form a whole.) (2) External Understanding: Understanding the thing to be understood "as a unity, whether or not it is capable of analysis" (p. 46). ***Understanding as ability.*** (The ability to recognize something is capable of analysis.)
Heidegger (1962)	**Philosophical** *Martin Heidegger (1889–1976)* German philosopher whose work is associated with phenomenology and existentialism.	(1) Understanding is subjective and results in an individualized state-of-mind. ***Understanding as product.*** (The product of understanding is an individualized state of mind.) (2) Understanding is intertwined with both interpretation and application and cannot be separated from them. ***Understanding as process*** (The process of understanding is intertwined with both interpretation and application.)
Gadamer (2006)	**Philosophical** *Hans-Georg Gadamer (1900-2002)* German philosopher whose work is associated with the development of 20th century hermeneutics.	(1) Understanding is seen as a recursive process where understanding is achieved through interpretation and by continually revisiting the interpretation in order to gain a deeper understanding. ***Understanding as process.*** (A recursive process.) (2) Gadamer views understanding as a negotiation between two parties in a hermeneutical dialogue where the process of understanding is a matter of coming to an agreement about some given topic. The coming to an agreement about a given topic means to establish a common framework or 'horizon' and Gadamer thus takes understanding to be a process of the 'fusion of horizons' (*Horizontverschmelzung*). ***Understanding as process.*** (The process of coming to an agreement.)
Malpas (2018)	**Philosophical** *Jeff Malpas* Philosopher and Professor at the University of Tasmania.	Malpas describes Gadamar's 'fusion of horizons' as the following: "Inasmuch as understanding is taken to involve a 'fusion of horizons', then so it always involves the formation of a new context of meaning that enables integration of what is otherwise unfamiliar, strange or anomalous." (p. 9). ***Understanding as process.*** (The process of the fusion of horizons.)

Authors, Year	Authors' Perspective of Understanding	Conceptions of Understanding
Bloom & Krathwohl (1956)	**Educational Psychology** *Benjamin S. Bloom (1913-1999)* American educational psychologist. *David R. Krathwohl (1921-2016)* American educational psychologist.	(1) Understanding is not well defined. (2) Understanding is a common objective of educators.
Bloom, Madaus & Hastings (1981)	**Educational Psychology** *Benjamin S. Bloom (1913-1999)* American educational psychologist.	The ability of the learner to comprehend the nature of the task to be learned and the procedures to be followed in learning it. ***Understanding as ability.*** (The ability to comprehend the nature of the task to be learned and the procedures to be followed in learning it.)
Anderson & Krathwohl (2001)	**Educational Psychology** *Lorin W. Anderson* Carolina Distinguished Professor Emeritus, University of South Carolina. Taught graduate courses in research design, curriculum development, assessment, and evaluation. *David R. Krathwohl (1921-2016)* American educational psychologist.	(1) Students connect prior knowledge with what is currently being learned. ***Understanding as process.*** (The process of connecting prior knowledge with what is being learned.) (2) Students integrate this new knowledge into their existing cognitive framework. ***Understanding as process.*** (The process of integrating new knowledge into an existing cognitive framework.)
Wiggins & McTighe (2005)	**Educational Psychology** *Grant Wiggins (1950-2015)* Ed. D. Harvard University. Grant Wiggins was the President of Authentic Education in Hopewell, New Jersey. *Jay McTighe* Educational writer and consultant.	6 facets of understanding. (1) When one can explain. (2) When one can interpret. (3) When one can apply. ***Understanding as ability.*** (The ability to explain, interpret, and apply.) (4) When one can have perspective. ***Understanding as process.*** (The process of seeing and hearing different points of view.) (5) When one can empathize. ***Understanding as process.*** (The process of finding value in what others may find different.) (6) When one can have self-knowledge. ***Understanding as product.*** (The product of understanding is self-knowledge.)
Gardner (1991)	**Educational Psychology** *Howard Gardner* American psychologist.	(1) The "process of understanding involve sets of performances carrying out analyses, making fine judgment, undertaking syntheses, and creating products that embody principles or concepts central to a discipline" (p.186). ***Understanding as process.*** (The processes of carrying out analyses, making fine judgment, undertaking syntheses, and creating products.) (2) Genuine understanding may be more likely to emerge if individuals possess several ways to represent the knowledge of a concept or skill and can readily move between these different forms of knowing. ***Understanding as product.*** (Genuine understanding is a product that may emerge if individuals possess several ways to represent the knowledge of a concept or skill and can readily move between these different forms of knowing.) (3) The ability to apply and interpret knowledge in several different contexts or domains. ***Understanding as ability.*** (The ability to apply and interpret knowledge in different contexts or domains.)
Nickerson (1985)	**Educational Psychology** *Raymond S. Nickerson* American psychologist, Tufts University. Research interests: Cognition, Reasoning, Decision Making, Problem Solving	Understanding means: (1) The ability to communicate with people who are experts in a particular domain. (2) The ability to consistently apply a principle in many different contexts. (3) The ability to consistently perform a procedure or process to obtain a desired result. (4) The ability to form analogies that experts in a particular domain would consider appropriate. ***Understanding as ability.*** (The ability to communicate, apply, perform a procedure, and form analogies.) (5) The confidence that a principle or relationship is understood or seen. ***Understanding as product.*** (The product of understanding is confidence.)

Authors, Year	Authors' Perspective of Understanding	Conceptions of Understanding
Ormell (1979)	**Educational Psychology** *Christopher Peter Ormell* Education Senior Fellow, University of East Anglia, Norwich, England.	To achieve a 'clear' understanding about a topic, the individual must be aware of the "meaning of the message, policy or principle" (p. 34) for the given topic. To achieve a 'clear' understanding, Ormell (1979) suggests that understanding should involve a connection between the 'word' and the world. ***Understanding as process*** (The product of understanding is connection between the 'word' and the world.)
Newton (2002)	**Science Education** *Douglas P. Newton* Durham University School of Education.	(1) Descriptive understanding. A student demonstrates 'descriptive understanding' when the student can describe understanding using "a mental picture and his or her own words to give a meaningful account of it" (p. 12). ***Understanding as ability.*** (The ability to describe understanding using a mental picture and words.) (2) Explanatory understanding. Explanatory understanding is exhibited by students if they have an "understanding of the situation and some relevant reason or causes for it" (p. 12). ***Understanding as ability.*** (The ability to understand a situation and some relevant reason or causes for it.) (3) Procedural understanding. Procedural understanding "is about grasping the way of doing something" (p. 13) ***Understanding as ability.*** (The ability to grasp the way of doing something.)
Skemp (1976)	**Mathematics Education** *Richard R. Skemp (1919-1995)* Pioneer in Mathematics Education who first integrated the disciplines of mathematics, education, and psychology.	(1) Relational understanding. The ability to know how and why rules and procedures work. "Knowing both what to do and why" (p. 2). ***Understanding as ability.*** (The ability to know what to do and why in the context of mathematics.) (2) Instrumental understanding. "Rules without reasons" (p. 2). The ability to know rules and procedures but not knowing how they work. ***Understanding as process.*** (The ability to know rules and procedures but not knowing how they work.)
Greeno & Riley (1987)	**Mathematics Education** *James G. Greeno* American educational psychologist. *Mary S. Riley* Disciplines: Cognitive Science, Cognitive Psychology, Experimental Psychology.	(1) Theoretical understanding. The ability of an individual to perform a cognitive procedure where the individual has knowledge about some general principle or structure that is related to the procedure. ***Understanding as ability.*** (The ability to perform a cognitive procedure using knowledge (knowledge development) of some general principle or structure related to the procedure. (2) Intrinsic understanding. The ability to perform a cognitive procedure in a rote and mechanical way. ***Understanding as ability.*** (The ability to perform a cognitive procedure in a rote and mechanical way.)

Note. Conceptions of understanding are often intertwined as ability, process, and product.
Key Definitions:

Process: A series of actions or steps taken in order to achieve a particular end.
Product: The result of an action or process.
Ability: Possession of the means or skill to do something.

2.3 Empirical Studies Investigating Conceptions of Understanding

The following two sections examine literature about what it means to understand physics from a non-phenomeongraphic and phenomenographic research methodology. This literature is based upon qualitative research that investigates and analyzes data.

2.3.1 Non-Phenomenographic Studies

This section examines some of the non-phenomenographic research about students' understanding of physics concepts to provide the reader with a background of the results achieved in studies utilizing a different methodology than phenomenography.

The following studies report on students' understanding for a number of different topics that appear in the literature. These studies include the following: university students' understanding of current flow (Wittmann et al., 2002), university physics students' understanding of impulse-momentum, and work-energy theorems (Lawson & McDermott, 1987), university physics students' lack of a qualitative understanding of acceleration (Trowbridge & McDermott, 1981), high school physics students' understanding of mechanics (Gunstone, 1987), and high school chemistry students' meanings for understanding (Burns et al., 1991).

Wittmann et al. (2002) investigated how university students in advanced physics classes understand the physics of current flow by using interviews, conceptual surveys, and examination questions given to students. Students were presented with a number of tasks where they had to make predictions and where they had to explain their reasoning in real contexts. In this way, the focus of the study was on inferring student understanding from how they described physical systems. For example, students "gave incorrect predictions and incomplete predictions of the physics" (Wittmann et al., 2002, p. 221) when thinking about the free electrons moving in a material. Wittman et al. contend that the findings from this study can be used as a guide to create a physics curriculum that can be effective in helping students to apply different models of conduction in electricity. Wittmann's research suggests that curriculum development that is grounded in research creates more effective learning for students. In addition, Wittmann et al., suggest that by providing students an opportunity to develop tools for understanding the physics, that this can have a measurable effect on student learning.

Lawson and McDermott (1987) reported that university physics students failed to understand the significance of the impulse-momentum and work-energy theorems. Specifically, Lawson and McDermott write that most university physics students were unable to connect the algebraic physics formulas they learned in class with real world applications. This study is significant for my research because applying physics knowledge in real world scenarios may be a conception revealed in my data by the teachers and the professors.

Trowbridge and McDermott (1981) investigated university physics students' understanding of one-dimensional acceleration and reported that students "frequently lack even a qualitative understanding of the concept of acceleration as the ratio $\Delta\mathbf{v}/\Delta t$" (p. 251). The significance of this research is that for students to overcome the confusion between related but different concepts, some form of intervention by the teacher is necessary. Trowbridge and McDermott contend that the information about student conceptual understanding that emerged from their study was useful in mitigating first year university student deficiencies when preparing for first year physics courses.

The Gunstone (1987) study examined 5500 high school physics students' responses to four research probes about understanding mechanics that were included on their final physics examination. As a consequence of this research, a number of propositions were made that related to student understanding for a variety of physics topics. These propositions have been summarized by Gunstone (1987) as follows:

(i) Students have ways of interpreting physical phenomena that develop before they study physics in school.

(ii) Students interpret physics differently from the way they are expected to learn physics in class.
(iii) Students' physics understanding is consistent across diverse samples of students.
(iv) Students' physics understanding is resistant to change by traditional instructional methods. (p. 691)

The significance of this research is that "students' physics understanding is consistent across diverse samples of students" (Gunstone, 1987, p.691), and this provides credibility to my study as the participants were sourced from one province in Canada. Therefore, it is likely that even if a more diverse sample of students was obtained for my study from other provinces in Canada, the students' conceptions of understanding physics would be similar.

Burns, et al. (1991) report findings from an empirical study where high school chemistry students' meanings for understanding showed a dual form, 'knowing why' and 'knowing what and how'. According to Burns et al., understanding "is generally accepted to be an active process in which meaning is constructed" (p. 277) and where new information is interpreted in the light of currently activated knowledge. The study conducted by Burns et al. (1991) utilized a grounded theory approach to investigate "students' understanding of "understanding" in the context of learning in chemistry" (p. 276). Thirty-nine grade twelve chemistry students from New Zealand participated in the study and the students' meanings for understanding showed two distinct orientations, a 'coherence orientation' and a 'knowledge orientation'. Students with a 'coherence orientation' of understanding wanted to know "why things happened as they did" (Burns et al., 1991, p. 279) and were "concerned about the relationship between pieces of new information and between these and recalled information" (p. 279). Students with a 'knowledge orientation' of understanding were concerned with the memorization of facts, the recognition of terms, and wanted to know the 'what and how' rules of chemistry (Burns et al., 1991).

Burns et al.'s (1991) 'coherence orientation' is similar to Skemp's (1976) 'relational understanding' and Greeno and Riley's (1987) 'theoretical understanding' where the focus is on knowing why. Burns et al.'s (1991) 'knowledge orientation' is similar to Skemp's (1976) 'instrumental understanding' and Greeno and Riley's (1987) 'intrinsic understanding' where the focus is on memorization and rote learning.

In summary, these non-phenomenographic studies reflect some of the research that has been undertaken about students' understanding of different topics. Many of the studies investigated university level students but fewer studies examined high school students. These studies highlight the deficit in the literature about what physics students consider it means to understand physics in general.

2.3.2 Phenomenographic Studies

This section examines several phenomenographic studies that have explored the nature of understanding as experienced by university students revising for degree examinations (Entwistle & Entwistle, 1991, 1992), several phenomenographic studies that investigated university students' conceptions of understanding specific physics concepts, a study that investigated university physics students' conceptions of understanding mechanics (Waterhouse & Prosser, 2000), and a study that investigated university students' "conceptions of understanding" (Irving & Sayre, 2012, p. 198).

The studies by Entwistle and Entwistle (1991, 1992) examined twenty-four psychology, medicine, zoology, biochemistry, and accountancy students' experiences of revising for degree examinations in order to clarify their concept of how understanding was experienced. The results of the phenomenographic analysis of students' descriptions of their "aspects of the experience to understand" (Entwistle & Entwistle, 1992, p. 7) represent a series of related categories of description and form a hierarchical outcome space (see Table 3). This hierarchy "indicates increasing complexity and inclusiveness, with the progression from one level to the next placing additional demands on students" (Entwistle & Entwistle, 1992, p. 21).

Table 3

Aspects of the Experience of Understanding, (Entwistle & Entwistle, 1992, p. 7)

The nature of understanding	Feelings of satisfaction Meaning and significance Coherence, connectedness, and 'provisional wholeness' Relative irreversibility Confidence about explaining Flexibility in adapting and applying
Developing understanding	Active engagement with the task Relating to previous knowledge and experience Using or developing a structure
Individual forms of understanding	Breadth of understanding Depth or level of understanding Source and nature of structures - from lectures or books - through own structure in revision notes - from theories - from an individual conception of the discipline

Entwistle and Entwistle (1992) identified three aspects of the experience of understanding. These aspects include: the nature of understanding, developing understanding, and individual forms of understanding. Entwistle and Entwistle (1992) found that there is less university student reliance on conceptions of understanding that promote reproduction and more reliance on conceptions of understanding that promote transformation. In addition, Entwistle and Entwistle found that there was a feeling tone associated or an emotional response to the experience of understanding, something which is categorized under 'the nature of understanding'. Entwistle and Entwistle write that "in terms of the student interviews, understanding itself can be seen, not as a cognitive process, but as an experience" (p. 18).

Several phenomenographic studies investigated university students' conceptions of understanding specific physics concepts. These studies examined students' conceptions of understanding: kinematics (Dall'Alba et al., 1989), displacement, velocity, and frames of reference (Bowden et al., 1992), relative speed (Walsh et al., 1993), speed, distance, and time (Ramsden et al., 1993), and acceleration (Trowbridge & McDermott, 1981; Dall'Alba et al., 1993). Other studies examined student conceptions of understanding force (Marton, 1986), electricity (van den Berg, 1994; Prosser, 1994), gravity (Sharma et al., 2004), terminal velocity (Bowden, 2000b), and student problem solving (Walsh et al., 2007). All of these studies listed above asked students how to solve or explain a certain physics problem or concept, which the authors then analyzed for conceptions of understanding. These studies differ from my study as I asked my participants, what it means to understand physics rather than how to solve or explain a certain physics problem or concept.

The phenomenographic research conducted by Waterhouse and Prosser (2000) and Irving and Sayre (2012) are both similar to my study. Waterhouse and Prosser (2000) examined twenty-four university physics students about their conceptions of understanding mechanics whereas Irving and Sayre (2012) examined eighteen university students about their "conceptions of understanding" (p. 198) but do not clarify what kind of understanding they investigated. My study builds upon these studies by investigating high school students', teachers', and professors' conceptions of what it means to understand physics rather than focusing on conceptions of mechanics (Waterhouse & Prosser) or conceptions of understanding (Irving & Sayre, 2012).

Waterhouse and Prosser (2000) developed categories of description for the variation in "students' conceptions of understanding mechanics" (p. 4). A hierarchical relationship between five student categories of description for student conceptions of understanding mechanics were developed and ranged from a low level, category A, to a high level, category E. The lowest level, category A, 'no physical description' is explained by Waterhouse and Prosser as "understanding is seen as given, no effort required" (p. 5), while the highest level, category E, 'understand when you consolidate your knowledge' is explained as "you know the phenomenon deeply" (p. 5) (see Table 4).

Table 4

Categories of Description for Conceptions of Understanding Mechanics, (Waterhouse & Prosser, 2000, p. 5)

Category	Description
A	No physical description
B	Understand when you can solve problems
C	Understand when you can relate to real life situations
D	Understand when you can explain it to others or yourself
E	Understand when you consolidate your knowledge

Irving and Sayre (2012) examined university students' "conceptions of understanding" (p. 198) and found a hierarchical relationship between the student conceptions of understanding. These 'conceptions of understanding' ranged from a low level, category A to a high level, category E. The lowest level, category A 'understand when can use and apply' is explained by Irving and Sayre as "when students know they can apply understanding to solve problems" (p. 200) while the highest level, category E 'understand when can apply mathematical description, consolidate knowledge' is explained by Irving and Sayre as knowing "a concept deeply and can apply a mathematical model to it" (p. 200) (see Table 5).

Table 5

University Physics Students' Conceptions of Understanding, (Irving & Sayre, 2012, p. 200)

Category	Description
A	Understand when can use and apply
B	Understand when can use, visualize and apply in different contexts
C	Understand when can teach someone else
D	Understand when can explain in more than one way, use analogies
E	Understand when can apply mathematical description, consolidate knowledge

Waterhouse and Prosser (2000) and Irving and Sayre (2012) each proposed a hierarchical outcome space, but they ordered similar categories of description into different hierarchical levels. For example, for an 'apply' category of description, Waterhouse and Prosser order category C 'understand when you can relate to real life situations', explained as "apply what you know to real life objects" (p. 5), into their third category. In comparison, Irving and Sayre ranked 'apply' into three different levels of their hierarchy. These three different 'apply' categories include: category A 'understand when can use and apply', category B 'understand when can use visualize and apply in different contexts' and category E 'understand when can apply mathematical description consolidate knowledge'.

The lowest hierarchical level and the highest hierarchical levels are both different for Waterhouse and Prosser (2000) and Irving and Sayre (2012). For the lowest level category A, Waterhouse and Prosser rank the category 'no physical description', which they explain as "understanding is seen as no effort required" (p. 5). In comparison, Irving and Sayre rank the category 'understand when can use and apply' as their lowest level category in the hierarchy. For the highest-level category E, Waterhouse and Prosser rank the category 'understand when you consolidate your knowledge', which they explain as "knowing a phenomenon deeply" (p. 5). In comparison, Irving and Sayre rank the category 'understand when can apply mathematical description, consolidate knowledge', which they explain as "understanding is when understand concept deeply and can apply mathematical model to it" (p. 200) as their highest level category in the hierarchy.

Both Waterhouse and Prosser (2000) and Irving and Sayre (2012) rank their 'explain' categories at the same category level D in their hierarchies. Irving and Sayre rank their 'teach' category C 'understand when can teach someone else' lower in their hierarchy than their 'explain' category D while Waterhouse and Prosser do not have a 'teach' category.

What the previous paragraphs highlight is that Waterhouse and Prosser (2000) and Irving and Sayer (2012) ordered similar conceptions differently into their hierarchies and that they did not provide a clear justification as to why the conceptions were ordered as they were. This is significant as authors have suggested that the "problem with a graded series [hierarchy] is that different readers have different opinions of what the proper order is" (American Association for the Advancement of Science, 1993, p. 312). Therefore, Waterhouse and Prosser and Irving and Sayer should justify their hierarchical ordering so that readers may comprehend why their conceptions were ordered where they were in their hierarchies.

In summary, Waterhouse and Prosser (2000) examined university students' conceptions of understanding mechanics and Irving and Sayre (2012) examined university students' conceptions of understanding. There is limited scholarship about high school students' conceptions of understanding physics concepts. It is important to keep in mind that my study, what it means to understand physics, is somewhat different from the understanding of mechanics that Waterhouse and Prosser (2000) investigated and the conceptions of understanding that Irving and Sayre (2012) investigated. Currently there is no published phenomenographic literature for what it means to understand physics and my study will begin to fill this gap in the literature.

2.3.3 Summary

As with the literature about ‘academic conceptions of understanding’ (see Section 2.2), it became clear that the literature about ‘empirical studies investigating conceptions about understanding’ (see Section 2.3) might also be categorized as an intertwined ability, process, and product. Understanding as ability means understanding as the skill to do something, understanding as process means understanding as a series of steps, and understanding as product means understanding as the result of a process. For example, Waterhouse & Prosser (2000) proposed categories of description of understanding mechanics that include the following: the ability to solve problems, the ability to relate to real life, the ability to explain, and the ability to consolidate knowledge. Therefore, these Waterhouse & Prosser (2000) categories of description may be categorized as understanding as ability.

The key findings of empirical studies investigating conceptions of understanding are found in Table 6. Table 6 includes the authors and year of the publication, the authors' perspective of understanding, the research objective, the research methodology, the participants, and the study findings. The research objectives include what the study investigated and is highlighted in bold text. For example, Burns et al., (1991) investigated students' understanding of chemistry. The ‘study findings’ include the authors' conceptions about understanding and includes a categorization of these conceptions as either an ability, process, or product and are highlighted in italicized bold text. Table 6 has been organized in such a way to differentiate between two regions. These two regions correspond to 'research methodology' as: (1) studies that did not use phenomenography, and (2) studies that used phenomenography.

Table 6

Summary of Key Findings of Empirical Studies Investigating Conceptions of Understanding for Some Given Concept

Authors, Year	Authors' Perspective of Understanding	Research Objective	Research Methodology	Participants	Study Findings
Wittmann, Steinberg, & Redish (2002)	**Physics Education** *Michael C. Wittmann* Department of Physics, University of Maine. *Richard N. Steinberg* Department of Physics, City College of New York. *Edward F. Redish* Department of Physics, University of Maryland.	The study investigated how students in advanced physics classes understand the physics of current flow. **Understanding of current flow.**	Unspecified qualitative methodology. (Interviews, conceptual surveys, and examination questions)	13 university students from 2 different physics classes.	(1) Giving students an opportunity to develop tools for understanding the physics has had a measurable effect on student learning. (2) Curriculum development that is grounded in research creates more effective learning for students.
Lawson &McDermott (1987)	**Physics Education** *Ronald A. Lawson* *Lillian C. McDermott* Department of Physics University of Washington Seattle.	The study investigated the results of an investigation of student understanding of the concepts of impulse and work and the relationship of these concepts to changes in momentum and kinetic energy. **Understanding of impulse and work.**	Unspecified qualitative methodology. (Interviews)	28 university students from introductory physics courses at the University of Washington. 12 from a calculus physics course and 16 from a non-calculus physics course.	The results of the investigation revealed that most of the students were unable to relate the algebraic formulas learned in class to the simple motion that they observed.
Trowbridge & McDermott (1981)	**Physics Education** *David E. Trowbridge* *Lillian C. McDermott* Department of Physics University of Washington Seattle.	The study investigated the understanding of the concept of acceleration among students enrolled in introductory physics courses at the University of Washington. **Understanding of acceleration.**	Unspecified qualitative methodology. (Pre and post course interview)	35 university students from introductory physics courses at the University of Washington. 28 from a calculus physics course and 7 from a non-calculus physics course.	Students "frequently lack even a qualitative understanding of the concept of acceleration as the ratio $\Delta v/\Delta t$" (p. 251).

Authors, Year	Authors' Perspective of Understanding	Research Objective	Research Methodology	Participants	Study Findings
Gunstone (1987)	**Physics Education** *Richard Gunstone*: Professor Emeritus. Previously Professor of Science and Technology Education, and Director (and founder) of the Monash-King's College (London) International Centre for the Study of Science and Mathematics Curriculum.	The study investigated grade 12 students' responses to 4 research probes about understanding mechanics that were included on their final physics exam. **Understanding of mechanics.**	Unspecified qualitative methodology. (Open ended survey)	5500 grade 12 physics students.	A number of propositions were made that related to student understanding for a variety of physics topics. (1) Students have ways of interpreting physical phenomena that develop before they study physics in school. ***Understanding as process.*** (The process having ways of interpreting physical phenomena) (2) Students interpret physics differently from the way they are expected to learn physics in class. (3) Students' physics understanding is consistent across diverse samples of students. (4) Students' physics understanding is resistant to change by traditional instructional methods.
Burns, Clift, & Duncan (1991)	**Chemistry Education** *Janet Marie Burns* 1989: Ed.S. (Specialist in Education) Central Michigan University.	The study investigated grade 12 chemistry students' meanings for understanding. **Understanding of chemistry.**	Grounded Theory (Interviews)	39 grade 12 chemistry students from New Zealand.	Students' meanings for understanding showed two distinct orientations. (1) Coherence. (2) Knowledge. **Coherence orientation of understanding:** Students wanted to know why things happened as they did and were concerned about the relationship between pieces of new information and between these and recalled information. ***Understanding as product.*** (The product of understanding is the relationship between pieces of new information and recalled information) **Knowledge orientation of understanding:** Students were concerned with the memorization of facts, recognition of terms, and wanted to know the 'what' and 'how' rules of chemistry. ***Understanding as process.*** (The process of memorization of facts and the recognition of terms.)
Entwistle & Entwistle, (1991, 1992)	**Education** *Noel Entwistle* *Abigail Entwistle* The University of Edinburgh Moray House School of Education	The study investigated the nature of understanding as experienced by students and how their understanding was developed when they revised for degree examinations.	Phenomenography (Interviews)	24 University of Edinburgh students taking courses in psychology, medicine, zoology, biochemistry, and accountancy.	Identified three aspects of the experience of understanding. (1) The nature of understanding. (2) Developing understanding. ***Understanding as process.*** (The process of developing understanding.)

Authors, Year	Authors' Perspective of Understanding	Research Objective	Research Methodology	Participants	Study Findings
		Understanding developed when revising for exams.			(3) Individual forms of understanding. "understanding itself can be seen, not as a cognitive process, but as an experience" (1991, p. 18). ***Understanding as product.*** (The product of understanding is an experience.)
Waterhouse & Prosser, (2000)	**Educational Psychology** *Michael Prosser* Associate Professor in Higher Education Curriculum and Assessment Melbourne CSHE *Fiona Waterhouse* La Trobe University.	The study investigated university students' conceptions of understanding mechanics. **Conceptions of understanding mechanics.**	Phenomenography (Interviews)	24 university physics students enrolled in the same mechanics course.	Categories of Description for Conceptions of Understanding Mechanics: (1) No physical description. (2) Understand when you can solve problems. (3) Understand when you can relate to real life situations. (4) Understand when you can explain it to others or yourself. (5) Understand when you consolidate your knowledge. ***Understanding as ability.*** (The ability to solve problems, relate to real life, explain, and consolidate knowledge.)
Irving & Sayre, (2012)	**Physics Education** *Paul Irving* 2011: Ph.D. in Physics Education, Dublin Institute of Technology. 2005: B.S. in Physics, Dublin Institute of Technology. *Elanor C. Sayre* 2007: Ph.D. in Physics, University of Maine.	The study investigated upper-level physics students' conceptions of understanding. **Conceptions of understanding physics.**	Phenomenography (Interviews)	18 university physics students from mechanics and electromagnetism courses.	University Physics Students' Conceptions of Understanding: (1) Understand when can use and apply. (2) Understand when can use, visualize and apply in different contexts. (3) Understand when can teach someone else. (4) Understand when can explain in more than one way, use analogies. (5) Understand when can apply mathematical description, consolidate knowledge. ***Understanding as ability.*** (The ability to apply, visualize, explain, and consolidate knowledge.)

Note. Conceptions of understanding are often intertwined as ability, process, and product.
Key Definitions:
Process: A series of actions or steps taken in order to achieve a particular end.
Product: The result of an action or process.
Ability: Possession of the means or skill to do something.

2.4 The Structure of Phenomenographic Conceptions

This section examines how the framework developed by Marton (1988) for analyzing the structure of conceptions of learning has been applied to a number of different studies in the educational literature. The conception is the main unit of description about an individual's experience for a given phenomenon (Marton, 1986; Svensson, 1997) and can be described as "different ways of understanding" (Marton & Pong, 2005, p. 335) or the smallest unit of analysis in phenomenography (Marton, 1981; Marton & Säljö, 1976; Säljö, 1979).

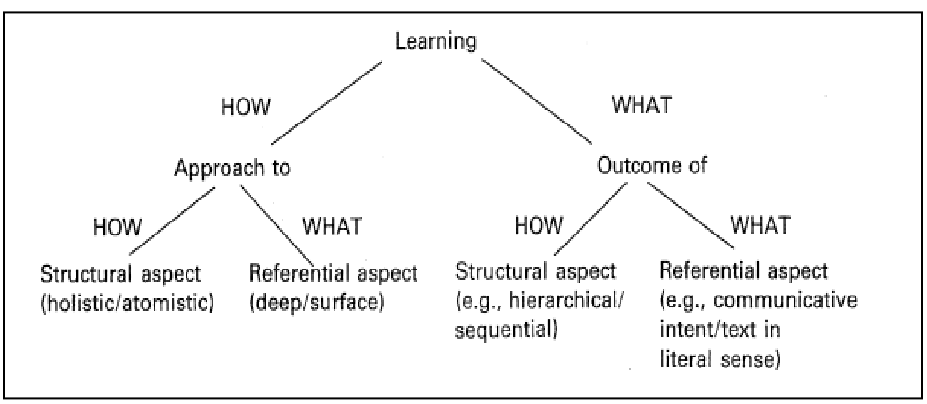
A phenomenographic conception of what it means to understand physics differs from an academic conception of understanding in general. A phenomenographic conception is based upon people's experiences for a given phenomenon whereas an academic conception may be based on theories and ideas about understanding that is apart from their experiences.

My study investigated the conceptions students, teachers, and professors have about what it means to understand physics. The literature presented in this section informs my study about how other researchers have applied the Marton (1988) framework to the analysis of conceptions from a number of different educational fields including learning.

A number of phenomenographic researchers employ a framework to "think apart important distinctions within conceptions" Harris (2011, p. 109). The framework was developed by Marton (1988) to analyze conceptions of learning and contains two levels (see Figure 1).

Figure 1

Diagram of the Structure of Categories Describing Learning, (Marton, 1988, p.66)



The first level contains 'what' and 'how' aspects while the second level contains 'referential' and 'structural' aspects. The aspects of the first level, 'what' and 'how', are described by Trigwell and Prosser (1996) as “what is being focused on and how it is being focused on” (p. 277). Marton (1988) examined learning and in terms of learning the ‘what’ aspect refers to what is being learned and the ‘how’ aspect refers to how the learning takes place.

The second level includes the ‘referential’ and the ‘structural’ aspects of learning and Marton and Booth (1997) describe these aspects in the following way:

> The structural aspect of a way of experiencing something is thus twofold: discernment of the whole from the context on the one hand and discernment of the parts and their relationship within the whole on the other. Moreover, intimately intertwined with the structural aspect of the experience is the referential aspect, the meaning. (p. 87)

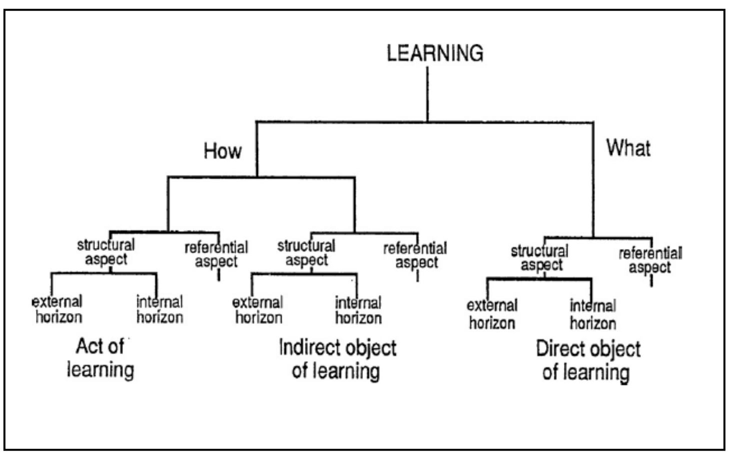
Marton (1988) further explains the difference between the referential and structural aspects of learning by describing a study by Wenestam (1978) where subjects read a text about a social welfare system that included a story about a family with many social problems. The subjects’ described their understanding of the text they read in two ways. The first way was the ‘meaning’ of the text “in the sense of the subjects’ understanding of what the text refers to” (Marton, 1988, p. 59) and the ‘structure’ of the text “in the sense of the subjects’ understanding of how the text is organized” (p. 59). Marton (1988) writes that the ‘meaning’ of understanding text may be referred to as the ‘referential’ aspect and the ‘structure’ of understanding text may be referred to as the ‘structural’ aspect.

Marton and Pong (2005) explain that both the structural and referential aspects are intertwined and describe the referential aspect as denoting the global meaning of the object conceptualized while the structural aspect is described as the structure or the “the specific combination of features that have been discerned and focused on” (p. 335). Therefore, the ‘referential’ aspect refers to the overall meaning of the experience and the ‘structural’ aspect refers to how the ‘referential’ aspect is understood.

The framework was revised by Marton and Booth (1997) and in this revised framework they describe how the various dimensions for a phenomenon are logically related. Marton and Booth describe this way of experiencing a phenomenon as the dimensions of variation or "the aspects of the phenomenon and the relationships between them that are discerned and simultaneously present in the individual's focal awareness" (p. 101). The revised framework includes: (1) a third level with internal and external horizons, (2) an act of learning, (3) a direct object of learning, and (4) an indirect object learning (Marton & Booth, 1997). Marton and Booth "no longer labelled referential and structural aspects as what and how" (Harris, 2011, p. 112) (see Figure 2).

Figure 2

Diagram of Conceptions of Learning, (Marton & Booth, 1997, p. 91)



Using learning as an example, the act represents the strategies applied to learning, the direct object refers to what to learn, and the indirect object refers to the motivation to learn (Zhao, 2015, p. 78). When applied to understanding, the act could potentially represent the strategies applied to understand, the direct object could refer to what to understand, and the indirect object could refer to the motivations to understand.

According to Marton and Booth (1997), the external horizon represents “that which surrounds the phenomenon experienced, including its contours” (p. 87) while the internal horizon represents “the parts and their relationship, together with the contours of the phenomenon” (p. 87). For example, Edwards (2005) analyzed student experiences of information searching and explained:

> Within the internal horizon, the thematic field of the awareness structure, the worldview is clear and in focus. This internal horizon shows us the primary theme or focus of each experience and the elements that may be simultaneously present in that experience. Within the external horizon limits, the lens is not as clear, and the items within it are fuzzy. This unfocused lens shows us the margins of the awareness for the student. (p. 136-137)

Marton (1988) describes the internal and external horizons in the following way:

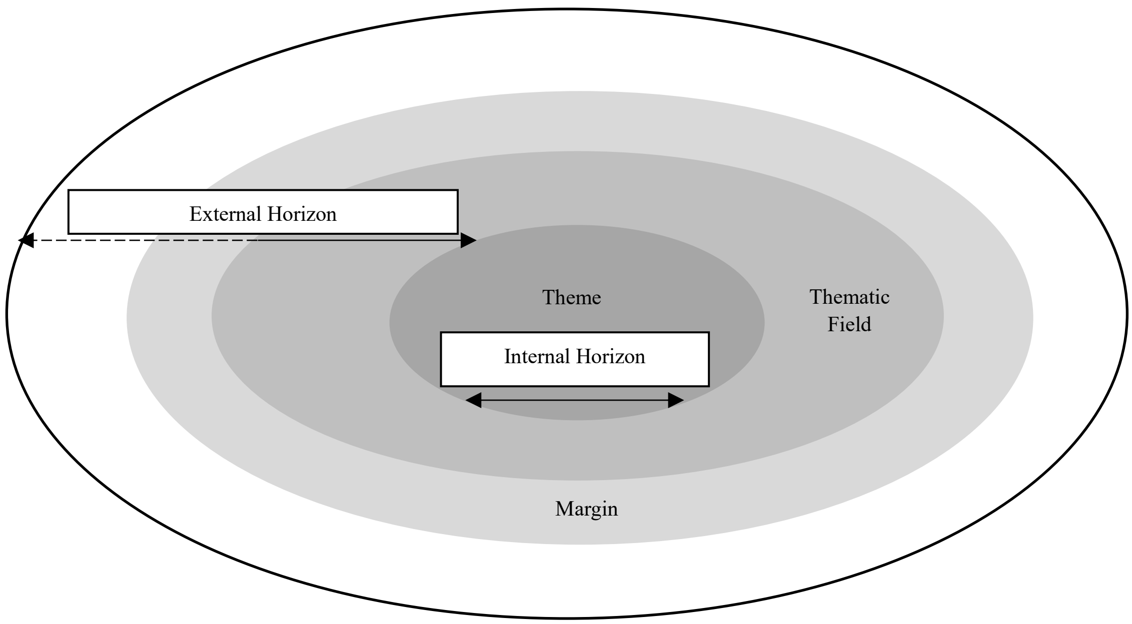
> In our interpretation, *external horizon* refers to the relations a phenomenon is seen to have to other aspects of a greater whole of which the phenomenon is a part. *Internal horizon* refers to the parts that a phenomenon itself is seen to have and to the relations seen between those parts. (p. 68)

Marton (1988) explains that approaches to learning text may be represented as an internal or an external sense. For the example of learning text, the subject’s approach to learning text in the internal sense refers to how the content of the text is dealt with while the subject’s approach to learning text in the external sense refers to “how the broader situation is perceived (e.g., how will I be tested, why am I doing this etc.)” (p. 69).

Another way of representing the ‘structure of awareness’ (Marton & Booth, 1997) for a phenomenon has been described by Gurwitsch (1964) as three overlapping areas, the margin, the thematic field, and the theme. Cope (2004) has built upon the work of Gurwitsch (1964) and has graphically represented the three overlapping areas to include the internal and external horizons (see Figure 3). Cope (2004) explains that when contemplating a particular phenomenon, the non-related aspects of the phenomenon constitutes the margin of the experience or the external horizon. The thematic field consists of aspects of the phenomenon that are triggered by the context and are simultaneously present in the awareness while the theme or internal horizon constitutes the focus of the awareness (Cope, 2004).

Figure 3

A Structure of Awareness, (Cope, 2004, p. 11)



The framework developed by Marton (1988) provides phenomenographers with a theoretical basis for phenomenography that originated from research about student learning. Harris (2011) conducted a systematic review of 56 studies that employed the Marton (1988) framework and these studies included student learning and other research areas. Harris indicates that these frameworks provide researchers with useful tools. The what/how framework “allows researchers to examine the processes or approaches participants associate with a particular understanding” (Harris, 2011, p. 117) and the referential/structural framework “gives researchers a way to examine the parts that make up conceptions and their contexts” (Harris, 2011, p. 117).

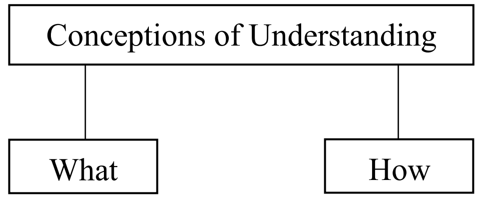
However, amongst the 56 phenomenographic studies, Harris (2011) discovered "divergent interpretations of theory, variations in the naming of the parts of a conception, and inconsistent or insufficient definitions and applications of the frameworks" (p. 115). Harris' review revealed most studies used the 'what' and 'how' aspects, heterogeneous definitions, and heterogeneous applications of the frameworks. The 'referential' and 'structural' aspects ceased to be used by researchers although these aspects were "originally termed as a second level of what and how" (Harris, 2011, p. 115). Harris also indicated that the internal and external horizons have diverse usages within phenomenographic work and have been applied differently by researchers. Other authors report differing interpretations, and according to Zhao (2015):

> Researchers of phenomenography do not report their results being composed of the 'what' and 'how' aspects or 'referential, and 'structural' aspects since these aspects are intertwined closely in their conceptions of learning and difficult to separate. What they report are the categories of the conceptions of learning and the outcome space, i.e. the logical relationship between these categories. (p. 148)

For my study, the structure of the conceptions of what it means to understand physics is proposed to contain "what' and 'how' aspects. The 'what' aspects refers to what students, teachers, and professors think it means to understand physics and the 'how' aspects refers to how students, teachers, and professors engage in the understanding process (see Figure 4).

Figure 4

The Structure of Conceptions of Understanding



These ‘what’ and ‘how’ aspects are difficult to separate and are integrated together. As Marton and Booth (1997) explain, “the ‘how’ and the ‘what’, are component parts of the entire conception.” (p. 112). The intertwined nature of the ‘what’ and ‘how’ aspects may be observed from the interview quotes of the participants and these quotes serve as exemplars in illustrating a particular conception about what it means to understand physics from either a student, teacher, or professor.

2.5 Drawing Together a Diverse Literature

This literature review has examined some of the research about ‘understanding’ to provide a background for the reader and so that the reader may be able to situate my study in the literature. ‘Understanding’ has been written about in different ways in the literature. Some of these ways include literature about academic conceptions of understanding, where the conceptions of understanding are based upon theory, and empirical studies that investigated conceptions of understanding, where the conceptions of understanding are based upon empirical data.

The literature about conceptions of understanding for both the academic conceptions of understanding and the empirical studies investigating conceptions of understanding seemed to categorize understanding as an ability, process, and product. Understanding as an ability, process, and product are intertwined and found across the literature for academic conceptions of understanding and empirical studies investigating conceptions of understanding. Understanding as an ability means understanding as the possession of the means or skill to do something, understanding as a process means understanding as a series of actions or steps taken in order to achieve a particular end, and understanding as a product means understanding as the result of an action or process (see Table 2 and Table 6). In this way, understanding seems to be described in the literature as an ability that enables a person to undertake a process that leads to a particular product. As demonstrated in the empirical studies presented in my literature review, experience drives a person's conception of understanding and it could be suggested that their conceptions of understanding drive the person through the process of developing meaning.

Drawing together the diverse literature revealed the originality of my study about what it means to understand physics. My study investigated the conceptions participants had about what it means to understand physics as a field itself rather than investigating participants' conceptions of understanding specific physics topics such as force, acceleration, etc. My study investigated three different populations (students, teachers, and professors) about what it means to understand physics whereas current empirical studies only investigated one population. My study used phenomenography to explore participants' conceptions about what it means to understand physics whereas some of the literature explored academic conceptions of understanding by using theory and philosophical ideas but not empirical data. In addition, four empirical studies appear to overlap with my study since they investigated conceptions of understanding similar to my study that investigated what it means to understand physics. These studies include Burns et al. (1991) that used grounded theory to investigate high school chemistry students' conceptions of understanding of chemistry, Entwistle and Entwistle (1991, 1992) that investigated university students' conceptions of understanding when revising for degree examinations, Waterhouse and Prosser (2000) that investigated university students' conceptions of understanding mechanics and Irving and Sayre (2012) that investigated university student conceptions of understanding (see Table 6). Therefore, my study will build upon these similar studies and will begin to add to the literature about what it means to understand physics.

Chapter 3 Methodology

This chapter describes the phenomenographic research methodology utilized for this study. The first section describes the interpretivist research paradigm and explains that phenomenography is underpinned by an interpretivist research perspective. The second section explores the phenomenographic research tradition and includes the history of phenomenography, the theoretical and philosophical foundations of phenomenography, and explains conceptions, categories of description, and the outcome space. The third section explains the justification for the selection of phenomenography as the research methodology for my study. The fourth section explains my study's data collection and includes the participants, research setting, the interviews, and the interview protocol. The fifth section describes my study's ethical considerations, elaborates upon informed consent, confidentiality, the ethical treatment of the data, and ethics approval. In the sixth section, I share the data analysis process I used to maximize the transparency of the qualitative research process in this dissertation. Finally, the seventh section discusses the quality considerations of the study and includes, trustworthiness, credibility, transferability, dependability, and confirmability.

3.1 Interpretivist Research Paradigm

The paradigm for this qualitative study is an interpretivist paradigm. My study is interpretivist since "rhetorical markers and signifiers related to meanings, understandings, experiences, and participants' perceptions" (Koro-Ljungberg et al., 2009, p. 694) are present in the research questions. Within the research questions of my study (see Section 1.6) are such signifiers as suggested by Koro-Ljungberg et al. (2009), and these provide the opportunity for the participants to share their conceptions about the phenomenon of what it means to understand physics.

Phenomenography is underpinned by an interpretivist research perspective and is based upon the presumption of the existence of multiple realities between individuals (Green, 2005). From a phenomenographic research perspective, reality is neither singular nor fixed, and an individual's different realities are constructed from interpretations made as a consequence of their interactions within the world (Green, 2005).

In general, interpretivism seeks to understand and describe the research participants' meanings and understandings of their social life world (Koro-Ljungberg et al., 2009). When using the interpretivist theoretical perspective, Koro-Ljungberg et al. (2009) contend that: the main data collection methods are interviews, the main knowledge producers are the participants, and the researcher's role is to interpret the data. Ercikan and Roth (2006) further describe this interpretive role of the researcher as involving their subjective judgements. When describing the process of interpretively constructing data from data sources, Ercikan and Roth (2006) present an "interpretation model" (p. 18) where the researcher "filters for extracting relevant data" (p. 18) resulting in the "types of expressions and events" (p. 18) that finally constitutes the findings.

Through the utilization of an interpretivist research paradigm, I seek to understand and describe the research participants' experiences about what it means to understand physics. My values are inherent in all aspects of the research process and the meanings that emerge from the research process are those negotiated and interpreted through the dialogue of the interviews.

3.2 Phenomenographic Research Tradition

In the following sections, the phenomenographic research tradition is examined. These sections include: the history of phenomenography, the theoretical and philosophical foundations of phenomenography, and an explanation about phenomenographic conceptions, categories of description, and the outcome space.

3.2.1 History of Phenomenography

Phenomenography is a qualitative research approach that was developed in the early 1970's by Ference Marton, Roger Säljö, Lars-Owe Dahlgren, and Lennart Svensson at the Department of Education, University of Gothenburg, Sweden (Richardson, 1999; Bowden & Walsh, 2000, Hasselgren & Beach, 1997). This research approach was designed as an empirical qualitative method in response to the dominance of quantitative research methods in education at the time (Sandbergh, 1997). The word 'phenomenography' was first described in 1979 by Ference Marton and since then it has become popular with some researchers in the United Kingdom, Hong Kong, Australia, and Sweden (Åkerlind, 2012). As a result, literature has been published describing the theoretical and methodological assumptions underlying phenomenography (Marton & Booth, 1997; Dall'Alba & Hasselgren, 1996; Bowden & Walsh, 1994, 2000; Bowden & Marton, 1998; Bowden & Green, 2005).

3.2.2 Theoretical and Philosophical Foundations of Phenomenography

Marton (1986) describes phenomenography as a "research method for mapping the qualitatively different ways in which people experience, conceptualize, perceive, and understand various aspects of, and phenomena in, the world around them" (Marton 1986, p. 31). The etymology of phenomenograhy is derived from the Greek words *phainomenon* (phenomenon or appearance) and *graphein* (write or describe) (Limberg, 2008; Pang, 2003) and can be interpreted as a written account of a given phenomenon. Marton (1986) contends that when investigating people's understanding of a given phenomenon, the phenomenon can be understood in a "limited number of qualitatively different ways" (p. 31). The phenomenographic research method yields a description of a group's experience of a given phenomenon and it is "an attempt to describe the qualitatively different ways the phenomenon is experienced by the group" (Edwards, 2007, p. 87).

Phenomenography has developed "as an empirical approach in educational research" (Uljens, 1996, p. 104) and it is "grounded in the belief that direct observation of phenomena is an appropriate way to measure reality and generate truth about the world" (Bhattacharya, 2008, p. 253). Understanding the nature of reality refers to ontology and in the social sciences, it refers to the question of social reality and how this reality can be studied (Ireland et al., 2009). According to Uljens (1996), an ontological assumption in phenomenography is that "the only reality there is, is the one that is experienced" (p. 114) and the essence of reality lies in the whole range of individual experience.

Phenomenographers do not make any assumptions about the nature of reality or claim that their research results represent 'truth' but rather "that their results are useful" (Orgill, 2007, p. 134). Svensson (1997) describes the position phenomenography takes on the nature of reality as follows:

> Phenomenography does not ... have an articulate metaphysical foundation. The question may be raised if it has implicit metaphysical assumptions. Individual researchers doing phenomenographic research may make such assumptions, but they certainly vary between the researchers. It is possible to have any and all of the metaphysical positions within the main categories of materialism and idealism and do phenomenographic research. The tradition is not based on any of these metaphysical beliefs and it is open in this respect. (p. 165)

Phenomenographers describe their research as non-dualist and as a second-order research methodology (Trigwell, 2000, 2006; Marton & Booth, 1997; Marton, 2000). Non-dualism means that phenomenography examines the relationship between the phenomenon and the individual (Marton & Booth, 1997; Marton, 2000; Trigwell, 2000, 2006). In comparison, research methodologies that are dualist consider the individual to be separate from the phenomenon. According to Ulgens (1996), the non-dualist, “must relate a theory not to the world but to one’s experience of the world” (p. 115) and that “in phenomenography it is claimed that we cannot meaningfully talk about inexperienced reality” (p. 112). As asserted through non-dualism, my study is grounded in the understanding that the reality that exists for the participants is their experienced reality.

The second-order approach adopted by phenomenographic researchers means that the basis of a researcher’s description of a phenomenon is formed from the experience of the phenomenon as described by others (Marton & Booth, 1997; Marton, 2000; Trigwell, 2000, 2006). In comparison, a first-order research approach involves the researcher describing a phenomenon as he or she perceive it. My study adopts a second-order research approach as the basis of my description of the phenomenon, what it means to understand physics, and is formed from the experience of this phenomenon as described by others, the students, teachers, and professors.

Although phenomenography makes no assumption about the nature of reality or ontology, it does make some assumptions about the nature of knowledge or epistemology (Orgill, 2007). Epistemology refers to how one comes to know reality and addresses questions such as “What is the relationship between the knower and what is known?, How do we know what we know?, and What counts as knowledge?” (Imel et al., 2002, p. 4). In phenomenography, knowledge is assumed to be based on thinking and is seen as created through human thinking and human activity (Svensson, 1997). However, knowledge is also seen as “dependent upon the world or reality external to the individual and external to human activity and thinking, that which the activity and thinking is directed towards” (p. 165). For the phenomenographer, conceptions are the result of a person thinking about the external world and the focus is on the variations in these conceptions between the individuals. Svensson (1997) adds that “conceptions may be expressed in different forms of action, but they are most accessible through language” (p. 166). Therefore, my study accessed the students’, teachers’, and professors’ conceptions through the language they used to describe what it means to understand physics during an interview process.

Bowden (2000a) describes a particular kind of phenomenographic research called ‘developmental research’. This kind of phenomenographic research takes place in a formal educational setting and “seeks to find out how people experience some aspect of their world, and then enables them or others to change the way their world operates” (Bowden, 2000a, p. 3). Phenomenographic research that is developmental is undertaken with the purpose of using the outcomes to “help the subjects of the research, usually students, or others like them to learn” (Bowden, 2000a, p. 4). For example, Bowden (2000a) describes a developmental project undertaken with several researchers that investigated students’ understanding of specific fundamental physics concepts (Bowden et al., 1992; Dall’Alba et al., 1993; Walsh et al., 1993; Ramsden et al., 1993). The research examined the relation between students’ understanding and application of physics and textbook treatments of acceleration. The aim of my study’s developmental phenomenographic research was to provide findings which could then be utilized in teaching and learning physics and possibly in other teaching and learning contexts.

My study represents developmental phenomenographic research since the study was conducted in the educational settings of a high school physics classroom and a university. As with developmental phenomenographic research, my study was conceived with the purpose of using the outcomes of the research to inform specifically teaching and learning of physics but it may be possible that the findings could translate to the general domain of teaching and learning.

3.2.3 Conceptions and Categories of Description, and the Outcome Space

The first section discusses what phenomenographic conceptions, categories of description, and outcome spaces are in relation to the literature. The second section presents an example of categories of description and an outcome space from one study found in the literature.

3.2.3.1 Conceptions and Categories of Description

A conception is a term used in phenomenographic research "to refer to people's ways of experiencing a specific aspect of reality" (Sandbergh, 1997, p. 203). The conception encapsulates the way in which people experience a phenomenon and identifies the relationship between the subject and the given phenomenon (Ireland et al., 2009). Phenomenographers try to identify the multiple conceptions or meanings that a group of people have for a phenomenon and the focus is on describing the variations in these conceptions across the group (Orgill, 2007). For my study, the conceptions encapsulate the variations in the ways each group (high school physics students, high school physics teachers, and university physics professors) experience the phenomenon of what it means to understand physics.

Categories of description are used by the researcher to depict the conceptions shared by the research participants during the interview and represent an attempt by the researcher to formalize their understanding of these conceptions (Marton et al., 1993). In terms of phenomenographic research, "each phenomenon, concept, or principle can be understood in a limited number of qualitatively different ways" (Marton, 1986, p. 30) and it is assumed that a limited number of conceptions for a given phenomenon under study can be found during the course of phenomenographic research (Dall'Alba et al., 1989). For a given phenomenographic study, the conceptions are the main outcome of the research process, and these conceptions are then presented as categories of description. The categories of description are taken from the data and there should be no attempt by the researcher to force or fit the categories into a pre-determined structure. According to Dall'Alba et al. (1989), the categories of description are based on the distinctive features that differentiate one conception from another. Once this differentiation has been determined, the categories of description are presented in a form that "displays the relation between the categories" (Dall'Alba et al., 1989, p. 58) which is the outcome space. The process of data analysis some authors use to develop categories of description are outlined in Section 3.6.2.

3.2.3.2 Outcome Space

Once all the categories of description have been determined, this set of categories of description for the given phenomenon being studied is referred to as an 'outcome space' (Marton, 2000; Säljö, 1996; Trigwell, 2000; Walsh et al., 2007). The outcome space describes how the categories of description are internally related (Trigwell, 2000) and describes "the minimum number of categories which explained all the variations in the data" (Walsh et al., 2007, p. 3). Marton (2000) describes the outcome space as a logically structured complex of the different ways of experiencing a phenomenon, and he writes that the outcome space is synonymous with “phenomenon: the thing as it appears to us” (p. 105).

The result of the process of phenomenography is the development of the outcome space. The outcome space is typically displayed as a diagram or table but is incorporated as part of the data presentation so that the ways the categories relate to each other may be easily displayed (Edwards, 2007). The phenomenographic data analysis from conceptions to categories of description to an outcome space may be summarized as the following process. The conceptions resulting from the phenomenographic data are reduced into a number of categories of description and these categories “represent the content and the form of the conceptions of the phenomenon together” (Svensson, 1997, p. 168). These conceptions are represented analytically as several qualitatively different ways of experiencing the phenomenon and are referred to as categories of description (Marton & Booth, 1997). The categories of description “distinguish the empirically interpreted category from the hypothetical experience that it represents” (Åkerlind, 2005a, p. 322) but include the structural relationships linking the variations in the many ways of experiencing the phenomenon. These relationships between the categories of description represent the structure of an “outcome space” (Marton & Booth, 1997) and elucidate the relationships between the qualitatively different ways of experiencing the phenomenon.

Marton and Booth (1997) present three criteria for judging the quality of the outcome space and they suggest the researcher should ensure that: (1) each category of description reveals “something distinct” (p. 125) about how the phenomenon is experienced, (2) each category “stands in a logical relationship with one another” (p.125) where this relationship is frequently hierarchical, and (3) the outcome space constitutes the categories of description and “as few categories should be explicated as is feasible and reasonable” (p. 125). According to Åkerlind

(2005a), the set of categories of description that make up the outcome space should not be "determined in advance, but 'emerge' from the data, in relationship with the researcher" (p. 323).

In addition to developing the outcome space, phenomenographic researchers are also concerned with determining the logical relationship that may exist between the categories of description. Determining the logical relationship between the categories of description implies that the researcher selects data so that the categories have a relationship to one another. This relationship may form a hierarchy where categories of description are inclusive of others. However, according to Walsh (2000), the hierarchical structure need not be linear, it may contain branches within the hierarchical structure, and it may not even exist depending on the research purpose. Furthermore, Åkerlind (2005a) sates "the structure of an outcome space need not always take the form of a linear hierarchy of inclusiveness" (p. 329) and Dahlin (2007) adds that "it may be observed that not all phenomenographic outcome spaces have a hierarchical structure of dimensions of variation" (p. 336). I describe the data analysis process I utilized to create my outcome space in Section 3.6.4.

3.2.3.3 An Example of Categories of Description and an Outcome Space from the Literature

The example of categories of description and an outcome space by Barnard (1998) is described to provide the reader with an example of phenomenographic research, which resulted in logically related categories of description and an outcome space represented by a diagram. The purpose of this study was to identify and describe the qualitatively different ways technology was understood and experienced by surgical nurses. For the study, twenty surgical nurses were interviewed, and audio recorded.

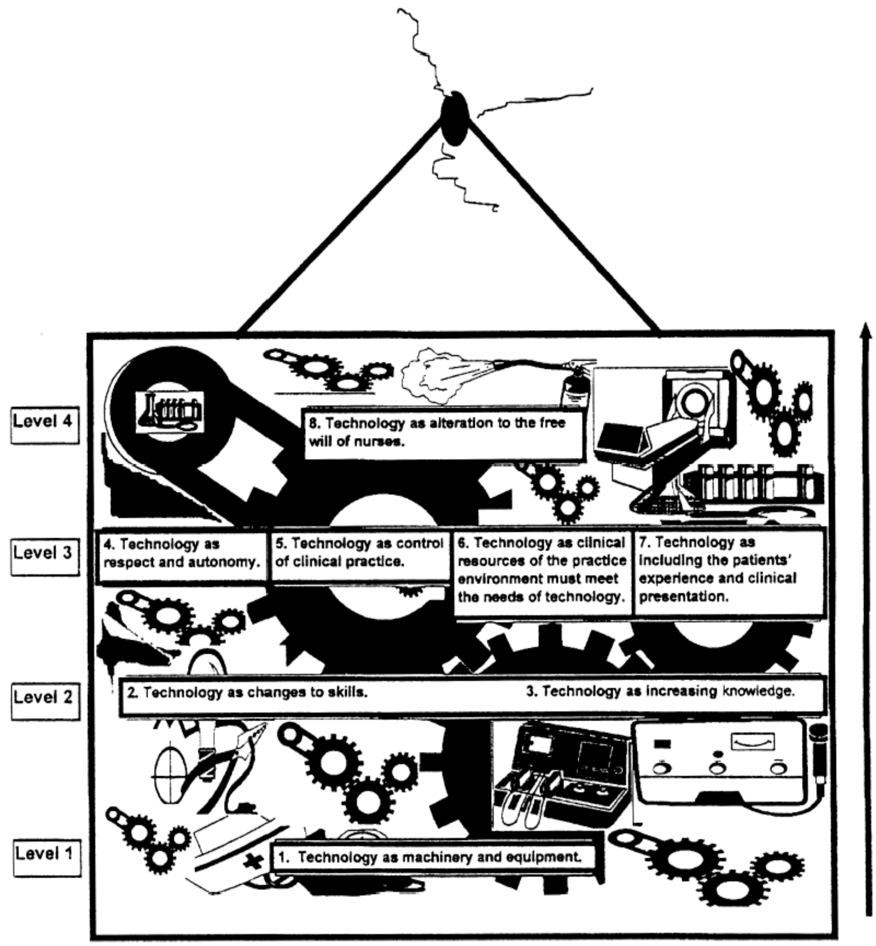
The research identified eight categories of description that constituted the nurses' experience and understanding of technology and an outcome space that portrayed the logical relationship between each of their conceptions (Barnard, 1998; Barnard & Gerber, 1999; Barnard et al., 1999). The eight categories of description include: (1) technology as machinery and equipment, (2) technology as changes to skills, (3) technology as increasing knowledge, (4) technology as respect and autonomy, (5) technology as control of clinical practice, (6) technology as clinical resources of the practice environment must meet the needs of technology, (7) technology as including the patients' experience and clinical presentation, and (8) technology as alteration to the free will of nurses (Barnard, 1998). The outcome space was represented as a diagram where the eight categories of description were related to each other as a hierarchy and delineated into four levels of awareness.

The outcome space was portrayed as a picture hanging on a wall as a method of portraying the nurses' experience and understanding of technology. The outcome space "illustrates the external horizon (the way in which the phenomenon is related to its context) and internal horizon (how component parts of the phenomenon are understood and are related to each other) of experience and understanding" (Barnard & Gerber, 1999, p. 163).

In Barnard's study, the internal and external horizons refer to the way in which technology is delimited and related to the practice of surgical nursing. Barnard (1998) presents the external horizon in the background, as a frame of a picture, and it represents the use of machinery and equipment (see Figure 5). The internal horizon is presented in the foreground, as the picture itself, and it refers to how the component parts are logically related.

Figure 5

Understanding Technology in Contemporary Surgical Nursing, (Barnard & Gerber, 1999, p. 163)



The ascending arrow on the right side of the outcome space represents the hierarchical relationship between the categories of description (Barnard, 1998). The left side of the diagram represents the awareness of the phenomenon and is arranged into four increasing and incremental levels. These incremental levels are described by Barnard (1998) as: (1) level one (machinery and equipment), (2) level two (readiness for clinical practice), (3) level three (the outcome of technology use in clinical practice), and (4) level four (volition and nursing practice) where 'volition' means the power of choosing or determining.

For this study, the nurse represents the subject while the machinery and equipment represent the object. The relationship between the subject and the object is expressed by the eight categories of description and is portrayed in the outcome space (Barnard & Gerber, 1999). In terms of the referential (what) aspect of the outcome space, it "has been identified as differing insight into the phenomenon of technology as experienced and understood in relation to the use of machinery, and equipment" (Barnard & Gerber, 1999, p. 164). Barnard and Gerber (1999) further describe the referential aspect as the nurses' insight into the experience of technology and how it evolves as a consequence and association with the ways they "experience and understand the effect of their use of machinery and equipment" (Barnard & Gerber, 1999, p. 164). In terms of the structural (how) aspects of the outcome space, Barnard and Gerber (1999) describe it as hierarchical. However, Barnard et al. (1999) clarify that although the eight conceptions were unique, they were "integrated in a conceptual order depicted as a hierarchy of four incremental levels of understanding, ranging from the most rudimentary or basic level (level 1) to the most complex level (level 4)" (p. 221).

At the lowest hierarchical level, level one, only the first category of description is included since the central focus of awareness is technology and equipment is described as the 'things themselves' (Barnard & Gerber, 1999). Since level one is the most rudimentary level of understanding, technology is seen as things or objects. The second hierarchical level, level two, includes the categories of description two and three. In level two, the focus of attention is on how the technology and machines are used rather than simply the outcomes of their use which is depicted in the first level. The third hierarchical level, level three, includes the categories of description four through seven. In level three, the conceptions reflect understanding from the perspective of how technology influences and effects: patients, clinical judgement, the surgical ward, and professional respect (Barnard & Gerber, 1999). Finally, the highest level of awareness is level four, and it contains the eighth category of description. In this level, understanding portrays an awareness that describes a reciprocal relationship between the nurse and technology (Barnard & Gerber, 1999). For this advanced level of awareness, technology is seen as challenging the desire and ability of the nurse to fulfill their roles and responsibilities (Barnard & Gerber, 1999).

Therefore, the Barnard (1998) study is an effective example that describes how categories of description are organized into a hierarchy, and how the referential (what), structural (how), and internal and external horizons for the conceptions are conceptualized from the data. Barnard and Gerber (1999) influenced the way I have depicted my categories of description because I have represented them in a logically ordered graphical outcome space. In addition, I have portrayed the categories of description from my findings as referential (what) and structural (how) aspects as Barnard and Gerber (1999) have done. The referential (what) aspects of the categories of description represent the differences in their overall conceptualizations and the structural (how) aspects of the categories of description represent the variation of internal structure of their overall conceptualizations. My process of developing the categories of description and the outcome space is described in Section 3.6.4.

3.2.4 Summary

This section described: the history of phenomenography, the theoretical and philosophical foundations of phenomenography, conceptions and categories of description, and the outcome space. The study by Barnard (1998) helped to inform me and hopefully the readers about how a diagram can be used to represent the outcome space and how logically related categories of description can be arranged in that outcome space.

3.3 Justifications for Choosing Phenomenography

The following section describes the justifications for choosing phenomenography as the methodology for my study. Phenomenography is appropriate since the research questions of my study are of an educational nature and phenomenography is well suited to answering such questions. In addition, phenomenography has been employed as the research methodology in several similar studies where student conceptions of understanding in general and understanding of specific physics concepts have been investigated as outlined in Chapter 2. When compared to other research methodologies such as phenomenology and grounded theory, phenomenography may be considered as an appropriate choice from philosophical, theoretical, and methodological grounds.

3.3.1 Phenomenography is Aimed at Educational Questions of Relevance

Phenomenography is a research approach that is aimed at research questions about learning and understanding in educational environments (Marton & Booth, 1997). It has a strong pedagogical interest (Giorgi, 1999), and was specifically developed in response to educational questions (Marton, 1986). Phenomenography also provides valuable insights into how students understand the content they are learning and these insights "can be used to evaluate students' variation in all forms of experience within learning and teaching contexts" (Trigwell, 2006, p. 367).

A phenomenographic study of the conceptions university physics students held about speed, distance, and time was undertaken by Ramsden et al. (1993) and they described a number of reasons why they adopted phenomenography as their theoretical and methodological choice. As my study is concerned with students', teachers', and professors' conceptions of what it means to understand physics, these reasons are also applicable for my study. For example, Ramsden et al. state that the hierarchical descriptions of student conceptions resulting from the phenomenographic analysis may assist teachers in developing assessments based upon such a hierarchy. In addition, the insight that phenomenography provides about student conceptions of their understanding of various subjects has educational value to inform pedagogy through developing valid assessment methods, curriculum development, and with classroom teaching (Ramsden et al., 1993).

In general, the units of phenomenographic research for a given study are the conceptions or the different ways of experiencing a phenomenon and the object of the research is the variation in the ways the phenomenon is experienced. For my study, the educational setting is a high school and a university, and the unit of research is the participants' conceptions of what it means to understand physics. The object of research is therefore the variations in the conceptions that students, teachers, and professors report about the phenomenon of what it means to understand physics. Since phenomenography is well suited to study research questions of an educational nature, it is an appropriate research methodology for my study. Phenomenography has a strong pedagogical interest and is well suited to providing insight into students', teachers', and professors' conceptions about what it means to understand physics.

3.3.2 The Comparison of Phenomenography, Phenomenology, and Grounded Theory

In the following sections, the research methodologies phenomenography, phenomenology, and grounded theory are compared. Phenomenology was considered as a potential research methodology for my study since Barnard et al. (1999) states that both phenomenology and phenomenography share some commonalities and they both aim to reveal human awareness and experience as an object of research. Grounded theory was considered as a potential research methodology for my study since Richardson (1999) states that phenomenography has similar analytic procedures to grounded theory and combines some of the elements of grounded theory including performing interviews and data analysis. The case will be made that phenomenography is the most appropriate research methodology for my study based upon philosophical, theoretical and methodological grounds.

3.3.2.1 Explaining Phenomenology

Giorgi (1999) suggests that phenomenology is a philosophical tradition initiated by Edmund Husserl and it places an emphasis on consciousness. Adams and van Manen (2008) defines this philosophical tradition as the reflective study of lived experience or "the study of the life-world as we immediately experience it, pre-reflectively, rather than as we conceptualize, theorize, categorize, or reflect on it" (p. 3). Therefore, phenomenology is the study of lived or experienced meaning, and it attempts to describe and interpret these meanings. These meanings are then interpreted in the ways that they emerge and are shared by "consciousness, language, our cognitive and non-cognitive sensibilities, and our pre-understandings and presuppositions" (Adams & van Manen, 2008, p. 3). Giorgi (1999) adds that phenomenological analysis depends on the relationship between three things that constitute a phenomenon through "acts, objects, &

meanings" (p. 79) where the goal is to describe the essential relationships about and how these 'acts, objects, and meanings' present themselves to our consciousness.

An important aspect of the phenomenological method is the 'reduction' and it is a phenomenological concept similar to the phenomenographic concept of bracketing (see Section 3.6.5). This 'reduction' or e'poche' allows the researcher to expose the phenomenon and its purpose is to "re-achieve a direct and primal contact with the world as we experience it rather than as we conceptualize it" (Adams & van Manen, 2008, p. 9). The reduction allows the discovery of the pre-reflective phenomenon and by bracketing it, meaning is experienced. Finally, the reduction is meant to focus the attention of the researcher upon the uniqueness of the phenomenon under study.

3.3.2.2 Comparing Phenomenology and Phenomenography

In comparing phenomenology and phenomenography, these research methodologies appear to share some commonalities in that both phenomenology and phenomenography aim to reveal human awareness and experience as an object of research (Barnard et al., 1999). The difference between the research methods is that while phenomenography is concerned with collective meaning of the phenomenon, phenomenology is concerned with the individual meaning of the phenomenon (Dahlgren, 1995).

According to Hasselgren and Beach (1997), the theoretical and methodological similarities of phenomenography and phenomenology are limited. Svensson (1997) contends that there are similarities between phenomenography and phenomenology but that phenomenography should not be totally included as part of the phenomenological tradition. Marton and Booth (1997) claim that phenomenography is no more than a "cousin-by-marriage of phenomenology"

(p. 117) but Giorgi (1999) makes the claim that phenomenography may be more similar to scientific phenomenology. Phenomenography is more similar to scientific phenomenology because scientific phenomenology looks for “typical essences” (Giorgi, 1999, p. 89) in the data. Giorgi (1999) adds that from the phenomenographic perspective, Marton and Booth (1997) have admitted that their term “architecture” (p. 117) is similar to these “typical essences” thereby making phenomenography similar to scientific phenomenology.

In reporting on the difference between phenomenology and phenomenography, Marton and Booth (1997) explain that phenomenography does not have as its aim the determining of a singular essence, but phenomenography seeks the variation and the structure of the variation that defines a phenomenon. Phenomenology is a first order research perspective where the world is described as ‘it is’ rather than as it is understood, rather then the second order perspective of phenomenography (Marton & Booth, 1997). Both research methodologies may use interviews as the source of data, but the results of the analysis are particularly different. Phenomenology may result in the identification of meaning units, while phenomenography results in categories of description of conceptions and a unique outcome space (Marton, 1981, 1986; Marton & Booth, 1997). Although there are some similarities between phenomenography and phenomenology, Hasselgren and Beach (1997) state quite emphatically “that most phenomenography is far from what might be considered as phenomenological” (p. 200).

Barnard et al. (1999) explored phenomenographic and phenomenological research approaches for exploring research in health care and they developed a table that succinctly describes the relationship between phenomenology and phenomenography (see Table 7).

Table 7

The Relationship Between Phenomenography and Phenomenology, (Barnard et al., 1999, p.214)

Phenomenography	Phenomenology
The structure and meaning of a phenomenon as experienced can be found in pre-reflective and conceptual thought.	A division is claimed between pre-reflective experience and conceptual thought.
The aim is to describe variation in understanding from a perspective that views ways of experiencing phenomena as closed but not finite.	The aim is to clarify experiential foundations in the form of a singular essence.
An emphasis on collective meaning.	An emphasis on individual experience.
A second-order perspective in which experience remains at the descriptive level of participants' understanding, and research is presented in a distinctive, empirical manner.	A noumenal first-order perspective that engages in the psychological reduction of experience.
Analysis leads to the identification of conceptions and outcome space.	Analysis leads to the identification of meaning units.

Table 7 provides a simplified comparison of both research methods including the phenomenological emphasis on the singular essence of individual experience compared to the phenomenographic emphasis on the variations in collective meaning.

In summary, phenomenology is interested in individual experience and the essence of a phenomenon whereas phenomenography is interested in collective meaning. For my study, phenomenography is the more appropriate research methodology since the differences in the variations in the collective meaning of the participants' conceptions of what it means to understand physics is being sought rather than seeking to obtain "the essence that withstands the variations" (Giorgi, 1999, p. 80) as with phenomenology. Phenomenology is interested in a first order perspective where the world is described from the perspective of the researcher describing a phenomenon as he or she perceive it while phenomenography is interested in a second-order perspective where the world is described as it is understood by the individual experiencing the phenomenon (Barnard et al., 1999).

The comparison of phenomenology with phenomenography indicate that the methodology of phenomenography is well suited to providing insight into students', teachers', and professors' conceptions about what it means to understand physics.

3.3.2.3 Explaining Grounded Theory

Grounded theory is a method of social scientific theory construction developed by Glaser and Strauss (1967) during their study of the social organization of dying in hospitals. Glaser and Strauss refer to the process of grounded theory as discovering theory from data while Birks and Mills (2011) refer to the theory as being "abstracted from, or grounded in, data generated and collected by the researcher" (p. 16). The method consists of analytic guidelines that enable the researchers to focus their data collection to build theories (Charmaz, 2011; Charmaz & Bryant, 2008) where the phenomenon under question is described from the context and the perspective of the participants who experience it (Birks & Mills, 2011).

The grounded theory methodology is fundamentally an iterative, comparative, and abductive process that proceeds from observation to hypothesis (Bryant & Charmaz, 2007). The abductive process can be described as the process of data processing where the data is assembled "on the basis of an interpretation of collected data, such combinations of features for which there is no appropriate explanation or rule in the store of knowledge that already exists" (Bryant & Charmaz, 2007, p. 219). In this way, the abduction proceeds from a known quantity to two unknown quantities where the researcher brings together things which had never been associated with one another. Grounded theory abduction is a form of reasoning that differs from deduction and induction. Deduction is an analytic process based on the application of general rules to particular cases with the inference of a result, induction infers the rule from the case and the result, while abduction infers the case from a rule and a result (Brachman & Levesque, 2004).

Two principles distinguish grounded theory from other research methodologies. The first principle pertains to change, and an important component of the research methodology is to build change into the process (Corbin & Strauss, 1990). The second principle is ‘determinism’ where participants can control their destinies according to their perceptions of the phenomenon they encounter. Therefore, grounded theory seeks to determine the relevant conditions of how participants respond to changing conditions as a consequence of their actions where the researcher is responsible to recognize these changes. A theory or model is then constructed that shows change and action or the reasons for the change if any (Corbin & Strauss, 1990).

In describing the formulation of grounded theory, Glaser and Strauss (1967) describe that comparative analysis is used for the generation of theory and two types of theory are generated, substantive and formal. Substantive theory is described as theory “developed for a substantive, or empirical, area of sociological inquiry, such as patient care, race relations, [and] professional education” (Glaser & Strauss, 1967, p. 32) while formal theory is described as theory “developed for a formal, or conceptual, area of sociological inquiry, such as stigma, deviant behavior, [and] formal organization” (p. 32). These types of theories are described by Glaser & Strauss (1976) as ‘middle range’ theories since they fall between the minor theories of everyday life and grand, all-inclusive theories. When a researcher is developing a final grounded theory, the theory undergoes a ‘rewriting’ so that it is grounded in only one of the theoretical areas (Glasser & Strauss, 1967).

3.3.2.4 Comparing Grounded Theory and Phenomenography

One of the differences between grounded theory and phenomenography are the different types of research questions each method may focus on. Phenomenography is interested in questions where the variations of participants' conceptions of a phenomenon are of interest, whereas grounded theory is interested in questions that result in the construction of a model or theory that demonstrates change (Kinnunen & Simon, 2012; Strauss & Corbin, 1990). In addition, grounded theory provides a step-by-step method about how the analysis should be undertaken while phenomenography does not have any similar such guidelines for a formal structured analysis (Strauss & Corbin, 1990).

Kinnunen & Simon (2012) compared grounded theory with phenomenography as applied to the field of computing education research. The comparison between grounded theory and phenomenography can be seen in Table 8 and it provides a concise differentiation between the two research methodologies, especially in the differences between their research focus and results.

Table 8

Summary of Some Aspects of Phenomenography and Grounded Theory, (Kinnunen & Simon, 2012, p. 213)

	Phenomenography	Grounded theory (Strauss and Corbin, 1990)
Focus	Variation in perceptions of the phenomenon. Second order perception.	Experience, perception, action.
RQ/goal of the research	E.g. instructors' perceptions of students' success.	E.g. to explore how computer science majors experience the process of doing programming assignments in a CS1 course.
Data source	Often semi-structured interviews or writings.	Semi-structured interviews, writings, observations, artefacts, even quantitative data.

	Phenomenography	Grounded theory (Strauss and Corbin, 1990)
Analysis process	Inductive, iterative, uses comparison. Sorting, categorizing, abstracting.	Inductive, iterative, uses comparison. Open, axial and selective coding phases. Paradigm model gives guidelines.
Results/outcome of the analysis	An outcome space = categories of description, which are logically related to each other. Often displayed as a table.	Models, stories that describe the variation in context, actions, intervening events and consequences.

In summary, although both phenomenography and grounded theory share some commonalities, phenomenography is the more appropriate choice of a research methodology for my study when compared to grounded theory as the research questions of my study are seeking the variations in participants' conceptions about what it means to understand physics rather than in developing a theory explaining these conceptions.

3.3.3 Summary

The case for using phenomenography for my study has been made on several grounds. The literature suggests that phenomenography is appropriate when researching questions of both a pedagogical and educational context. In addition, many similar studies exist in the literature directly related to my study's area of research, namely the conceptions of what it means to understand physics. Finally, phenomenography is the more appropriate research choice from philosophical, theoretical, and methodological considerations than either of phenomenology or grounded theory.

3.4 Data Collection

In the following five sections, the data collection for my study is discussed. The participants, the research settings, the interview guide, the pilot interview, the interview protocol and process, and the interview transcripts are described.

3.4.1 Participants and Setting

The research participants for my study were drawn from three different groups, grade twelve physics students, high school physics teachers, and university physics professors. Purposeful sampling (Åkerlind et al., 2005) was employed for participant inclusion in my study since the logic and power of such sampling lies in the selection of information-rich cases for in depth study since “information-rich cases are those from which one can learn a great deal about issues of central importance to the purpose of the research” (Patton, 1990, p. 169). The purpose of my study was not to select a random statistically representative sample that would permit confident generalization from the sample to the population, but the purpose was to select physics students, teachers, and professors who would provide information-rich cases for in-depth study about their conceptions of what it means to understand physics.

Trigwell (2000) suggests a sample size of ten to fifteen participants, while Bowden (2005) and Åkerlind et al. (2005) suggest that phenomenographers interview between twenty to thirty participants. The twenty to thirty interviews proposed by Bowden (2005) and Åkerlind et al. (2005) provides an adequate sample to “ensure sufficient variation in ways of seeing, but not so many that make it difficult to manage the data” (Bowden, 2005, p. 17). According to Åkerlind et al. (2005), the most important criteria with respect to the sampling process is to obtain the maximum variation within the sample by ensuring that a wide enough range of variation is represented for key indicators of gender, age, and experience. The point of selecting as much demographic variation as possible is that it increases the probability of there being as much variation in the experience of the phenomenon under investigation within the sample as possible (Åkerlind, 2005b). University students have not been selected as part of the study group since two similar phenomenographic studies appear in the literature that examine university students' conception of understanding mechanics (Waterhouse & Prosser, 2000) and university students' conceptions of understanding (Irving & Sayre, 2012).

For my study, the following number of interviews were conducted and includes the demographic data: (1) twenty-two high school students were interviewed, fourteen males, and eight females, (2) twenty-three high school teachers were interviewed, eighteen males and five females, (3) twenty-eight physics professors were interviewed, twenty-one males, and seven females (see Table 9).

Table 9

Demographic Data for the Participants

Participant	Number of Interviews	Male	%Male	Female	%Female
Students	22	14	64	8	36
Teachers	23	18	78	5	22
Professors	28	21	75	7	25
Total	73	53		20	

The three participant groups resulted in a total of seventy-three interviews. Some recent phenomenographic dissertations completed at the University of Alberta, Faculty of Education, have conducted fifteen interviews (van Kessel, 2016) while another recent dissertation conducted ninety-six interviews (Zhao, 2015). Yet, although the Zhao (2015) dissertation conducted ninety-six interviews, only thirty interviews were analyzed "based on how detailed and representative the conversation was" (p. 266). For my study, all seventy-three interviews were analyzed as they were all sufficiently detailed and representative of the conversation about what it means to understand physics. The seventy-three interviews resulted in 43.5 hours of recorded data and many pages of transcribed data. Although I found it very challenging to deal with the large volume of data collected, all seventy-three interviews were used during the data analysis since the twenty-two student, twenty-three teacher, and twenty-eight professor interviews provided information-rich cases. My process of organizing and analyzing the interviews are described in Section 3.6.4.

The first group of research participants consisted of twenty-two high school physics students and this group was purposefully selected from the students of the teachers who agreed to participate in the study. I asked the participating teacher to talk to their class about the research and to identify students who were willing to discuss their conceptions of what it means to understand physics. I conducted the student interviews within the participating physics teacher's classroom during a mutually convenient time for both the teacher and the student. Grade twelve physics students have been included in my study rather than grade eleven physics students because grade twelve students represent a population of students who have taken the highest level of physics education available by the public school system and who may be on their way to transitioning into university studies.

The second group of research participants consisted of twenty-three high school physics teachers and this research sample was drawn from both public and private high schools from Winnipeg, Manitoba. The teacher interviews were conducted at the teacher's convenience during a mutually beneficial time and place. The population of the physics teachers included both in-field and out-of-field teachers where an out-of-field physics teacher is defined as "teachers teaching subjects for which they have little education or training" (Ingersoll, 1999, p. 26), (see Table 10).

Table 10

Physics Teacher In-Field and Out-of-Field Data

	Number of Teachers	Percentage %
In-Field	5	39
Out-of-Field	18	61
Total	23	

For the purpose of my study, an in-field physics teacher is defined as a teacher who has a Bachelor of Education degree with a physics major, a Bachelor of Science in Engineering, or a Bachelor of Science with a physics major. During the interviews, the teachers were asked if they considered themselves to be in-field or out-of-field and this self-reporting was consistent with the academic backgrounds of the teachers. In total, five teachers were in-field and eighteen teachers were out-of-field.

The final participant group consisted of twenty-eight university physics professors selected from two Manitoba universities. I contacted the physics professors through email and arrangements were made to interview the professors at their convenience in their office.

3.4.2 Semi-Structured Interviews

The data for my phenomenographic study was collected from semi-structured interviews where participants answered several open-ended questions about what it means to understand physics. My study used semi-structured interviews because they, "are the standard data collection method for phenomenography" (Dunkin, 2000, p. 143) and have been well documented in the phenomenographic literature (Åkerlind et al., 2005; Åkerlind, 2005b, 2005c; Patrick, 2000; Edwards, 2007). The benefits of the semi-structured interview includes the following: (1) questions can be prepared ahead of time and allows the interviewer to be prepared, (2) the semi-structured interview allows the participants the freedom to express their views in their own terms, and (3) the semi-structured interview provides reliable, comparable qualitative data for the researcher (Cohen & Crabtree, 2006a).

The open-ended questions were adopted for my study as they are favored in phenomenographic research because these types of questions "allow the interviewees to decide on those aspects of the question which appear most relevant to them" (Bowden, 2000a, p.8). Marton (1986) adds that open-ended questions "let the subjects choose the dimensions of the question they want to answer" (p. 42). As with the semi-structured interviews, the use of open-ended interview questions is well documented in the phenomenographic literature (Marton et al., 1993; Marton, 1986; Åkerlind; 2005b, 2005c; Patrick, 2000; Bowden, 2000a).

The characteristics of using a semi-structured interview include asking participants the same questions, asking these questions in the same order, and include using a completely open-ended format when wording the questions (Patton, 1990). The strengths of such interviews include facilitating the organization and analysis of the data and increasing the comparability of responses since respondents answer the same questions (Patton, 1990). The weaknesses of such interviews include modest flexibility in relating the interview to a participant's circumstances, and in the way standardized wording of the questions may constrain the participant's responses (Patton, 1990).

When interviewing university students about their revising for university examinations, Entwistle and Entwistle (1992) used a "relaxed manner to encourage active engagement, with the interviewer interacting, exploring issues and, on occasion, even challenging ideas" (p. 5). Therefore, for my study, I interviewed participants in a similar 'relaxed' manner as Entwistle and

Entwistle (1992) because their strategy produced "a natural conversational style which ensured extensive contributions from every student" (p. 5).

The length of the semi-structured interview varies. Newton et al. (1998) suggest thirty minutes, Green (2005, p.39) suggests forty to sixty minutes, Dunkin (2000, p. 143) suggests about an hour, and Åkerlind (2005b, p. 105) suggests between sixty to ninety minutes. For my study, the audio of the student interviews totaled 7.19 hours with an average interview length of 21.2 minutes. The audio of the teacher interviews totalled 14.9 hours with an average interview length of 38.0 minutes. The audio of the professor interviews totaled 20.7 hours with an average interview length of 43.8 minutes (see Table 11).

Table 11

Interview Lengths

	Student	Teacher	Professor	Total
Number of Interviews	22	23	28	73
Total interview time (hours)	7.9 hours	14.9 hours	20.7 hours	43.5 hours
Average interview time (mins.)	21.2 mins	38.0 mins.	43.8 mins.	

Therefore, the lengths of the interviews for my study range from twenty-one minutes to forty-four minutes and are consistent with the interview lengths suggested in the literature (Green, 2005). It may be speculated that the professors had the longest interview length when responding to the interview questions because they have the most experience and expertise to draw upon when compared to the students and teachers.

3.4.3 Pilot Interviews

Before the interviews were conducted, a pilot interview was undertaken as suggested by Åkerlind (2005c), Bowden (2000a), Green (2005), Francis (1996), Edwards (2007), and Patrick (2000). The importance of the pilot interview lies in its ability to "test whether the questions will illicit the types of answers required to identify the possible categories" (Edwards, 2007, p. 93) of the research. Bowden (2005) asserts that the pilot interview is important since it "maximises the power of the research outcomes" (p. 15) and allows the researcher "to perfect their phenomenographic interviewing skills" (p. 19).

The pilot interview was conducted with one high school physics teacher, so that the interview protocol could be tested, and so that I could get a feel for how the interview protocol would translate during a real interview. The pilot interview was not transcribed since Bowden (2005) suggests the data collected from the pilot interviews should be "discarded and not used" (p. 19). The pilot interview teacher signed a consent form prior to the interview.

Prior to the pilot interview, I asked the teacher to think about how the interview might me improved and to speculate if the language I used in the interview questions would be understood by a high school student. After the interview, the teacher said that the interview questions would be understood by a high school student and suggested that I needed to articulate my words, that I needed to speak clearly, and that I needed to speak slowly. Upon reviewing the audio recording of the pilot interview, I confirmed the suggestions provided by the teacher. In addition, I noticed that I needed to not interrupt the participant when the participant was speaking, and that the sound recorder needed to be placed closer to the participant to optimize the volume of the recording.

Only one pilot interview was conducted because after I received the teacher's suggestions about the interview process and after I reviewed the audio recording of the interview, I felt that I had obtained enough valuable information about the interview process to be able to successfully conduct the interviews. In addition, since the pilot interview data is discarded and not used

(Bowden, 2005), I did not want to discard the data from another valuable interview since I was having difficulty finding interview participants at the time the pilot interview was conducted.

3.4.4 Interview Protocol and Process

Prior to commencing the interview, I asked each participant if he/she was still willing to participate in my study. I asked if he/she understood the benefits and risks involved in participating in the research study and I asked if he/she had any questions about the study. I reiterated that the interview would be audio recorded and his/her direct quotes may be used in research reports such as presentations and publications. I assured the participant that his/her identifying information would be anonymized and that he/she could withdraw from the study at any time after which any information directly linked to him/her would be excluded from the study. I checked to ensure that the participant's assent/consent form was signed and then I began the interview. Appendix A contains the student, teacher, and professor interview protocol. The interview is divided into two parts, Part 1: Introduction to the Interview and Part 2: Interview Questions. Part 2: Interview questions is further subdivided into (a) Student Interview Questions, (b) Teacher Interview Questions, and (c) Professor Interview Questions.

The first part of the interview consisted of a common introduction that I read to each participant group prior to asking any questions and this common introduction included the following statement:

> The purpose of my research is to determine your conceptions of understanding physics by asking you to respond to a series of questions. The interview should only take about thirty minutes. I will be audio recording the interview and I appreciate your willingness to allow me to do so with your signed informed consent. The audio recording will be kept secure and confidential. Once the interview has been transcribed, and after the data has been analyzed, the audio recording will be erased. There is no right or wrong answer to the questions. Consider this interview as simply a conversation between us where you

have the opportunity to tell me what you think about the topic of what it means to understand physics.

The second part of the interview consisted of interview questions adapted from the interview protocol developed by Åkerlind (2005b, p. 105) and each group (students, teachers, and professors) was asked the same series of questions. The differences in the interview questions between the students, teachers, and professors consisted of questions about descriptive statistics. For example, the students were asked what grade they were in, the teachers were asked if they considered themselves to be an in-field or out-of-field physics teacher, what degrees they held, and how long they have taught high school physics for, and the professors were asked about their research interests and the university physics courses they have taught and are currently teaching.

Question probes were included in the interview protocol because these questions helped to clarify what the participant said (Åkerlind, 2005b) and provided the opportunity for the participant to elaborate upon a given response to a question. For example, some question probes include the following: (1) " Tell me a bit more about that.", (2) "Why was this helpful to your understanding?", and (3) "Why did you do it that way?". These question probes provided new questions to emerge as I asked the participants to clarify their responses during the interview. The question probes were important to the interview because in phenomenography, it is important "to go beyond 'what' questions ('What did you do?') to 'why' questions ('Why did you do it *that* way?')" (Åkerlind, 2005c, p. 65).

Since "phenomenographic interviews are potentially uncomfortable for interviewees" (Åkerlind, 2005b, p. 115), I tried to make the interviewee as comfortable as possible. During the interview process, I was careful not to "point out errors in [a participant's] reasoning nor to try to get a [participant] to understand the physics" (Walsh, 2000, p. 31). Rather than being critical or correcting errors in physics during the interview, I allowed the participants to reveal their conceptions of what it means to understand physics.

3.4.5 Utilization of Interview Transcripts

Phenomenography investigates the qualitatively different ways in which people experience a given phenomenon (Marton, 1986) and its goal is to understand, describe, and analyze experience (Marton, 1981). My study suggests that variations exist among students, teachers, and professors regarding the qualitatively different ways in which they conceive of what it means to understand physics. In addition, my study suggests that a limited number of categories of description may possibly represent these variations. To determine these variations, I analyzed the transcripts from the interviews of students, teachers, and professors.

The interviews were audio recorded as suggested by Bowden et al. (2005). Each interview was recorded on two Olympus WS-500M Digital Voice Recorder flash drive sound recorders and each interview was transferred to a computer. The interviews were transcribed verbatim, and I compared the transcription with the audio recordings to check for any discrepancies in my transcription process. Following my transcription process, I was able to begin familiarizing myself with the data.

3.5 Ethics

In the following four sections, the ethics for my study is discussed, the issue of informed consent is presented, the 'power over' concern between students and teachers is addressed, and the confidentiality and ethical treatment of the research data is presented. Finally, the ethics approval from the University of Alberta and the University of Winnipeg is explained.

3.5.1 Informed Consent

Informed consent "insists that research subjects have the right to be informed about the nature and consequences of experiments in which they are involved" (Christians, 2011, p. 65). The research participants must voluntarily agree to participate in the research without any form of coercion and the participants must be given all the information about the experiment for which they will participate (Christians, 2011). In addition, the participants must be ensured of their privacy and confidentiality during the research and the data must appear to be accurate and not fraudulent in any way (Christians, 2011).

I adhered to the informed consent criteria outlined by Christians (2011) by informing the research participants about the content of the research through information letters and their participation through letters of informed assent and consent. Information letters were given to students, parents, teachers, school superintendents, and professors. The informed assent and consent were obtained from the following six groups of research participants: (1) consent from the university professors, (2) consent from the high school superintendents, (3) consent from the high school teachers, (4) consent from the legal guardians of the students who were under 18 years of age, (5) assent from the students who were under 18 years of age, and (6) consent from the students who were over 18 years of age.

Each of the informed assent and consent letters indicated that participation in the research is voluntary and that the participants could withdraw their participation at any time. Additionally, the student letter emphasized that their participation would have no effect on their course assessment. If a high school student's legal guardian consented to allow the student to participate, then the letter stipulated that the student could still decline their assent if desired. The information letters and the informed assent and consent forms are found in Appendices B-L.

The data for my study was collected from the audio recording of the participants and the letters of assent and consent included a statement that indicated audio recording as the data collection method. The participants were assured in the letters that their audio recording would only be used to transcribe their conversation and that only I would listen to the audio. In addition, assurances were made to the participants that their audio recording would be destroyed after the study had been concluded.

3.5.2 Student-Teacher ‘Power Over’ Concerns

For the high school teachers who agreed to participate in my study, their students were invited to be student participants. As a result, it was important for me to ensure that no bias was introduced into the research from the ‘power over’ (Hamre & Pianta, 2006; Jamieson & Thomas, 1974) relationship teachers hold with respect to their students. This bias was minimized by reassuring students that although their teacher is part of the study, the students should not feel compelled to participate and their course grade would not be affected based upon their participation.

To further ensure that students were comfortable and were not influenced by the ‘power over’ dynamic of their physics classroom, students were interviewed outside of regular class time either during a lunch break or before or after school. The teachers and the university professors were also interviewed at a time that was convenient for them. All attempts were made to ensure that the interview participants were comfortable and that their participation was voluntary. No coercion was used to recruit participants and no deception was used during the interview process.

3.5.3 Confidentiality and Ethical Treatment of the Data

The data for my study was treated ethically by ensuring the anonymity of the data collected from the students, teachers, and professors. The interview data was kept confidential by using pseudonyms and the data was kept in a secure area during the research. The research data, which included the audio recorded interviews, the electronic transcripts of the interviews saved on a computer hard drive, and the printed transcripts were all kept secure and confidential by storing this data in a locked cabinet. Finally, all the research data will be destroyed after a prescribed period of time as per the University of Alberta requirements.

3.5.4 Ethics Approval

Two ethics approvals were obtained for my study, one from the University of Alberta and one from the University of Winnipeg. Two ethics approvals were necessary because some of the research data was collected at the University of Winnipeg Collegiate Division in Winnipeg, Manitoba.

The University of Alberta ethics approval was granted for the study Pro00061042 and the ethics was valid from May 24, 2016 to May 23, 2017. The University of Alberta granted approval for the participant information letters and for the informed assent and consent letters. The ethics approval from the University of Winnipeg was granted on June 29, 2016 and provided the researcher with permission to contact students and teachers at the University of Winnipeg Collegiate Division for the purpose of inviting them to participate in the study. The ethics approval for my study may be found in Appendix M, N, and O.

3.6 Data Analysis

In the following five sections, my phenomenographic data analysis is discussed. First, I describe the process of data analysis used by some phenomenographic researchers. Second, I present some of the literature regarding how categories of description are developed from the data. Third, I devote a section to maximizing transparency in the phenomenographic data analysis process. Fourth, I present my data analysis process. Finally, the process of bracketing is explained and involves the researcher setting aside assumptions and biases.

3.6.1 Phenomenographic Data Analysis from the Literature

This section describes the process of data analysis used by some phenomenographic researchers in the literature. The phenomenographic data analysis process according to Åkerlind (2005b) is “a continual process of iterating between a focus on parts and on wholes” (p. 120). I describe the phenomenographic data analysis process used by Aflague and Ferszt (2010) because I employed their data analysis process to analyze my data.

Aflague and Ferszt (2010) examined suicide assessment by psychiatric nurses and provide a list of seven analytical steps that researchers should consider when attending to the iterative and interpretive process of phenomenographic data analysis. This iterative process of phenomenographic data analysis represents a methodological aspect of Marton’s (1986) phenomenographic research tradition. The seven steps include the following: (1) familiarization, (2) condensation, (3) comparison, (4) grouping, (5) articulating, (6) labeling, and (7) contrasting.

The first step in the data analysis process presented by Aflague and Ferszt (2010) is ‘familiarization’ and refers to a process where the audio is transcribed, and these transcripts are read a number of times while the researcher listens back to the audio. The second step is ‘condensation’ and refers to the process where significant statements are given a short but representative version of the complete dialogue concerning the phenomena. The third step is ‘comparison’ and refers to the process where selected excerpts of significant subject responses are compared to find sources of agreement or variation. The fourth step is ‘grouping’ and involves putting statements together that appear to be similar. The fifth step is ‘articulating’ and at this stage of the analysis an attempt is made to describe the essence of the similarity within each group of subject responses. At this stage ‘grouping’ and ‘articulating’ may be repeated several times. The sixth step involves ‘labeling’ and at this stage of the analysis categories are denoted by constructing a representative linguistic expression for each category. Finally, the seventh step represents ‘contrasting’ where the categories are compared for any similarities and differences (Aflague & Ferszt, 2010).

The result of the seven steps of the phenomenographic data analysis is a set of categories of description. Once these categories are determined, they are reapplied to the data from which they originated, and a judgement is made in each individual case concerning what categories of description they are applicable to (Marton 1994). Finally, once the categories of description have been finalized, the researcher can “obtain the distribution of the frequencies of the categories of description” (Marton 1994, p. 4428). The following section provides some of the literature that describes how categories of description are determined from the data analysis process.

3.6.2 Development of Categories of Description from the Literature

When writing about the phenomenographic analysis of phenomenographic interview data, Dahlin (1999) describes that “if the analysis is based on interview transcriptions, statements and expressions of direct relevance to the experience being investigated” (p. 195) then this data is marked, indexed and compared with each other. The meaning of each of the statements made by participants is then considered in relation to the context of the interview in which it belongs and to the context of all the interviews taken as a whole (Dahlin, 1999). The interview context is important "because the same verbal expression may mean different things in different interviews" (Dahlin, 1999, p. 195) while the context in relation to all the interviews taken together is "necessary in order to make the comparisons and see the variations" (p. 195).

When developing categories of description, Marton and Booth (1997) suggest that there are "certain criteria for the quality of a set of descriptive categories" (p. 125). The first criterion is that the "categories should each stand in clear relation to the phenomenon of the investigation so that each category tells us something distinct about a particular way of experiencing a phenomenon" (Marton & Booth, 1997, p. 125). The second criterion is that "the categories have to stand in a logical relationship with one another, a relationship that is frequently hierarchical" (Marton & Booth, 1997, p. 125). Although the relationship between the categories is frequently hierarchical, Åkerlind (2005a) sates "the structure of an outcome space need not always take the form of a linear hierarchy of inclusiveness" (p. 329) and Dahlin (2007) adds that "it may be observed that not all phenomenographic outcome spaces have a hierarchical structure of dimensions of variation" (p. 336). Finally, the third criterion states that as few categories should be explicated as is possible in order that the variation in the data is captured (Marton & Booth, 1997).

The potential hierarchical structure of the categories of description is defined "in terms of increasing complexity, in which the different ways of experiencing the phenomenon in question can be defined as subsets of the component parts and relationships within more inclusive or complex ways of seeing the phenomenon" (Marton & Booth, 1997, p. 125). Although Marton and Booth (1997) suggest that the relationship between the categories of description is "frequently hierarchical" (p. 125), Green (2005) cautions that novice phenomenographers should not make this assumption. Instead, Green (2005) suggests that the relationships between the categories should be "represented in the way they are found in the transcript data rather than simply through some reflective, logical analysis by the researcher" (p. 43). Green (2005) adds that the hierarchy should not be based on value judgements of ways of understanding, whether better or worse, but on evidence of some categories being inclusive of others.

Therefore, the data for my study was indexed, tabulated, and compared between transcripts of the same group. The categories of description described distinctions about what it means to understand physics, the categories stood in a non-hierarchical relationship with one another, and as few categories were explicated in order that the variation in the data was captured. I did not impose a structure on the data but rather the structure between the categories of description emerged from the data.

3.6.3 Maximizing Transparency

Transparency in qualitative research data analysis is necessary for accountability especially in a doctoral dissertation (Bringer et al., 2002). I advocate that qualitative research presented in a doctoral dissertation should illuminate the research process by providing a rich description of the data analysis, in order to move away from the ambiguity in the description of some qualitative research (Anfara et al., 2002). I am further supported by Anfara et al. (2002) who, "call for the public disclosure of methods dealing with careful data cataloguing, cross-referencing and tabulation" (p. 34) such as a "matrix of findings" (p. 34). This section provides the reader the opportunity to become informed with the details of my qualitative data analysis process in the hope that it will provide clarity and serve as an exemplary section for future candidates pursing a qualitative research dissertation.

The goal of my study was to describe and analyze the participants' conceptions of what it means to understand physics. Multiple iterations of data analysis were performed to describe the participants' conceptions of what it means to understand physics and the variations or the qualitatively different ways the phenomenon was experienced by the group. The following section provides the detailed process of my data analysis.

3.6.4 My Process of Data Analysis

As described in the previous section, I have based my interpretive an iterative phenomenographic data analysis on the process presented by Aflague and Ferszt (2010).

In the first stage of my data analysis or the 'familiarization' stage, "the audiotapes [were] transcribed and the transcripts [were] read a number of times while listening to the audio tape" (Aflague & Ferszt, 2010, p. 250). Following transcribing the interviews, I printed a hard copy of each anonymous transcript and read and re-read it many times. The importance of reading and re-reading the interview transcripts and maintaining a matter of focus with the reading is made apparent by Åkerlind (2005a). Åkerlind (2005a) suggests reading "all the transcripts many times-at least six and sometimes a dozen times" (p. 328) because "on each occasion, some new perspective is being sought in order to clarify what the participant means" (p. 328). The necessity of multiple readings of the interview transcript is explained by Åkerlind (2005a) as follows:

> The multiple readings are necessary in order to explore all possible perspectives and because whenever an aspect is being queried it must always, I believe, be explored with reference to the whole transcript rather than one small section of it. (p. 328)

I alternated between searching for similarities and differences in the overall meaning of each transcript and as I read, I searched for 'dimensions of variation' in the meaning that ran throughout each transcript (Åkerlind, 2005b). As the number of transcripts that I read increased, I was able to identify 'themes of expanding awareness' that ran throughout the groups of transcripts as a whole, where each of these themes could be potentially linked to a set of different dimensions of variation (Åkerlind, 2005b).

I was able to conduct a few interviews per week and at any given time I only had several interviews to transcribe and read. The interview schedule was based upon participants availabilities, which facilitated my having a combination of student, teacher, and professor interviews to read at any one time. I was teaching full time as I conducted the interviews and as a result, I set aside my reading of the transcripts for weeks at a time. By setting the interviews aside for this extended period, each time I came back to the interviews I had different questions and thoughts about the interviews than those I had originally had upon my first reading.

In the second stage of the analysis or the 'condensation' stage, "the most significant statements are given a short but representative version of the complete dialogue concerning the phenomena of interest" (Aflague & Ferszt, 2010, p. 250). Marton (1986) describes this stage of the analysis as "the phenomenon in question is narrowed down to and interpreted in terms of selected quotes from all the interviews" (p. 42). Researchers often utilize computer-assisted qualitative data analysis software packages to aid in data management and I used Microsoft Excel 2011 (Microsoft Corp., Redmond, WA) for my data management. Following the highlighting of selected quotes in the computer text files and on the printed transcripts, I made a 'data catalog' (Anfara et al., 2002) that combined all the quotes from each group into Microsoft Excel 2011 spreadsheets (see Appendix P: Sample Data Catalog of Students' Interviews,

Appendix Q: Sample Data Catalog of Teachers' Interviews, and Appendix R: Sample Data Catalog of Professors' Interviews). I found that the Excel spreadsheets provided excellent data management and provided me the opportunity to see all the selected quotes for each potential conception at once.

Appendix P contains a sample data catalog for the students' interviews, Appendix Q contains a sample data catalog for the teachers' interviews, and Appendix R contains a sample data catalog for the professors' interviews. Each of these data catalog spreadsheets contain the following information: participant number, interview number, a conception, the page the conception was found on in the transcript, and examples of the conception from the participants' direct quotes. If a participant reported a conception multiple times, then each of the quotes for the corresponding conceptions were added to the Excel spreadsheet in a horizontal cell.

For example, in Appendix P, for student one, interview twenty, the conception 'solve questions' is found on page two and page four of the transcript. The quote was highlighted in orange if I thought the quote had potential to be used as an exemplar when describing this conception. For student one, five conceptions are shown in blue (solve questions, teach others, remember formulas, derive formulas, and apply) and their corresponding quotes are shown next to each conception. If multiple quotes referred to a given conception, then each of these occurrences was saved in a corresponding horizontal cell. For example, for student one, the conception 'teach others' can be found on three different occasions, on page two, page four, and page seven of this student's transcript. Since there are twenty-two student interviews there are twenty-two such delineations in the Excel spreadsheet for the student group. This process was repeated for the teachers and the professors. The process of organizing all the significant quotes in this way provided me with immediate access to the text I highlighted in the corresponding transcribed interviews.

In the third stage of the data analysis, or the ‘comparison’ stage, “the selected significant dialogue excerpts are compared in order to find sources of variation or agreement” (Aflague & Ferszt, 2010, p. 250). In order to compare all the significant quotes that resulted in conceptions, I made another Excel spreadsheet that combined all of the conceptions from every interview within each group (see Appendix S: Matrix of Students’ Conceptions, Appendix T: Matrix of Teachers’ Conceptions, and Appendix U: Matrix of Professors’ Conceptions). These tabular strategies “are introduced for use in documenting the relationship between data sources and a study’s research questions, and the development of themes and categories” (Anfara et al., 2002, p. 28). Appendix S represents the matrix of students’ conceptions, Appendix T represents the matrix of teachers’ conceptions, and Appendix U represents the matrix of professors’ conceptions.

For example, in Appendix S, the student conceptions that emerged from each interview are documented in a matrix form. Each of the matrix columns represent each of the conceptions for a particular student and similar conceptions have been color coded throughout the Excel spreadsheet. The matrix rows represent the number of conceptions for each student. For example, for student one, the first column is labelled student 1.20 where the one refers to the participant number and the twenty refers to the interview number. For student one, there are five rows representing five different conceptions for this student’s interview and include solve questions (lime green), teach others (pink), remember formulas (white), derive formulas (dark blue), apply (yellow), and feelings/insight (white with a black border). The solve questions cell is colored lime green and every lime green cell in the spreadsheet represents this conception. By color coding the conceptions in this way, I could compare the conceptions and get a sense of the distribution of all the conceptions throughout the interviews for each group. Marton (1994) suggests that once the categories of description have been finalized, the researcher can "obtain the distribution of the frequencies of the categories of description" (p. 4428).

In the fourth stage of the data analysis, or the 'grouping' stage, "answers that appear to be similar are put together" (Aflague & Ferszt, 2010, p. 250). I took each of the conceptions from Appendix S, T, and U and made another Excel spreadsheet for each of the groups' conceptions. Appendix V demonstrates all of the students', teachers', and professors' conceptions combined into one Excel spreadsheet. Having all the conceptions for the students, teachers, and professors in one 'matrix of results' (Anfara, 2002) helped me to visualize all the conceptions and helped me to identify any similar or different potential categories of description between each group.

Appendix V was read and re-read many times to determine which of the conceptions could be grouped together or which of the conceptions could remain separate for each of the students, teachers, and professors. Marton (1986) provides guidance for this stage of the analysis when he writes "definitions for categories are tested and against the data, adjusted, retested, and adjusted again. There is, however, a decreasing rate of change, and eventually the whole system of meanings is stabilized" (p. 28). As Marton (1986) suggests in the 'grouping' stage, I attempted to stabilize the meanings for the conceptions that had emerged from the data analysis for each of the groups.

As this stage progressed, I read and re-read the interviews and tried to provide a label for the categories of description that the conceptions could be organized into. Aflague & Ferszt (2010) describe this stage in the data analysis as the 'labeling' stage where "the various categories are denoted by constructing a suitable linguistic expression." (p. 250). Once a label was finalized for a category of description, a map of conceptualization was drawn that represented the structure for the category of description and represented how the category of description logically related to the subcategories of description.

These maps of conceptualization were hand drawn on large sheets of 22 x 34 paper (four 11 x 17 sheets taped together) where the conceptualization and variations in the conceptualization could be visualized. An example of one version of my hand drawn maps of conceptualization for the students, teachers, and professors may be seen in Appendix W. For each category of description, lines radiate from the category of description to corresponding subcategories. Each of the subcategories also have lines radiating from them that include a description of the subcategory, further clarification, and examples of some of the participants' interview responses.

The conceptualization maps led to a refinement of each groups' outcome space, as the subcategories of description within each became clear. As subcategories of description were modified for each of the groups, a new updated map of conceptualization was redrawn for every change. The maps of conceptualization helped to visually display the logical relationships between the subcategories of description and the category of description it belonged to in the outcome space. Once the categories of description and the subcategories of description were finalized, I used the mind mapping software 'DRAWIO' (Diagrams.net, 2020) to produce computerized maps of conceptualization (see Appendix X, Y, Z).

Finally, a circular outcome space was proposed that described the link between the categories of description and represents the last stage of my data analysis (see Figure 21, Section 4.6). The proposed circular and holistic structure of the students', teachers', and professors' outcome space is discussed in Section 4.6.

3.6.5 Bracketing

Bracketing is the "need for the researcher to set aside his or her own assumptions, in order to document the interviewee's own point of view" (Ashworth & Lucas, 2000, p. 298). Ashworth and Lucas (2000) further describe some of the presuppositions the researcher must bracket, and these include the researcher's personal knowledge and beliefs, the assumption of particular interpretations or theoretical structures, and the use of earlier research findings. After the interviews have been transcribed and the analysis has begun, Marton (1994) emphasizes the importance of bracketing the presuppositions in phenomenographic research and he suggests the following:

> It is the researcher who is supposed to bracket preconceived ideas. Instead of judging to what extent the responses reflect an understanding of the phenomenon in question which is similar to their own, he or she is supposed to focus on similarities and differences between the ways in which the phenomenon appears to the participants. (Marton, 1994, p. 4428)

Although bracketing may only be partially successful according to Ashworth & Lucas (2000) the suggestion is made by Karlson (1993) that through empathy, the researcher may greatly assist the process of bracketing.

I am a former high school physics teacher, a current instructor of pre-service physics teachers in a Faculty of Education, and I am a content area specialist in high school physics. Walsh (2000) suggests that the content area specialist must be aware that his or her content area specialization may bias the analysis when reading the data. In addition, Walsh (2000) contends that the most important skill a phenomenographer possesses is the ability to "bracket one's own perceptions and being able to read the data for the ways in which the interviewees are understanding the phenomenon" (p. 32).

Therefore, since I am a high school physics content area specialist and physics educator, I bracketed the following as best as I could. I attempted to bracket my personal knowledge about physics content, physics teaching, particular interpretations and theoretical structures that have been read in the literature, and previous research that investigated phenomenographic studies related to physics student understanding.

3.6.6 Summary

An iterative and interpretive process was used to analyze the interview data for my study and involved a continual process where the parts and the whole were iterated between each other. Marton, et al. (1993) suggest "the analysis has to be of an iterative and genuinely interpretative nature" (p. 282) and Barnacle (2005) suggests "the interpretive process in the phenomenographic approach is devoted to the task of formulating categories of description" (p. 251). Furthermore, Marton et al. (1993) refer to the iterative and interpretive process of phenomenographic analysis as "the hermeneutics of phenomenography" (p. 282). At the final stage of analysis, maps of conceptualizations were drawn and represent the logical connections between the categories of description and the corresponding subcategories of description (see Appendix X, Y, and Z).

Lastly, the structural relationships between the categories of description were described in an outcome space that graphically represented the unique relationships that existed in the data, refer to Figure 21 in Section 4.6.

3.7 Quality Considerations

In the following sections, the quality considerations for my study are described. The trustworthiness of the research methodology is examined and how I addressed credibility, transferability, dependability, and confirmability (Guba & Lincoln, 1989) is described.

3.7.1 Trustworthiness

In traditional or rationalistic research approaches, validity, reliability, and generalizability have reached the status of a “scientific holy trinity” (Kvale, 1996, p. 229) that distinguish quantitative research from qualitative research. However, in naturalistic research approaches with an interpretivist epistemology, trustworthiness has developed to become an alternative for measuring the value of the research and a way to provide rigour in the research process (Collier-Reed et al., 2009).

In arguing for the trustworthiness of qualitative research, Guba (1981) and Guba and Lincoln (1989) brought in the notions of credibility, transferability, dependability, and confirmability as the appropriate measures to establish rigour in qualitative research. By making trustworthiness the alternative construct to adopting both validity and reliability, there is an obvious difference in assumptions about how the world is constituted for qualitative and quantitative research paradigms (Collier-Reed et al., 2009). Quantitative researchers seek prediction, causal determination, and the generalization of research findings by quantitative measurement and experimentation. By contrast qualitative researchers seek understanding, illumination, and the extrapolation to similar situations by using a naturalistic approach in context-specific settings (Collier-Reed et al., 2009).

3.7.2 Credibility

According to Guba and Lincoln (1989), credibility refers to the idea of “isomorphism between constructed realities of respondents and the reconstructions attributed to them” (p. 236) where ‘isomorphism may be defined as being of identical or similar form. What this means is that instead of focusing on a ‘real’ reality, the focus is on the match between the constructed realities of the research participants and the reality represented by the researcher and attributed to the participants (Guba & Lincoln, 1989).

In my study, credibility was achieved through the following six criteria advanced by Guba and Lincoln (1989) and include: (1) prolonged engagement, (2) persistent observation, (3) peer debriefing, (4) negative case analysis, (5) progressive subjectivity, and (6) member checking.

First, I achieved prolonged engagement by conducting seventy-three interviews which constituted “substantial involvement at the site of the inquiry” (Guba & Lincoln, 1989, p. 237). This ‘substantial involvement’ was further achieved as the interviews ranged in length from twenty to forty-four minutes. The length of the interviews served to establish rapport with the participants and build trust. According to Guba and Lincoln (1989), this trust and rapport is necessary to uncover constructions and to facilitate the researcher understanding the context’s culture.

Second, according to Green (2005), persistent observation relates to the researcher looking for patterns within the data. Since interviews were the sole data collection method for my study, the seventy-three interviews provided me with enough observations to allow patterns to emerge and categories of description to be described. The large number of interviews for my study allowed me to “identify those characteristics and elements in the situation that are most relevant to the problem or issue being pursued and [to focus] on them in detail” (Lincoln & Guba, 1986, p. 304).

Third, peer debriefing allowed me to discuss “the research with a critical but a disinterested peer in order to keep the researcher honest” (Green, 2005, p. 44). Guba and Lincoln (1989) describe the importance of the peer debriefing process in that it affords the researcher the opportunity to discuss "one's findings, conclusions, tentative analyses" (p. 237) and it allows the researcher to test out working hypotheses. I was able to participate in peer debriefing with my thesis advisor and we discussed the findings, conclusions, and the analysis that resulted from the data.

Fourth, the negative case analysis is the "search for data that contradicts the findings" (Green, 2005, p. 44). In my study, this negative case analysis was achieved through "devils' advocacy" (Cherry, 2005; Green, 2005). This 'devil's advocacy' process encourages critical debate amongst other researchers where other possible meaning-structures for the outcomes of the research may be discussed amongst the researchers (Åkerlind, 2005b; Cherry, 2005; Åkerlind et al., 2005). Through this process, the sum of the research group is seen as greater than the individual researcher's interpretation. Although my study did not involve a research group, I did rely upon my thesis advisor when undertaking the 'devil's advocacy' process.

Fifth, progressive subjectivity is a process of monitoring the researcher's developing construction of the data as the research progresses (Guba & Lincoln, 1989). For my study, this process began with me writing down initial constructions of the data on large pieces of paper and at regular intervals, developing constructions were added to avoid the feeling of being constrained to the initial constructions. The constructions I focused on were the conceptions and possible categories of description about what it means to understand physics. According to Guba and Lincoln (1989), if the researcher "affords too much privilege to the original constructions (or to earlier constructions as time progresses), it is safe to assume that he or she is not paying attention to the constructions offered by other participants as they deserve" (p. 238). Guba and Lincoln (1989) suggest that if the researcher finds only what he or she expected initially, then the researcher must recognize that he or she has become ‘frozen’ on some immediate construction and the analysis should be re-examined so that credibility does not suffer.

Sixth, member checking occurs when the researcher takes “the data back to participants for verification” (Green, 2005, p. 44) and the participants are encouraged to add comments or edit the transcript data for example. In phenomenography, the focus is not on the individual participant but rather the outcome space that goes across individuals in the form of categories of description. Therefore, member checking was not used for my study.

Based upon Guba and Lincoln’s (1989) credibility criteria, my study attended to prolonged engagement, persistent observation, peer debriefing, negative case analysis, progressive subjectivity, but not member checking.

3.7.3 Transferability

Transferability may be thought of as parallel to generalizability or external validity and “requires both sending and receiving contexts to be at least random samples from the same population” (Guba & Lincoln, 1989, p. 241). What this means is that for transferability to be established in a study, the researcher must provide evidence that the research results could be applicable to other situations, contexts, or populations. Lincoln and Guba (1985) write that “it is, in summary, not the naturalist’s task to provide an index of transferability, it is his or her responsibility to provide the data a base that makes transferability judgements possible on the part of potential appliers” (p. 316). Therefore, for the researcher to provide data that makes transferability possible, Guba and Lincoln (1989) suggest that a “thick description” (Guba & Lincoln, 1989, p. 241) of the data should be undertaken. A ‘thick description’ of the data means that the researcher seeks to provide a comprehensive range of assertions from the study and a careful description of the study's time, place, context, and culture. According to Sin (2010), if the motivation of a phenomenographic study is transferability then it is important that the research design "considers the possible contexts and the extent in which the findings can be usefully applied at the outset of the study and also in determining the scope and adequacy of the selection of participants" (p. 309).

Therefore, for my study, I relied upon a 'thick description' of what the participants reported about what it means to understand physics. I have developed the categories of description and the resulting outcome space to provide substantial reference information for the reader because it is the reader who determines transferability via the descriptions provided by the author.

3.7.4 Dependability

Dependability, "is parallel to the conventional criterion of reliability, in that it is concerned with the stability of the data over time" (Guba & Lincoln, 1989, p. 242). For my study, dependability was optimized by examining two types of reliability checks for qualitative research that utilized interviews. These two reliability checks are referred to in the literature as coder reliability and dialogic reliability checks (Åkerlind, 2012). Both of these reliability checks use several researchers and are appropriate for phenomenographic research because the phenomenographic method also uses interview data. The reliability checks help to offset the potential impact that one researcher may have when evaluating the interview data and multiple researchers are a way to ensure reliability. For my study, I ensured reliability by including my thesis advisor in the analysis of the interview data. In the following two sections, coder reliability and dialogic reliability are described.

3.7.4.1 Coder Reliability

Coder reliability is described as the process where different researchers independently code interview transcripts and then compare their categorizations (Åkerlind, 2012). Kvale (2009) refers to this coding as "arithmetic intersubjectivity" (p. 243) and describes it as the measure of reliability by the amount of agreement that exists between independent observers, while Cope (2004) refers to it as "interjudge communicability" (p. 10). Sandbergh (1997) defines coder reliability as "interjudge reliability" (p. 206) and describes the process applied to phenomenography as "a form of replicability in the sense that it gives a measurement of the extent to which other researchers are able to recognise the conceptions identified by the original researcher, through his/her categories of description" (p. 205).

Marton (1986) argues that the results of the phenomenographic findings should be replicable but suggests there are two issues of concern with this process. The first issue is the "process of discovery" (Marton, 1986, p. 35) and this involves the ability of other independent researchers being able to find the same conceptions and categories of description in the data when performing the research for the first time. The second issue is whether a category or conception would be recognized by others once it was described to them by the original researcher. However, Marton (1986) argues for replicability of phenomenographic results in the second case rather than the first. In arguing for the second case, Marton (1986) contends that the original findings for the categories of description is a form of 'discovery' and these discoveries do not have to be replicable. Further, Marton (1986) suggests that "once the categories have been found, it must be possible to reach a high degree of intersubjective agreement concerning their presence or absence if other researchers are to be able to use them" (p. 35). Therefore, what Marton (1986) is suggesting is that no one necessarily requires different researchers to discover the same categories from the data independently. However, once these categories are discovered, there should be agreement between researchers about their presence or absence.

Säljö (1988) refers to the use of interjudge reliability in phenomenographic research as measuring "the communicability of categories and thus gives the researcher information that someone else can see the same differences in the material as he or she has done" (p. 45). Walsh (2000) also argues for interjudge reliability by using the method of giving the phenomenographic categories to other researchers. The researchers are asked to classify the set of transcripts against the set of categories and to confirm a process of discovery. Walsh (2000) describes this process as follows:

> And so, a different researcher might come to the same data [and] could construct another set of categories . . . You don't ask someone else to take your transcripts away and identify the categories and then see how that person's categories matches yours because it's not necessary that person should construct the same sort of categories. What we do is . . . give someone else our descriptions of our categories and ask that [person] . . . to look at the transcripts to see if they [can] . . . categorise them. You don't have to replicate the discovery process for it to be discovery but rather you need to establish the reliability of the results by indicating that somebody else can categorise the transcripts [not necessarily in the same way as you have]. (p. 24)

Sandbergh (1997) suggests that interjudge reliability is "an unreliable way of establishing reliability of phenomenographic results" (p. 211) for two reasons. The first reason is that the interjudge reliability does not consider the researcher's procedures for achieving the 'fidelity' of the conceptions being investigated. Sandbergh (1997) suggests that this means that the researcher may have obtained poor data about the participant's experience of the phenomenon because the researcher may have their own pre-understandings. The categories of description would therefore be influenced by the researcher's pre-understandings making the categories easy to recognize by other co-judges. The second, and most fundamental reason, is that interjudge reliability is based on an objectivistic epistemology and gives rise to methodological and theoretical inconsistencies within phenomenography (Sandbergh, 1997). What this means is that from on objectivist epistemology, knowledge exists within reality itself and the reliability problem exists with the need to check the researcher's subjectivity in producing knowledge (Sandbergh, 1997). In this way, a researcher may have biased the results because his or her subjectivity may not represent the aspect of reality investigated in an objective manner (Sandbergh, 1997). Therefore, the alternative that Sandbergh (1997) presents for ensuring reliability with the phenomenographic results is through the researcher using interpretive awareness.

The interpretive awareness that Sandbergh (1997) is arguing for means that the researcher must both acknowledge and attend to their subjectivity throughout the research process rather than overlooking it. Cope (2004) describes Sandbergh's (1997) interpretive awareness as the requirement of the researcher to be aware of their interpretations during the research process and to be able to demonstrate how the interpretation process was checked and controlled for. However, the use of interjudge reliability in phenomenography is not a test to be used to determine whether other researchers can come up with the same phenomenographic outcome space. Rather, interjudge reliability should be a means to ensure the reliability of the description of the outcome space determined by the researcher (Cope, 2004).

Therefore, to ensure coder reliability for the categories of description for my study, my thesis advisor and a University of Manitoba qualitative researcher were used to confirm the data analysis. These co-judges examined my conceptions and categories of description to determine if they could recognise them within the data. Each conception and category of description was scrutinized by my thesis advisor and the qualitative researcher to reach a high degree of intersubjective agreement concerning their presence or absence.

3.7.4.2 Dialogic Reliability

Dialogic reliability checks are advocated by Trigwell (2000), Prosser (2000), and Bowden (2000b).The dialogic reliability check refers to the agreement between researchers as being "reached through discussion and mutual critique of the data and of each researcher's interpretive hypotheses" (Åkerlind, 2012, p. 125). Kvale (1996) refers to this as "dialogical intersubjectivity" (p. 65) and describes this reliability check as the "agreement through a rational discourse and reciprocal critique among those identifying and interpreting a phenomenon" (p. 65). Kvale (1996) further asserts that this reliability check is referred to as communicative validation among researchers and their research participants.

During the process of dialogic reliability, only one researcher is responsible for analyzing the interview transcripts and determining the categories. The categories of description are then confirmed through an iterative process where further discussion within the research group "leads to new insights" (Bowden, 2000b, p. 57). Bowden (2000b) suggests that the group discussions help in consolidating category conclusions and allows a researcher's category proposal to be challenged by the group thereby allowing for further critique. Through this challenge process, the categories of description are either consolidated or modified depending on the consensus of the group.

Green (2005) recognizes that some phenomenographers may choose to work alone but suggests that the team option is preferable since "there is a high level of intellectual engagement, critique, and rigorous checking of data within such team dynamics" (p. 43). Bowden (2000b) agrees and adds that "I don't believe I would have achieved the same outcomes and I believe the categories of description developed alone would be less accurate than those developed by the group" (p. 59). Further, Bowden (2000b) argues that the group process should be a normal feature of phenomenographic analysis.

I address the process of dialogic reliability by having had my categories examined by my thesis advisor and a University of Manitoba qualitative researcher. In this way, the categories of description that I determined from the interview transcripts had the opportunity to be challenged by these academics and allowed for further critique and refinement.

3.7.5 Confirmability

Confirmability is concerned with assuring that the research data, interpretations, and outcomes "are rooted in contexts and persons apart from the evaluator and are not simply figments of the evaluator's imagination" (Guba & Lincoln, 1989, p. 243). What this means is that the data can be readily located back to their sources and the logic used to formulate the data interpretations is available "to be inspected and confirmed by outside reviewers of the study" (Guba & Lincoln, 1989, p. 243). To confirm the researcher's data interpretations, an audit trail is suggested and is defined as a transparent description of the steps the researcher took in developing and reporting the research findings (Halpren, 1983; Schwandt & Halpren, 1988; Lincoln & Guba, 1985; Cohen & Crabtree, 2006b; Cutcliffe & McKenna, 2004). For a researcher's audit trail, Halpern (1983) suggests including all raw data, all notes, the structures of any categories of the data that were developed, methodological notes, personal notes, and any preliminary notes pertaining to the data analysis.

My audit trail consisted of an Excel file where I made my notes about my data analysis process. This file was named and dated each time I worked on the analysis and was saved on a password protected computer. Having a new file named and dated for each time I worked on the analysis allowed me to look back at previous work to see what had changed in my analysis and any special notes that I had made.

3.8 Summary

In this chapter, the phenomenographic research methodology that was used during my study was described. The phenomenographic research tradition including its history, theoretical and philosophical foundation, and justifications for choosing this research approach were discussed. The overall research process was described, which included: the research participants and setting, data collection procedures, interview methods, research questions, and data analysis. I provided the reader the opportunity to gain insight into the techniques I utilized to achieve my data analysis and I refer to my tabulated data structures and matrices (found in Appendices P-Z) in order to promote transparency in my doctoral dissertation. The ethical considerations were discussed, and the confidentiality, and the ethical treatment of the research data was presented. Lastly, the credibility, transferability, dependability, and confirmability of the phenomenographic research process was described and was designed to meet strict quality controls associated with interpretivist research.

Chapter 4 Results

4.1 Introduction

This chapter presents the results of the analysis of seventy-three interviews that investigated what it means to understand physics from twenty-two physics students, twenty-three physics teachers, and twenty-eight physics professors. First, the referential and structural aspects of the categories of description and subcategories of description are discussed. Second, the students' categories of description, subcategories of description, and outcome space are presented. Third, the teachers' categories of description, subcategories of description, and outcome space are presented. Fourth, the professors' categories of description, subcategories of description, and outcome space are presented. Finally, an outcome space that represents the logical relationship between the categories of description for the students, teachers, and professors is presented and a justification is given for the proposed non-hierarchical relationship between the categories of description.

4.2 Referential and Structural Aspects of the Categories of Description

The categories of description for my study are presented as having referential 'what' aspects and the subcategories of description are presented as having structural 'how' aspects (Marton & Booth, 1997; Trigwell, 2000). Marton and Booth (1997) contend that the referential 'what' aspect of a category of description represents the differences in the overall conceptualizations of the participants' experience for a given phenomenon while the structural 'how' aspect represents the variations in the internal structure of these conceptualizations (Marton & Booth, 1997). What this means for my study is that for a category of description, the referential 'what' aspect refers to the variation in the participants' overall conceptualization of the experience of what it means to understand physics and for a subcategory of description, the structural ‘how’ aspect refers to the variation in the internal structure for a given category of description. For example, I found five different referential ‘what’ aspects, categories of description, and these consist of ‘feelings’, ‘achievement’, ‘communication’, ‘making meaning’, and ‘application’. For the students’ category of description ‘communication’, I found two different structural ‘how’ aspects, subcategories of description, and these include ‘explaining’, and ‘teaching’. Furthermore, Trigwell (2000) refers to the ‘what’ and ‘how’ as “two internally related aspects of a category of description. If you like, an action (how) and the something being acted upon (what)” (p. 97). For example, for the category of description ‘communication’, communication is ‘what’ is being acted upon and ‘explaining’ and ‘teaching’ represent the action or ‘how’ the participants experience communication. In this example, how the students experienced what it means to understand physics as communication is through ‘explaining’ and ‘teaching’.

For each of the three participant groups, five categories of description comprising the outcome space resulted from the data analysis. The five categories of description (referential aspects) are: (1) feelings, (2) achievement, (3) communication, (4) making meaning, and (5) application. Each of these categories of description each contain subcategories of descriptions (structural aspects) that represent variations in the internal structure for a given category of description for each of the participant groups. For each of the participant groups, the following five experiences were described: (1) what it means to understand physics is to experience a feeling, (2) what it means to understand physics is to experience the achievement of a goal or to experience being able to do something that was not possible previously, (3) what it means to understand physics is to experience communicating about physics to other people, (4) what it means to understand physics is to experience making meaning about physics, and (5) what it means to understand physics is to experience applying physics for some purpose.

The individual outcome spaces for the students, teachers, and professors are reported after the results for each group, Table 12, Student Outcome Space (see Section 4.3.5), Table 13, Teacher Outcome Space (see Section, 4.4.5), and Table 14, Professor Outcome Space (see Section 4.5.5). Tables 12, 13, and 14 include the categories of description, subcategories of description, the total number of subcategories, and describe what the 'focus is on' for each of the subcategories of description.

The following sections describe the categories of description, subcategories of description, and outcome space for the students, teachers, and the professors. For my data analysis, the categories of description and their corresponding subcategories of description are presented with illustrative quotes from the data, which is the standard practice in phenomenography (Åkerlind, Bowden, & Green, 2005; Green & Bowden, 2005; Åkerlind, 2005c).

4.3 Student Categories of Description

Physics students experienced and perceived what it means to understand physics in several qualitatively different ways. Five categories of description emerged from the interview analysis and these categories each contained several subcategories. The five qualitatively different categories of description include: (1) what it means to understand physics as feelings, (2) what it means to understand physics as achievement, (3) what it means to understand physics as communication, (4) what it means to understand physics as making meaning, and (5) what it means to understand physics as application.

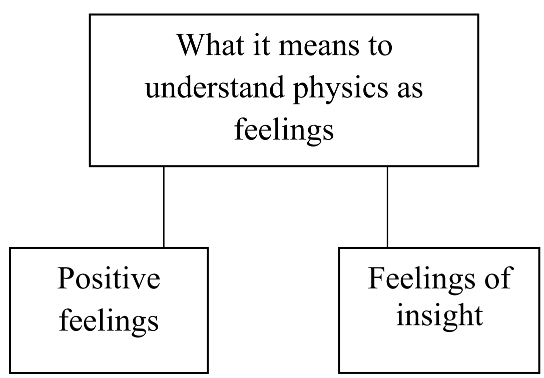
The following sections describe each of the categories of description (referential aspects) and their subcategories of description (structural aspects) with reference to student quotes. Finally, a graphical representation of the students' outcome space for the five categories of description is presented and includes the subcategories of description.

4.3.1 Student Category One: Feelings

In this category of description, students said what it means to understand physics is to experience a feeling. The structure of the feelings category of description can be seen in Figure 6 and contains two subcategories: (1) positive feelings and (2) feelings of insight. Figure 6 represents the structure for the category of description, what it means to understand physics as feelings.

Figure 6

Students: The Structure of What it Means to Understand Physics as Feelings



Entwistle and Entwistle (1992) reported that when students were revising for an examination, they described their experience of understanding as having a feeling associated with it. According to Entwistle and Entwistle "students repeatedly commented that the experience of understanding generally had a feeling tone associated with it - there was necessarily an emotional response, at least where significant understanding had been achieved" (p. 7). Entwistle and Entwistle reported the following positive feelings: feelings of satisfaction, meaning, significance, coherence, connectedness, and wholeness. In addition to these feelings, several students said what it means to understand physics is to experience an 'aha' or a 'eureka' moment. According to Entwistle and Entwistle (1992), this feeling may be considered to represent an insight while Topolinski and Reber (2010) refer to an 'aha' feeling as a feeling of insight.

For my study, students said what it means to understand physics is to experience feelings in two ways. For the subcategory, positive feelings, students said what it means to understand physics is to experience positive feelings such as happiness and enjoyment. For the subcategory, feelings of insight, students said what it means to understand physics is to experience an 'aha' or 'eureka' feeling.

4.3.1.1 Student Subcategory: Positive feelings

In this subcategory of description, students said what it means to understand physics is to experience a positive feeling.

Marc, Brianne, Amelia, Olivia, and Mel said what it means to understand physics is to experience a good, happy, and enjoyable feeling.

> I think understanding means to have a good feeling. (Marc)
>
> I feel happy, a sense of accomplishment. (Brianne)
>
> I'm happy when I understand. (Amelia)
>
> I feel good, I think it's more enjoyable if you understand it. (Olivia)
>
> Understanding means a good feeling, a positive feeling, yes. (Mel)

John stated what it means to understand physics is to experience a positive feeling that can be expressed in the word ‘supercalifragilisticexpialidocious’ from the movie *Mary Poppins*.

> I feel supercalifragilisticexpialidocious! Feels really good. (John)

Michelle stated what it means to understand physics is to experience positive feelings of pride and reassurance.

> What it means I think is you feel proud and you feel a little reassured. (Michelle)

Becky said what it means to understand physics is to experience curiosity and Alice experienced a feeling of relief and relaxation.

> So, when you finally get it it’s, like, ‘Yes!’ I get a feeling of curiosity, wanting to know more. (Becky)

> I feel relief, I don't know. I feel relaxed because it’s like I don't have to go back and put any more effort that I've already put in. (Alice)

In summary, students said what it means to understand physics is to experience positive feelings. Students experienced positive feelings of happiness, enjoyment, confidence, pride, and reassurance.

4.3.1.2 Student Subcategory: Feelings of insight

In this subcategory of description, students said what it means to understand physics is to experience a feeling of insight or an ‘aha’ feeling. The ‘aha’ feeling that students experienced has been referred to in the literature as a feeling of insight (Topolinski & Reber, 2010; Ohlsson, 1984; Knoblich et al., 1999; Öllinger, Jones et al., 2013; Kounios & Beeman, 2014). Topolinski and Reber (2010) describe insight as an ‘aha’ feeling having four characteristics:

> Suddenness (the experience is surprising and immediate), ease (the solution is processed without difficulty), positive affect (insights are gratifying), and the feeling of being right (after an insight, problem solvers judge the solution as being true and have confidence in this judgment). (p. 402)

Students said that their ‘aha’ or ‘eureka’ feelings had the same ‘suddenness’ that Topolinski and Reber (2010) reported. Zhang et al., (2016) also report insight as a ‘suddenness’ and write “insight is defined as a sudden access to a solution by restructuring or changing problem representations” (p. 1).

Although students did not use the word ‘insight’ in their interview responses, I interpreted the word insight as a subcategory of description since the literature describes insight as an ‘aha’ feeling (Topolinski & Reber, 2010).

Carl and Ben stated that what it means to understand physics is to experience a feeling of insight, the ‘aha’ moment. Carl experienced an ‘aha’ feeling and Ben experienced a ‘eureka’ feeling. Carl added that he also experienced a physical feeling of lightness in his stomach when physics made sense to him.

> Understanding means to suddenly have an ‘aha’ moment. I guess like a feeling of lightness in my stomach where this physics actually makes sense. (Carl)

> Yes. It’s like a ‘eureka’ moment. At the same time, it’s more like finally, I know this. (Ben)

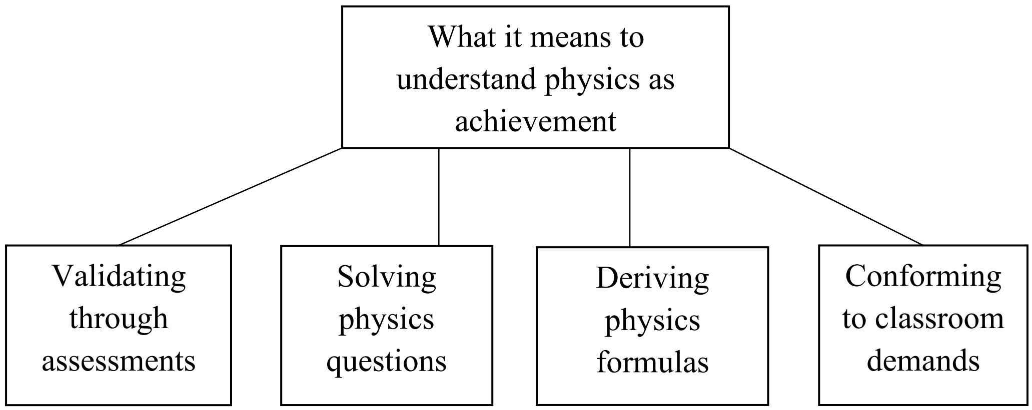
In summary, students said they had a feeling of insight when describing what it means to understand physics. This insight was described by students as an ‘aha’ or a ‘eureka’ feeling.

4.3.2 Student Category Two: Achievement

In this category of description, students said what it means to understand physics is to achieve a goal or to achieve the ability to do something that was not possible before. The structure of the achievement category of description can be seen in Figure 7 and contains four subcategories: (1) validating through assessments, (2) solving physics questions, (3) deriving physics formulas, and (4) conforming to physics classroom demands.

Figure 7

Students: The Structure of What it Means to Understand Physics as Achievement



Students said what it means to understand physics is to achieve a goal or the ability to do something in four ways. For the subcategory, validating through assessment, students said what it means to understand physics is to achieve validation of their physics knowledge through writing assessments such as classroom physics tests. For the subcategory, solving physics questions, students said what it means to understand physics is to achieve the ability to solve physics questions such as textbook physics questions. For the subcategory, deriving physics formulas, students said what it means to understand physics is to achieve the ability to derive physics formulas. Finally, for the subcategory, conforming to classroom demands, students said what it means to understand physics is to achieve the goal of following along and listening to the teacher during instruction.

4.3.2.1 Student Subcategory: Validating through assessments

In this subcategory of description, students said what it means to understand physics is to achieve validation of their physics knowledge by writing assessments such as classroom physics tests.

Mike, Michelle, John, and Marc said what it means to understand physics is to have their physics knowledge validated by writing a test and receiving a grade.

> That's easy to know, understanding means I do really good on the test. Understanding means when I get a good grade. (Mike)

> Sometimes you'll think you understand something but then you won't do well on a test, but then I think understanding means when you do a test and when you're doing it, it's easy, it comes quick, you've finished it early, you get a good grade. So, when you get the test back, I did get a grade of ninety percent, so I understand. (Michelle)

> Wow, when I can get a good grade on a test. (John)

> I think understanding physics means that it's reflected in your grade on a test. So how much you understand something, how much you've put time into it, how dedicated you are to understanding physics, that is all reflected in your grade. (Marc)

In summary, students said what it means to understand physics is to achieve validation of their physics knowledge by writing a physics test. The students also stated that their grade could reflect the amount of time they spent studying.

4.3.2.2 Student Subcategory: Solving physics questions

In this subcategory of description, students said what it means to understand physics is to achieve correct solutions when completing the task of solving physics questions and being able to select the correct formula when solving a physics question.

Harry, Jim, Olivia, Becky, and Alex said what it means to understand physics is to achieve the ability to correctly solve physics questions.

> Understanding physics means you can solve physics textbook questions. (Harry)
>
> If I end up with the correct answer to a question, that is what it means to understand physics. (Jim)
>
> Understanding means doing worksheets and stuff and when you are finally able to do questions correctly. (Olivia)
>
> Understanding means trying the textbook questions and getting the answers correct. (Becky)
>
> Understanding means when I'm able to solve the physics questions I'm given. (Alex)

Irma, Brianne, and Dean said what it means to understand physics is to select the correct formula to solve a physics question.

> I think understanding means when I can solve physics questions and I immediately know what equation I need to use. (Brianne)
>
> But in grade twelve, understanding means you know what formula to use to solve the question. You can analyze the formula using any variable and solve the question. (Irma)

In summary, students said what it means to understand physics is to achieve the ability to solve physics questions and to select the correct formula to solve physics questions.

4.3.2.3 Student Subcategory: Deriving physics formulas

In this subcategory of description, students said what it means to understand physics is to achieve the ability to derive physics formulas.

Amelia and Olivia stated what it means to understand physics is to derive physics formulas. Amelia said understanding physics means she can derive formulas while Olivia said understanding physics means deriving a physics formula from a graph.

> Most of what it means to understand physics is that you can derive formulas. (Amelia)
>
> Understanding means to derive physics formulas and how to get the correct end result formula overall. [It's] as basic as deriving an equation from a graph. (Olivia)

In summary, students stated what it means to understand physics is to achieve the ability to derive physics formulas.

4.3.2.4 Student Subcategory Four: Conforming to classroom demands

In this subcategory of description, one student said that what it means to understand physics is to achieve the goal of conforming to the demands of the physics classroom and the demands of the teacher. These demands include following along with the teacher in class, listening to the teacher in class, and doing all the physics examples the teacher writes on the board.

Alex stated what it means to understand physics is to follow along with the teacher, listen to the teacher, and doing all the physics examples provided by the teacher on the board. Alex said understanding physics means conforming to the demands placed on him by the teacher in the physics classroom.

> What it means to understand physics is being able to follow along, listen, and keep up with the teacher. Understanding physics means following along with all the questions, if you're following along in class and listening to the teacher and doing all the physics examples that are down on the board. (Alex)

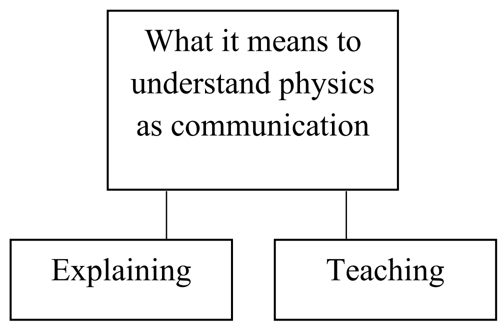
In summary, one student said what it means to understand physics is to conform with the demands of the teacher during classroom instruction. These classroom demands include following the teacher, listening to the teacher, and completing physics examples the teacher provides on the board.

4.3.3 Student Category Three: Communication

In this category of description, students said what it means to understand physics is to communicate physics with other people. The structure of the communication category of description can be seen in Figure 8 and contains two subcategories: (1) explaining, and (2) teaching.

Figure 8

Students: The Structure of What it Means to Understand Physics as Communication



Students said what it means to understand physics is to communicate physics in two ways. For the subcategory, explaining, students said what it means to understand physics is to communicate a physics concept in more detail by providing information to make physics concepts clearer. For the subcategory, teaching, students said what it means to understand physics is to communicate physics through the transmission of knowledge where information or skills are imparted to the learner.

4.3.3.1 Student Subcategory: Explaining

In this subcategory of description, students said what it means to understand physics is to communicate physics by explaining. The Cambridge Online Dictionary defines the word 'explain' as "to make something clear or easy to understand by describing or giving information about it" ("Explain", 2019a). Similarly, Merriam-Webster.com defines the word 'explain' as follows: "1a: to make known, b: to make plain or understandable, 2: to give the reason for or cause of, 3: to show the logical development or relationships of" ("Explain", 2019b). Therefore, based upon these definitions, when students are explaining they are making physics clear, plain, and understandable by describing physics and providing information about physics.

Alice, Carl, Marc, Annie, and Harry said what it means to understand physics is to explain physics.

> Understanding physics means I'd be able to back up what I learned and explain what it is… having a conversation about physics. (Alice)
>
> Physics is also how you can explain what you've learned, and I think that's what it means when it's understood. (Carl)
>
> Understanding means when I'm able to explain physics to others. I can explain my own understanding and thereby reinforce my own ideas on the subject. (Marc)
>
> I guess with all these questions, I think understanding physics means being able to explain it. (Annie)
>
> When you can explain physics to other people. (Harry)

In summary, students said what it means to understand physics is to communicate physics through explanation. By explaining physics, the students are making their knowledge of physics concepts clear, plain, and understandable to other people.

4.3.3.2 Student Subcategory: Teaching

In this subcategory of description, students said what it means to understand physics is to communicate physics through teaching. When students teach physics, they are involved in a process of knowledge transmission where they facilitate learning to impart information or skills to learners for the purposes of the learners. Through teaching, the students' intention is to facilitate learning where "teaching is considered as deliberate actions undertaken with the intention of facilitating learning" (Taber, 2016, p. 144).

Adedokun-Shittu and Shittu (2015) describe teaching as “the activities involved in facilitating or educating to impart knowledge or skills to learners (p. 2515). Burchill and Anderson (2019) describe teaching as “the act of imparting of knowledge with others” (p. 231) and Ampadu and Adjei-Boateng (2018) describe teaching as “the art and science of facilitating students’ construction of meaning and understanding” (p. 293). Furthermore, Starr-Glass (2015) state that there are two fundamentally different ways of understanding teaching. First, Starr-Glass (2015) describe teaching as ‘knowledge transmission’ or “an instructor-centered activity in which knowledge is transmitted from someone who has acquired that knowledge to novice learners” (p. 83). Second, Starr-Glass (2015) describe teaching as ‘assisted knowledge creation’ or “as a learner-centered activity in which the instructor ensures that learning is made possible for novice learners and supports, guides, and encourages them in their active and independent creation of new knowledge” (p. 83).

What these definitions of teaching indicate is that there is a distinction between teaching and the previous subcategory explaining. Explaining is distinct from teaching because explaining does not imply educating, i.e.) explaining and teaching have different goals. Therefore, for the purposes of my study, when students explain physics, they describe a physics concept in more detail, but when students teach physics, they are facilitating learning through the transmission of knowledge as suggested by the aforementioned literature.

John said what it means to understand physics is to teach physics to his little brother. When teaching physics to his little brother, John said that he used simple language so that his brother could understand the concept of inertia.

> What it means to understand physics? What it means to me is that I can teach what’s going on to my little brother in a way that he can understand without throwing in all those

professorial terms. Showing that you understand physics in the real world is as easy as teaching it to my younger brother, like teaching the concept of inertia. (John)

Annie, Ben, and Jay said what it means to understand physics is to teach by communicating their physics knowledge to other people.

When you're able to teach it to others. I would say what it means to understand would be to teach. Because I am teaching physics, I'm able to understand it, I would have to be able teach it. (Annie)

What it means to understand physics is when I could teach it to others. (Ben)

What it means to understand physics is when I can teach it to other people or other students. Teaching it to people basically. If you can teach it to people, you're pretty good at that topic. (Jay)

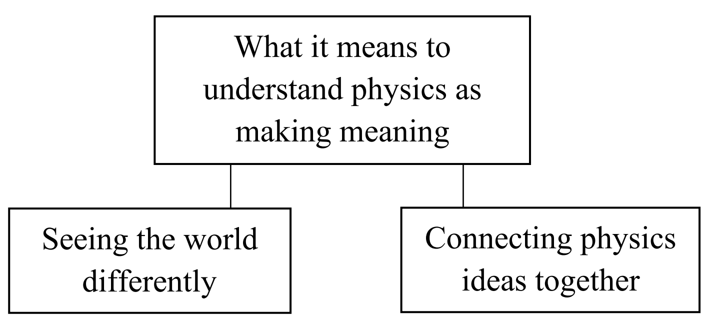
In summary, students said what it means to understand physics is to teach physics. Through teaching, students are transmitting physics knowledge to other people.

4.3.4 Student Category Four: Making Meaning

In this category of description, students said what it means to understand physics is making meaning. The structure of the making meaning category of description can be seen in Figure 9 and it contains two subcategories of description: (1) seeing the world differently, and (2) connecting physics ideas together.

Figure 9

Students: The Structure of What it Means to Understand Physics as Making Meaning



Students said what it means to understand physics is to make meaning in two ways. For the subcategory, seeing the world differently, students said what it means to understand physics is to see the world differently by connecting physics to the real world. The term 'real world' was previously defined in Section 1.2 as "the realm of practical or actual experience, as opposed to the abstract, theoretical, or idealized sphere of the classroom, laboratory, etc." ("Real World", 2019)" and 'real world' is a term extensively used in physics education literature (Adorno et al., 2015; Astin et al., 2002; Finkelstein et al., 2005; Jones, 2015; Joshua, 1995; Redish, 2015; Schauer et al., 2009; Spam & van den Berg, 2015; Whitelegg, & Parry, 1999; Wieman & Perkins, 2005). The students used the term 'real world' during the interviews when referring to the world outside of the classroom and laboratory. For the subcategory, connecting physics ideas together, students said what it means to understand physics is to make connections between different physics ideas, concepts, and theories within the field of physics.

4.3.4.1 Student Subcategory: Seeing the world differently

In this subcategory, students said that what it means to understand physics is to see the world differently. Students see the world differently when they connect physics to the real world. Some of the connections that students made between physics and the real world include connecting physics to the following: an Olympic sprinter, a cellular phone, car crashes, light bulbs, and the refraction and reflection of light.

John said what it means to understand physics is to connect physics to real life. John made the connection between the Olympic athlete Usain Bolt and the physics related to this athlete's kinematic motion and acceleration when sprinting.

> Understanding physics means to be able to look at something that you've learned in class and make a real world connection to it. I know that I've actually understood physics

> when I can see physics in the motion of real life like the kinematic motion and acceleration of Usain Bolt sprinting. (John)

Michelle said what it means to understand physic is to connect physics to how the world works around her. Michelle added that this connection is made through understanding how a cellular phone works and how physics concepts manifest themselves in her daily life through energy, waves, and mathematics.

> I think understanding physics basically means to connect physics to how the world works around you based on energy, waves, and the mathematics between our daily lives. And then I can see how my cell phone works. (Michelle)

Jim said what it means to understand physics is to connect physics to the interactions between objects in the world. Jim provided the example of car crashes and how the interactions between the cars was connected to the physics of momentum.

> Understanding physics means how things in the world interact and how physics connects these together. An example could be a car crash. Two cars crash with each other and they start moving and they hit a pole, their momentum connects to physics. (Jim)

Amy connected physics to the real world by connecting physics to her understanding of how a light bulb works.

> Understanding physics means when I connect physics happening in the real world to understand how a light bulb works, or how light refracts or reflects off an object. That's what understanding means, when I can connect it to the real world and see how something works. (Amy)

In summary, students said what it means to understand physics is to make meaning by seeing the world differently when they connect physics to the real world.

4.3.4.2 Student Subcategory: Connecting physics ideas together

In this subcategory of description, students said what it means to understand physics is to connect physics ideas together within the field of physics. Students connect physics ideas together when then they link, and associate different physics ideas, concepts, and theories together to form a more holistic view of physics. Some of the physics ideas that students connected together include: connecting matter, energy and forces together, connecting some of the main theories of physics together, and connecting as many physics ideas together as possible and building upon those connections.

In the following quotes, Becky, Ben, and Carl said what it means to understand physics is to connect physics concepts together.

> When I think about what it means to understand physics, the first thing that comes to my mind is how matter and energy and forces all connect together. It's about making connections between physics topics. (Becky)

> What it means to understand physics is to look at all of the ideas and main theories of physics and connect them together. To take what you just learned in class and just connect these physics ideas to each other. (Ben)

> I think understanding physics means being able to connect it. I think we did that a lot in physics class, we would always connect something back to what we learned before. I think connecting as many physics ideas together as possible and building upon those connections. (Carl)

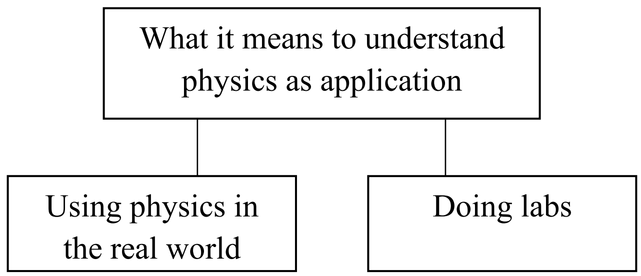
In summary, students said what it means to understand physics is to make meaning by connecting different physics ideas, concepts, and theories together within the field of physics.

4.3.5 Student Category Five: Application

In this category of description, students said what it means to understand physics is to apply physics. The structure of the application category of description can be seen in Figure 10 and it contains two subcategories of description: (1) using physics in the real world, and (2) doing labs.

Figure 10

Students: The Structure of What it Means to Understand Physics as Application



Students said what it means to understand physics is to apply physics in two ways. For the subcategory, using physics in the real world, students said what it means to understand physics is to apply physics to situations outside of the classroom and the lab for some specific purpose. For the subcategory, doing labs, students said what it means to understand physics is to apply physics in a hands-on way in the lab.

4.3.5.1 Student Subcategory: Using physics in the real world

In this subcategory, students said what it means to understand physics is to use physics in the real world outside of the classroom and the lab for some specific purpose. For example, applying physics to satellite motion, x-rays, magnetism, engineering, and hobbies such as golf and pool.

Chris said what it means to understand physics is to apply physics to satellite motion.

> Understanding physics for me means when I can apply it to real life scenarios such as satellites and how many times satellites revolve around the Earth. (Chris)

Marc said what it means to understand physics is to use x-rays for the purpose of determining bone structure and to map the human brain.

> Well understanding physics means I can see potential applications. It's about how physics can be applied in real life. I find it really interesting to look into x-rays because we can use them to determine bone structure and we're building other methods to determine and map the human brain because of this. (Marc)

Olivia said what it means to understand physics is to apply her knowledge of magnetism for a given purpose.

> What it means to understand is when I can apply my own knowledge and use it. If I understand magnets, I can understand how magnets work and how people can use magnets. As a student, I think that understanding means I'm able to apply the physics I've been taught by an instructor. (Marc)

Brianne suggested that understanding physics means being able to observe physics in the real world and to apply it there.

> I think understanding physics means applying it to the real world because you can only go so far in a classroom. You keep doing these questions on the chalk board but until you actually see physics in the real world and try to apply it there, I don't think you really understand it. (Brianne)

Amy said what it means to understand physics is to apply it in the real world.

> To understand physics means if I'm able to apply what I've been taught in the real world. (Amy)

Finally, Alice said what it means to understand physics is to apply her physics knowledge to her hobbies of playing pool and golf.

> To understand physics means to apply it. A hobby of mine has been playing pool and golf and these are just applications of physics. If you understand physics, what this means is you can see it and apply it, like in your hobbies. (Alice)

In summary, students said what it means to understand physics is to apply physics by using it in situations outside of the classroom and the lab for some specific purpose. The quotes revealed that students recognised that through applying physics, it could be used and manipulated for some specific purpose.

4.3.5.2 Student Subcategory: Doing labs

In this subcategory, students said what it means to understand physics is to apply physics knowledge and concepts at school.

Jay, Alex, and Harry said what it means to understand physics is to apply physics concepts and formulas to perform physics laboratories. Jay suggested that doing labs allowed him to do physics practically and to try physics on his own. Alex added that he is a hands-on learner and doing labs helped him apply a physics formula.

> Understanding means when you do labs and do physics practically. For labs, it's when you try stuff on your own, trying to figure out the masses and other stuff, it makes you understand what's going on when you use it. (Jay)

> Understanding physics means doing labs because I'm a hands-on kind of learner. If I'm doing something like a lab for example, I would get the concept easier than if it was just an example done on the board. You get to put the formula to use when you're actually doing a lab. (Alex)

> Doing class experiments and labs, that's what understanding means. When you can do labs and when you can do other experiments with physics. (Harry)

In summary, students said what it means to understand physics is to apply physics by doing labs. The students said it was important to do labs because labs provided them with a hands-on experience where they could explore physics principles for themselves that they had learned in the classroom.

4.3.5 Student Outcome Space

Table 12 describes the five categories of description (referential aspects) and the twelve subcategories of description (structural aspects). The referential aspects describe the differences in the students' overall conceptualizations and the structural aspects describe the variation of internal structure of the conceptualizations. For each of the categories and subcategories, a brief description is given that reflects what the focus of each of the conceptualizations refers to.

Table 12

Student Outcome Space

Students What it means to understand physics.		
Categories of Description (Referential Aspect)	**Subcategories of Description (Structural Aspect)**	
What it means to understand physics as:		**The Focus is on:**
Feelings		The focus is on affect such as an experienced feeling. Students conceive of what it means to understand physics as an experienced feeling.
	Positive feelings.	The focus is on positive feelings when the understanding of physics is achieved. The focus is on positive experienced feelings of happiness, enjoyment, confidence, pride, and reassurance.
	Feelings of insight.	The focus is on feelings of insight such as an 'aha' or a 'eureka' moment.
Achievement		The focus is on the achievement of a goal or ability. Students conceive of what it means to understand physics as achieving validation of their physics knowledge through writing assessments, achieving the ability to correctly solve physics questions, achieving the ability to correctly derive physics questions, and achieving the goal of conforming to classroom demands.
	Validating through assessment.	The focus is on achieving validation of physics knowledge through writing assessments such as a classroom physics test.
	Solving physics questions.	The focus is on achieving the ability to correctly solve physics questions, and the ability to correctly select the formula to solve a physics question.
	Deriving physics formulas.	The focus is on achieving the ability to correctly derive physics formulas.
	Conforming to classroom demands.	The focus is on achieving the goal of conforming to classroom demands such as following along and listening to the teacher during class instruction.
Communication		The focus is on communicating physics with other people. Students conceive of what it means to understand physics as communicating physics to other people by explaining, and teaching.
	Explaining.	The focus is on communicating physics with others by explaining.
	Teaching.	The focus is on communicating physics with others by teaching.
Making Meaning		The focus is on making meaning with physics.
	Seeing the world differently.	The focus is on seeing the world in a different way by linking or associating physics with the real world.
	Connecting physics ideas together.	The focus is on making links between different physics concepts and theories within the field of physics.
Application		The focus is on being able to use and apply physics in situations for some purpose. Students conceive of what it means to understand physics as using physics in the real world and as applying physics in a hands-on way in the lab.
	Using physics in the real world.	The focus is on using and applying physics in the real world for some purpose.
	Doing labs.	The focus is on applying physics by doing labs.

4.4 Teacher Categories of Description

Physics teachers experienced and perceived what it means to understand physics in several qualitatively different ways. Five categories of description emerged from the interview analysis and these categories each contained several subcategories. The five qualitatively different categories of description include: (1) what it means to understand physics as feelings, (2) what it means to understand physics as achievement, (3) what it means to understand physics as communication, (4) what it means to understand physics as making meaning, and (5) what it means to understand physics as application. The categories of description were the same as those for the students.

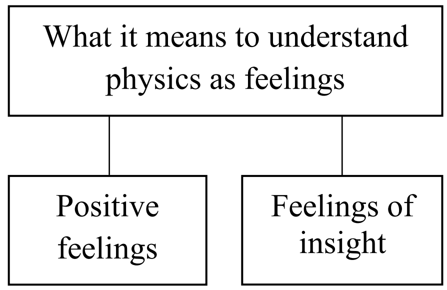
The following sections describe each of the categories of description (referential aspects) and their subcategories of description (structural aspects) with reference to teacher quotes. Finally, a graphical representation of the teachers' outcome space for the five categories of description is presented and includes the subcategories of description.

4.4.1 Teacher Category One: Feelings

In this category of description, teachers said what it means to understand physics is to experience a feeling. The structure of the feelings category of description can be seen in Figure 11 and contains two subcategories: (1) positive feelings, and (2) feelings of insight. Several teachers said what it means to understand physics is to experience an 'aha' or a 'eureka' moment, and this feeling may be considered to represent an insight. As previously noted, Topolinski and Reber (2010) refer to an 'aha' feeling as a feeling of insight.

Figure 11

Teachers: The Structure of What it Means to Understand Physics as Feelings



Teachers said what it means to understand physics is to experience feelings in two ways. For the subcategory, positive feelings, teachers said what it means to understand physics is to experience positive feelings such as happiness and excitement. For the subcategory, feelings of insight, teachers said what it means to understand physics is to experience an 'aha' or 'eureka' feeling.

4.4.1.1 Teacher Subcategory: Positive feelings

In this subcategory of description, teachers said what it means to understand physics is to experience positive feelings.

Joe, Helen, Bryan, Graham, and Deana said what it means to understand physics is to experience a good feeling.

> Understanding means a good feeling. Yeah! (Joe)
>
> I think there's a good feeling associated with understanding. I've witnessed this good feeling in students, and I know what it feels like too. (Helen)
>
> When I understand. It means a good feeling, and I get goose bumps. (Bryan)
>
> It's a good feeling when you feel like you understand something. Absolutely, it's a good feeling for sure. (Graham)
>
> Well, understanding means I feel good, it feels fantastic. (Deana)

Dabney, Brody, and Ruben said what it means to understand physics is to experience happiness, joy, excitement, awe, and wonder.

> What it means is to experience a feeling of happiness and joy. Joy if you understand something, happiness and joy. (Dabney)

> What it means to understand something is to experience joy. I mean, it's excitement, it's appreciation. It's all of those things. (Brody)

> My feeling of understanding physics is of awe and wonder. (Ruben)

Wade and Miles said what it means to understand physics is to experience a feeling of contentment and euphoria.

> Contentment because then you know that you understand something. (Wade)

> It means euphoria and contentment. (Miles)

Martin, Dafni, Raphael, and Bill said what it means to understand physics is to experience satisfaction, confidence, inspiration, and a feeling of relief.

> Understanding means I feel excitement, satisfaction, and confidence. (Martin)

> Confidence and pride in myself. It makes you feel better about yourself knowing that you grasped this difficult thing. (Dafni)

> I think it feels inspiring. It confirms that you're making progress. You're moving in the right direction. You're ready for the next step, something harder, different topic possibly. (Raphael)

> Understanding means a feeling of relief. I would describe it as sort of an emotional relief. (Bill)

In summary, teachers said what it means to understand physics is to experience positive feelings. Teachers experienced positive feelings of happiness, joy, excitement, awe and wonder, contentment, euphoria, satisfaction, confidence, inspiration, and a feeling of relief.

4.4.1.2 Teacher Subcategory: Feelings of insight

In this subcategory of description, teachers said what it means to understand physics is to experience a feeling of insight or an 'aha' feeling. Feelings of insight were previously discussed in Section 4.3.1.2. Although teachers did not use the word 'insight' in their interview responses, for the purposes of my study, I have interpreted the word insight as a subcategory of description since the literature describes insight as an 'aha' feeling (Topolinski & Reber, 2010).

Jace and Les said what it means to experience physics is to experience an 'aha' feeling of insight while Anne, Gavin, and Darren experienced a 'eureka' feeling of insight.

> Understanding physics means to experience an 'aha' light bulb moment and it's a great feeling (Jace)

> A feeling? Yeah, there's sort of an 'aha' feeling. (Les)

> What it means, I think when you just figure something out, there's this kind of 'aha' moment. A light bulb goes off and you see the connection. The 'eureka' moment when you understand something for yourself. (Anne)

> Understanding means to experience a 'eureka' moment. (Gavin)

> I would say that understanding means a feeling of euphoria, almost a 'eureka' moment, 'I've found it'. I think its a feeling of contentment. (Darren)

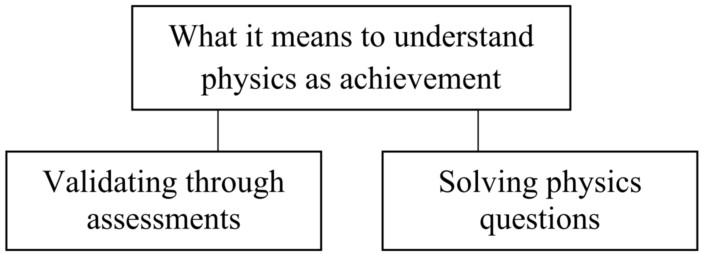
In summary, teachers said what it means to understand physics is to experience feelings of insight such as an 'aha' feeling or a 'eureka' feeling.

4.4.2 Teacher Category Two: Achievement

In this category of description, teachers said what it means to understand physics is to achieve a goal or to achieve the ability to do something. The structure of the achievement category of description can be seen in Figure 12 and contains two subcategories: (1) validating through assessments, and (2) solving physics questions.

Figure 12

Teachers: The Structure of What it Means to Understand Physics as Achievement



Teachers said what it means to understand physics is to achieve the ability to do something in two ways. For the subcategory, validating through assessments, teachers said what it means to understand physics is to achieve validation of their physics knowledge through writing assessments. In the subcategory, solving physics questions, teachers said what it means to understand physics is to achieve the ability to correctly solve physics questions such as those found in physics textbooks.

4.4.2.1 Teacher Subcategory: Validating through assessments

In this subcategory of description, teachers said what it means to understand physics is to achieve validation of their physics knowledge by writing assessments such as physics tests.

Darren, Dabney, and Graham said what it means to understand physics is to successfully write a physics test. The teachers said their understanding of physic is validated when they can answer questions on a test and to pass a test.

> That’s what I think understanding means, when I can answer the questions on a test and pass a test. (Darren)
>
> Understanding means to be able to pass a test. (Dabney)
>
> Can I pass the test? If I get the grade I need, then I understand physics and that’s what it means. (Graham)

In summary, teachers said what it means to understand physics is to achieve validation of their physics knowledge by writing a physics test.

4.4.2.2 Teacher Subcategory: Solving physics questions

In this subcategory of description, teachers said what it means to understand physics is to achieve correct solutions when completing the task of solving physics questions.

Simon and Ruben said what it means to understand physics is to solve textbook physics questions.

> When I was in university, understanding meant if I could do textbook questions on the topic. (Simon)

> So, back in university, to me understanding physics meant I knew it because I was able to solve the problems that matched the answers in the back of the textbook or the same answers that the prof. had on the board. (Ruben)

Anne, Joe, and Raphael said what it means to understand physics is to solve physics questions and to be able to work physics questions out.

> Understanding physics means you should be able to solve physics questions. (Anne)

> The understanding part is when you do the mathematics and work the questions out. (Joe)

> Understanding physics means to just work through the questions. I think that's something that a physicist needs to do. What a student of physics needs to do is solve physics questions. (Raphael)

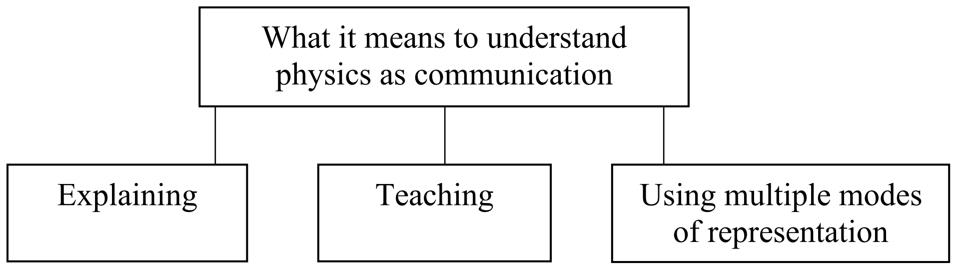
In summary, teachers said what it means to understand physics is to achieve the ability to solve physics questions such as textbook physics questions.

4.4.3 Teacher Category Three: Communication

In this category of description, teachers said what it means to understand physics is to communicate physics with other people. The structure of the communication category of description can be seen in Figure 13 and contains three subcategories: (1) explaining, (2) teaching, and (3) using multiple modes of representation.

Figure 13

Teachers: The Structure of What it Means to Understand Physics as Communication



Teachers said what it means to understand physics is to communicate physics in three ways. For the subcategory, explaining, teachers said what it means to understand physics is to communicate a physics concept in more detail. For the subcategory, teaching, teachers said what it means to understand physics is to communicate physics through the transmission of knowledge. Finally, for the subcategory, using multiple modes of representation, teachers said what it means to understand physics is to communicate physics concepts in different ways using multiple modes of representation.

4.4.3.1 Teacher Subcategory: Explaining

In this subcategory of description, teachers said what it means to understand physics is to communicate physics by explaining. When teachers are explaining physics, they are trying to make physics clear, plain, and understandable by describing physics and providing information about physics. Explaining was previously defined in Section 4.3.3.1.

Anne and George said what it means to understand physics is to explain physics to somebody else.

> I think that's what understanding physics means. It is if you can explain it to somebody else. If you understand, you can turn to your partner in class and explain to them what's going on. (Anne)

> At a certain level, understanding physic means being able to explain something so that someone else understands it. (George)

Dabney said what it means to understand physics is to explain it to someone else and that his explanation indicates his level of understanding.

> I would say to understand means if I can explain physics to someone and that illustrates a pretty decent understanding of it. (Dabney)

Jace said what it means to understand physics is to explain physics in such a way that a general audience can understand it.

> But I think the biggest thing that understanding means is if you can explain it in a way that your friends or a general audience would understand. (Jace)

In summary, teachers said what it means to understand physics is to communicate physics through explanation. By explaining physics, the teachers are making their knowledge of physics concepts clear, plain, and understandable to other people.

4.4.3.2 Teacher Subcategory: Teaching

In this subcategory of description, teachers said what it means to understand physics is to communicate physics through teaching. Teaching was previously discussed in Section 4.3.3.2. When teachers teach physics, they are involved in a process of knowledge transmission where they facilitate learning to impart their knowledge or skills to learners for the purposes of the learners. Through teaching, the teachers' intention is to facilitate learning where "teaching is considered as deliberate actions undertaken with the intention of facilitating learning" (Taber, 2016, p. 144).

Gavin said what it means to understand physics is to teach and suggested that teaching is a benchmark of understanding physics.

> I think when you can teach someone a topic means you understand it. So, that would be my benchmark. (Gavin)

George said what it means to understand physics is to teach it and added that because he had to teach physics, he had to understand physics.

> My number one explanation is having to teach it made me have to understand it so understanding physics means you would be able to teach it. (George)

Ollie said what it means to understand physics is to teach other people so that they could in turn teach physics to someone else.

> To understand means if I can teach others and they can teach others. So, if we have some good students in the class that I can teach to, they'll be able to teach other kids. (Ollie)

Finally, Graham said what it means to understand physics can be described by the cliché, 'to teach is to understand'.

> What do I think it means to understand physics? Like probably the old cliché is you understand it when you can teach it. (Graham)

In summary, teachers said what it means to understand physics is to teach physics. Through teaching, teachers are transmitting their physics knowledge to other people.

4.4.3.3 Teacher Subcategory: Using multiple modes of Representation

In this subcategory of description, teachers said what it means to understand physics is to communicate physics using multiple modes of representation.

Darren said what it means to understand physics is to communicate physics using multiple modes of representation or to communicate physics in multiple ways.

> I think understanding physics means to be able to represent the same thing in multiple ways, modes of representation like numerical, graphical, formulas. I would say that one

aspect of what it means to understand is being able to take physics and to understand it on different levels through multiple modes of representation. (Darren)

Miles said what it means to understand physics is to communicate physics using different modes of representation such as diagrams, formulas, and graphs.

> Understanding physics means being able to communicate it to someone else using different modes of representation such as diagrams, formulas, and graphs. (Miles)

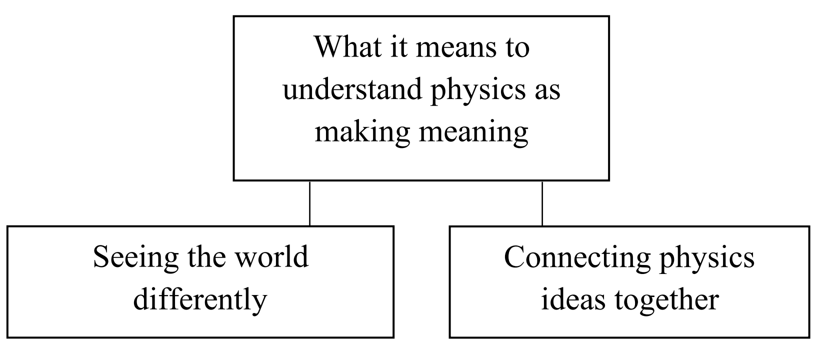
In summary, teachers said what it means to understand physics is to communicate physics through different modes of representation or multiple ways such as diagrams, formulas, and graphs.

4.4.4 Teacher Category Four: Making Meaning

In this category of description, teachers said what it means to understand physics is making meaning. The structure of the making meaning category of description can be seen in Figure 14 and it contains two subcategories of description: (1) seeing the world differently, and (2) connecting physics ideas together.

Figure 14

Teachers: The Structure of What it Means to Understand Physics as Making Meaning



Teachers said what it means to understand physics is to make meaning in two ways. For the subcategory, seeing the world differently, teachers said what it means to understand physics is to see the world differently by connecting physics to the real world. The term 'real world' has been previously defined in Section 4.3.4. The teachers used the term 'real world' during the interviews when referring to the world outside of the classroom and laboratory. For the subcategory, connecting physics ideas together, teachers said what it means to understand physics is to make connections between different physics ideas, concepts, and theories within the field of physics.

4.4.4.1 Teacher Subcategory: Seeing the world differently

In this subcategory, teachers said that what it means to understand physics is to see the world differently. Teachers see the world differently when they connect physics to the real world. Some of the connections that teachers made between physics and the real world include connecting physics to the following: walking, the collision of cars, tides, lightning and thunder, and the motion of the Earth.

Helen said what it means to understand physics is to connect physics to situations around her such as the connections that can be made between walking and Newton's third law.

> I think understanding means being able to connect physics to situations around you. I think even something like walking. Thinking of Newton's third law when you're pushing off the floor and the floor is pushing off of you. (Helen)

Les said what it means to understand physics is to connect physics to things he sees everyday.

> Understanding means connecting physics to things that you would see every day. How can you connect physics to the traffic? How can you connect physics to collisions of cars? How can you connect physics to the ocean tides? (Les)

Bryan said what it means to understand physics is to connect physics to the real world to account for physical phenomenon such as thunder and lightning.

> Understanding physics means connecting physics to the real world to understand the universe. It's looking around and understanding what happens when I see a flash of light and then I hear the thunder and how this connects to physics. To understand physics means to understand the universe around us and to connect physics to the universe. To understand physics means to start putting a meaning to what we see around us and to make connections to the real world. (Bryan)

In summary, teachers said what it means to understand physics is to make meaning by seeing the world differently when they connect physics to real world.

4.4.4.2 Teacher Subcategory: Connecting physics ideas together

In this subcategory of description, one teacher said what it means to understand physics is to connect physics ideas together within the field of physics. This teacher connected physics ideas together by linking, and associating different physics ideas, concepts, and theories together.

For example, Brody said what it means to understand physics is to connect everything he knows about physics together and to connect physics with other physics ideas.

> I think understanding physics means when I can connect everything I know about physics together. It's about making those connections. (Brody)

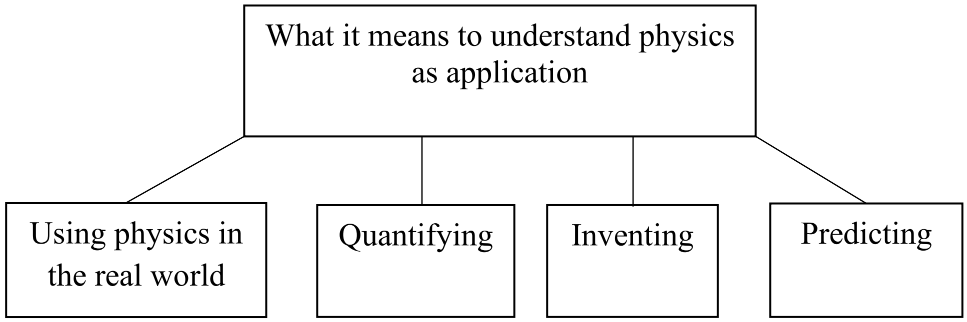
In summary, one teacher said what it means to understand physics is to make meaning by connecting different physics ideas, concepts, and theories together within the field of physics.

4.4.5 Teacher Category Five: Application

In this category of description, teachers said what it means to understand physics is to apply physics knowledge and concepts. The structure of the application category of description can be seen in Figure 15 and contains four subcategories of description: (1) using physics in the real world, (2) quantifying, (3) inventing, and (4) predicting.

Figure 15

Teachers: The Structure of What it Means to Understand Physics as Application



Teachers said what it means to understand physics is to apply physics in four ways. For the subcategory, using physics in the real world, teachers said what it means to understand physics is to apply physics to situations outside of the classroom and the lab for some specific purpose. For the subcategory, quantifying, teachers said what it means to understand physics is to apply physics by making measurements about a given phenomenon. For the subcategory, inventing, teachers said what it means to understand physics is to apply physics by creating or designing something new. Finally, for the subcategory, predicting, teachers said what it means to understand physics is to apply physics by predicting how the world works.

4.4.5.1 Teacher Subcategory: Using physics in the real world

In this subcategory, teachers said what it means to understand physics is to use physics in the real world outside of the classroom and the lab for some specific purpose.

George said what it means to understand physics is to apply it to new situations and to apply what he has learned.

> I would say understanding means application. I think when you can apply it to real world situations. If you have some understanding of theories, you can take what you've learned and apply it. (George)

Sadie said what it means to understand physics is to apply the equations of physics to a given situation.

> If you can take a situation and apply physics equations to a real world context, I think it means that you understand what's going on behind the scenes. (Sadie)

Brody said what it means to understand physics is to apply physics to a situation that has not been encountered before.

> To understand physics means that you can apply it to a situation you've never seen before, preferably to a real world context. (Brody)

In summary, teachers said what it means to understand physics is to apply physics by using it in situations outside of the classroom and the lab for some specific purpose. The quotes revealed that teachers recognised that through applying physics, it could be used and manipulated for some specific purpose.

4.4.5.2 Teacher Subcategory: Quantifying

In this subcategory of description, teachers said what it means to understand physics is to apply physics by making measurements about a specific physics phenomenon. Through quantifying or making measurements, the teachers are engaging in a process whereby they measure some given physics quantity and collect data about it. In this subcategory, teachers used the words quantify and measure to describe what it means to understand physics. Merriam-Webster.com defines quantify as "to determine, express, or measure the quantity" ("Quantify", 2020). Therefore, for the purposes of my study, quantify and measure are considered to have similar meanings.

Simon said what it means to understand physics is to quantify or measure through collecting data from physics experiments and to analyze this collected data.

> Understanding means being able to take measurements and collect quantitative data through experiments and to do analysis. (Simon)

Les said what it means to understand physics is to quantify. Les added that quantifying physics helps the teacher to determine what happens in a physical situation.

> Quantifying in a general way means understanding. You have to quantify physics to determine what happens to the flight of a baseball when it goes from a pitcher to catcher or what happens to the baseball when it hits the bat. (Les)

In summary, teachers said what it means to understand physics is to quantify. Through the process of quantifying physics, teachers collect measurements about a given physics phenomenon to understand its behaviour.

4.4.5.3 Teacher Subcategory: Inventing

In this subcategory of description, teachers said what it means to understand physics is to apply physics through invention. Merriam-Webster.com defines 'invention' as "1: something invented such as a device or process originated after study and experiment, 2: a product of the imagination, productive imagination, or discovery" ("Invention", 2019). Invention is the application of physics to produce something new such as an idea, method, or product.

George said what it means to understand physics is to invent. George added that invention means to use physics knowledge and apply it in such a way that something completely new is developed.

> What understanding physics means is that you take all your physics knowledge and then you use it to invent. I would say understanding through application, but almost understanding through invention. (George)

Darren said what it means to understand physics is to invent. Darren added that invention means to take physics knowledge and to extend it to something completely new and to apply physics to new areas of study.

> I think understanding physics means being able to take what you know and extend it to something completely new by invention. Invention is where you're extending it to new things. (Darren)

In summary, teachers said what it means to understand physics is to apply physics through invention. Through inventing, physics is being used to produce something new.

4.4.5.4 Teacher Subcategory: Predicting

In this subcategory of description, teachers said what it means to understand physics is to make predictions. When making predictions, teachers are applying physics to make predictions about the world.

Graham said what it means to understand physics is to predict and added that prediction is at the core of what it means to understand physics.

> Prediction is the core of what it means to understand, to make predictions. (Graham)

Simon said what it means to understand physics is to make predictions and to extrapolate based upon a prediction.

> I would say understanding means to make predictions. The ability to predict where an object will be after a certain amount of time like with projectiles. (Simon)

Raphael said what it means to understand physics is to make predictions and these predictions should yield answers to physics questions and they can be confirmed through experiments and demonstrations.

> Understanding physics means to make predictions and you should be able to work towards a solution. You go and do an experiment, do a demonstration, build an apparatus, and your prediction should give you answers. (Raphael)

Sadie added that predictions are important to what understanding physics means and that predictions are fundamental to science.

I think that the prediction part is why we do science. I think what is really important to what understanding means is the prediction part. (Sadie)

In summary, teachers said what it means to understand physics is to apply physics to make predictions about the world. The teachers said that when predicting, they are using evidence about physics to make future predictions about what might happen for a given physical phenomenon.

4.4.5 Teacher Outcome Space

Table 13 describes the five categories of description (referential aspects) and the thirteen subcategories of description (structural aspects). The referential aspects describe the differences in the teachers' overall conceptualizations and the structural aspects describe the variation of internal structure of the conceptualizations. For each of the categories and subcategories, a brief description is given that reflects what the focus of each of the conceptualizations refers to.

Table 13

Teacher Outcome Space

Teachers What it means to understand physics.		
Categories of Description (Referential Aspect)	**Subcategories of Description (Structural Aspect)**	
What it means to understand physics as:		**The Focus is on:**
Feelings		The focus is on affect such as an experienced feeling. Teachers conceive of what it means to understand physics as an experienced feeling.
	Positive feelings.	The focus is on positive feelings when the understanding of physics is achieved. The focus is on positive experienced feelings of happiness, excitement, joy, awe and wonder, contentment, euphoria, satisfaction, confidence, inspiration, and a feeling of relief.
	Feelings of insight.	The focus is on feelings of insight such as an 'aha' or a 'eureka' feeling.
Achievement		The focus is on the achievement of a goal or ability. Teachers conceive of what it means to understand physics as achieving validation of their physics knowledge through writing assessments and achieving the ability to correctly solve physics questions.
	Validating through assessments.	The focus is on achieving validation of physics knowledge through writing assessments such as a physics test.
	Solving physics questions.	The focus is on achieving the ability to correctly solve physics questions.
Communication		The focus is on communicating physics with other people. Teachers conceive of what it means to understand physics as communicating physics by explaining, teaching, and using multiple modes of representation.
	Explaining.	The focus is on communicating physics with other people by explaining.

Teachers What it means to understand physics.		
Categories of Description (Referential Aspect)	**Subcategories of Description (Structural Aspect)**	
What it means to understand physics as:		**The Focus is on:**
	Teaching.	The focus is on communicating physics with other people by teaching.
	Using multiple modes of representation.	The focus is on communicating physics to other people by using multiple modes of representation such as a visual mode, a numerical mode, a graphical mode, and a symbolic mode.
Making Meaning		The focus is on making meaning with physics.
	Seeing the world differently.	The focus is on seeing the world in a different way by linking or associating physics with the real world.
	Connecting physics ideas together.	The focus is on making links between different physics concepts and theories within the field of physics.
Application		The focus is on being able to use and apply physics in situations for some purpose. Teachers conceive of what it means to understand physics as using physics in the real world, as quantifying, as inventing, and as predicting.
	Using physics in the real world.	The focus is on using and applying physics in real world for some purpose.
	Quantifying.	The focus is on quantifying or making measurements about the world so that the world can be explained.
	Inventing.	The focus is on using physics to create or design something new.
	Predicting.	The focus is on using physics to make predictions about the world.

4.5 Professor Categories of Description

Physics professors experienced and perceived what it means to understand physics in several qualitatively different ways. Five categories of description emerged from the interview analysis and these categories each contained several subcategories. The five qualitatively different categories of description include: (1) what it means to understand physics as feelings, (2) what it means to understand physics as achievement, (3) what it means to understand physics as communication, (4) what it means to understand physics as making meaning, and (5) what it means to understand physics as application. The categories of description were the same as those for the students and the teachers.

The following sections describe each of the categories of description (referential aspects) and their subcategories of description (structural aspects) with reference to professor quotes.

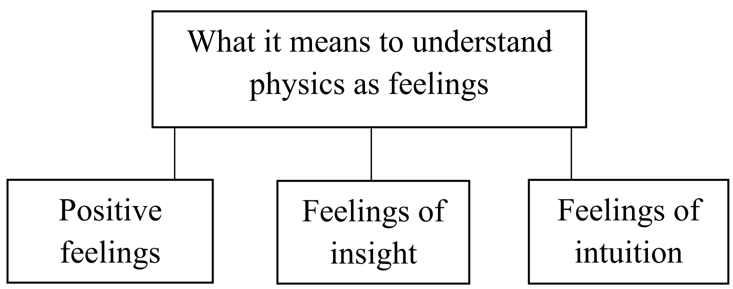
Finally, a graphical representation of the teachers' outcome space for the five categories of description is presented and includes the subcategories of description.

4.5.1 Professor Category One: Feelings

In this category of description, professors said what it means to understand physics is to experience a feeling. The structure of the feelings category of description can be seen in Figure 16 and contains three subcategories: (1) positive feelings, (2) feelings of insight, and (3) feelings of intuition. The professors experienced the same 'aha' and 'eureka' feelings of insight that the students and the teachers did, but only the professors reported experiencing the feeling of intuition.

Figure 16

Professors: The Structure of What it means to Understand Physics as Feelings



Several professors said what it means to understand physics is to experience an 'aha' or a 'eureka' moment, and this feeling may be considered to represent an insight. As previously noted, Topolinski and Reber (2010) refer to an 'aha' feeling as a feeling of insight.

A conceptualization unique to the professors was the feeling of intuition that they experienced when describing what it means to understand physics. Although insight and intuition "share many commonalities and are intimately linked with each other" (Zhang et al., 2016, p. 1), the professors were the only participants to report intuition as a conception. The subcategory, ‘feelings of intuition’, differentiates the unique feeling that the professors experienced that is different from the students and the teachers.

Professors said what it means to understand physics is to experience feelings in three ways. For the subcategory, positive feelings, professors said what it means to understand physics is to experience positive feelings such as happiness and excitement. For the subcategory, feelings of insight, professors said what it means to understand physics is to experience an ‘aha’ or ‘eureka’ feeling. Finally, for the subcategory, feelings of intuition, the professors said what it means to understand physics is to experience a ‘gut feeling’ or a ‘knowing’ (Chen, 2019) that cannot be explained.

4.5.1.1 Professor Subcategory: Positive feelings

In this subcategory of description, professors said what it means to understand physics is to experience positive feelings.

Riley, Cam, Venus, and Carter said what it means to understand physics is to experience a positive feeling of triumph, excitement, euphoria, and happiness.

> What it means when I actually understand physics is there’s a huge feeling of triumph. It’s just a big feeling, a rush, a feeling of joy when something clicks, and you understand something that’s been challenging. Then there’s excitement, that’s what it means if you understand something. (Riley)

> I think it’s like a feeling of euphoria, you know, when you finally go wow, I get this. (Cam)

> I have a feeling of happiness when I think I’ve understood something and that’s a general happiness which actually drives me to research it. (Venus)

> Understanding means you feel really happy. (Carter)

Blair said what it means to understand physics is to experience a great feeling, Kelly experienced a feeling of excitement, and Paul experienced a ‘high’.

> It's a great feeling because you know it means I understand this. I may be the only one who understands it, but it's a great feeling. (Blair)

> It means I feel excited that I now understand something that maybe in the past sounded too abstract or too difficult. (Kelly)

> You definitely get a high that you don't need to take anything to get [laughs] when you understand physics. (Paul)

Ben, Jen, Paula, and Peter said what it means to understand physics is to experience a feeling of satisfaction.

> What it means is there's a satisfaction that once you get to that point, you really feel that now I understand. (Ben)

> Its very satisfying. So what does it feel like? It feels triumphant I would say. (Jen)

> Satisfaction, it means it feels good. (Paula)

> I think a feeling of satisfaction. (Peter)

Mike, Mark, and Denise said what it means to understand physics is to experience a feeling of confidence and pride.

> When you understand means you feel confident, you feel good about yourself, you feel proud. (Mike)

> Is there a feeling? I think confidence in knowing that it's right. (Mark)

> A feeling. I think if I've understood something perfectly it means there's a confidence with it. (Denise)

In summary, professors said what it means to understand physics is to experience positive feelings. Professors experienced positive feelings of triumph, excitement, euphoria, happiness, excitement, accomplishment, satisfaction, gratitude, confidence, and pride.

4.5.1.2 Professor Subcategory: Feelings of insight

In this subcategory of description, professors said what it means to understand physics is to experience a feeling of insight or an 'aha' feeling. Feelings of insight were previously discussed in Section 4.3.1.2.

A feeling of insight was experienced by several professors. Mark said that what it means to understand physics is to experience a deep physical insight.

> What it means to understand physics is to have a deep physical insight. (Mark)

Blair and Jen said what it means to understand physics is to experience a feeling of insight as an 'aha' moment. Jen added to her description of insight by comparing this feeling to a 'light bulb' moment.

> It means there's an 'aha' moment, whether it's in elementary physics or even in research. I've had those 'aha' moments of insight. (Blair)

> When I understand, I think it means there's an 'aha' or a 'light bulb' moment. (Jen)

Larry, Ellie, and Allan said what it means to understand physics is to experience a 'eureka' moment. Allan added that a light bulb being turned on could be used to describe his feeling of insight.

> Every now and then you get a 'eureka' moment. (Larry)

> Well, the 'eureka' moment, I feel it means this is understanding. (Ellie)

> A 'eureka' moment when you understand something in physics, like the light bulb goes on. (Allan)

In summary, professors said what it means to understand physics is to experience feelings of insight such as an 'aha' feeling or a 'eureka' feeling.

4.5.1.3 Professor Subcategory: Feelings of intuition

In this subcategory of description, professors said what it means to understand physics is to experience a feeling of intuition. Jung (1921/2014) describes intuition as a content that "presents itself whole and complete, without our being able to explain or discover how this content came into existence" (par. 770, p. 453). Cholle (2011, Aug 31) describes intuition as a "process that gives us the ability to know something directly without analytic reasoning, bridging the gap between the conscious and nonconscious parts of our mind" (p. 1). Chen (2019, Dec. 24) contends that intuition is a 'knowing' that cannot be explained and can be described as a 'gut feeling', while Jung and Pauli (2014) write about the "value of intuition to science's empiricism" (p. xxxiv). Marton et al., (1994) interviewed Nobel Laureates from physics, chemistry, and medicine and asked them how they would define intuition. The 1997 Nobel Laureate in medicine, Andrew V. Serially, described intuition in the following way:

> Scientists can have intuition, but perhaps it's based on pure logic. We make the right decisions, we at times don't understand it fully, but perhaps our brain is able to compute better than that of other people what decision to make. And sometimes you make the right decision and very often we make the right decision. So there is such a thing as intuition, yet it's difficult to define it as pure intuition. Maybe simply, cool logic, computed by a brain of a very high level. (Marton et al., 1994, p. 466)

Therefore, the difference between intuition and insight is that intuition can be conceived of as the spontaneous processing of information without one's conscious awareness, while an insight is a sudden access to a solution such as an 'aha' or 'eureka' moment.

Larry said what it means to understand physics is to experience an intuition. Possessing intuition is important to Larry because he needs to have a sense about what his physics experiments require and what the results of these experiments might be.

> To understand means to have an intuition. That sounds a little airy-fairy, but I think it's especially important for a physicist in general to have. I think it's especially important for

> an experimentalist to have because you need to know or have a good idea about what your experiments require, to make them work, and what the results might be…it's a feedback process. (Larry)

Dean said what it means to understand physics is to experience an intuition. Dean explained that he has an intuitive built-in mechanism in his brain that allows him to anticipate the way the physical world will proceed under certain circumstances. Dean said to really understand physics means he has an intuition for how things work, and his intuition leads him to the right approach when problem solving.

> What it means to understand physics is you acquire an intuition. There's a certain intuition. It just comes out naturally from your brain so that it becomes a natural everyday occurrence, and you can convey very complex ideas just from intuition. Sooner or later you get an intuition for things and even small things don't throw you usually. Things will still puzzle you every now and then, but in general, you have the right approach, and your intuition leads you to the right approach for problem solving. You have the intuition for going in the right direction. I mean to understand physics means that you have almost an intuitive mechanism built into your brain in such a way that you can anticipate the way the physical world will proceed under certain circumstances. To really understand physics means that you have an intuition for how things will work. (Dean)

Paula said what it means to understand physics is to experience an intuitive feeling for when she is feeling uncertain.

> I guess understanding physics means you develop an intuitive feeling to know when things are getting a little fuzzy or uncertain logically or mathematically. (Paula)

Bill said what it means to understand physics is to experience an intuitive feeling about what is right or wrong in physics.

> You tend to get an intuitive feeling about physics, what's right and what's wrong. Physics I think is so intuitive. (Bill)

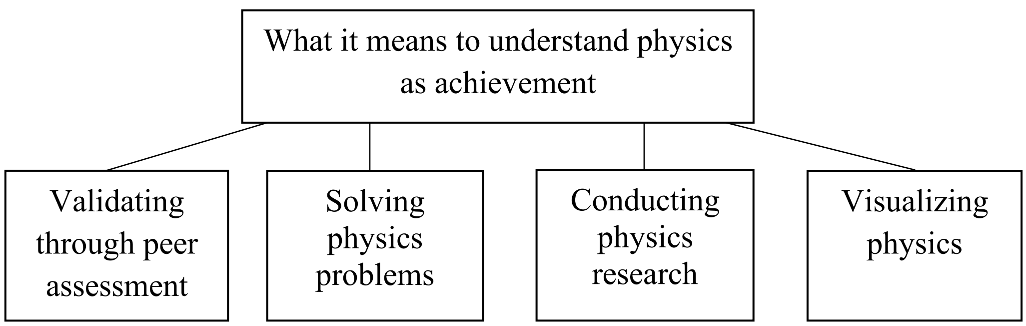
In summary, professors said what it means to understand physics is to experience a feeling of intuition. The professors' feeling of intuition represents a 'gut feeling' and intuition seems to arise without conscious awareness of it (Jung, 1921/2014).

4.5.2 Professor Category Two: Achievement

In this category of description, professors said what it means to understand physics is to achieve a goal or to achieve the ability to do something. The structure of the achievement category of description can be seen in Figure 17 and contains four subcategories: (1) validating through peer assessment, (2) solving physics problems, (3) conducting physics research, and (4) visualizing physics.

Figure 17

Professors: The Structure of What it Means to Understand Physics as Achievement



Professors said what it means to understand physics is to achieve a goal or the ability to do something in four ways. For the subcategory, validating through peer assessment, professors said what it means to understand physics is to achieve validation of their physics knowledge through publishing peer reviewed papers. For the subcategory, solving physics problems, professors said what it means to understand physics is to achieve the ability to solve physics problems. For the subcategory, conducting research, professors said what it means to understand physics is to achieve the ability to successfully conduct physics research. Finally, for the subcategory, visualizing, professors said what it means to understand physics is to achieve the ability to visualize physics.

4.5.2.1 Professor Subcategory: Validating through peer assessment

In this subcategory of description, professors said what it means to understand physics is to achieve validation of their physics knowledge through publishing peer reviewed physics papers. Through publishing peer-reviewed physics papers, professors are being assessed by their peers.

Bill said what it means to understand physics is to publish physics papers and to work collaboratively with colleagues. Bill considers the publishing of papers as a collaborative process that advances the field of physics. Through advancing physics with scholarship, Bill suggests that a base of knowledge is produced from which other physicists can solve more difficult problems.

> Understanding physics means you can publish papers. You can help other people go forward on more difficult problems, setting sort of a base for other investigations. (Bill)

Paul said what it means to understand physics is to publish and to write something new about physics.

> Well, when you've gone a bit further than what the common understanding means is when you can write something new about physics and publish it. (Paul)

In summary, professors said what it means to understand physics is to achieve validation of their physics knowledge through publishing peer reviewed physics papers. The professors are being assessed by their colleagues through their submission of papers during the peer review process.

4.5.2.2 Professor Subcategory: Solving physics problems

In this subcategory of description, professors said that what it means to understand physics is to achieve the ability to correctly solve physics problems. For all of the quotes, professors used the words 'physics problems' whereas the students and teachers all used the words 'physics questions'. The teachers and students seem to be referring to physics questions from physics textbooks that have given solutions. The professors seem to be referring to solving physics problems not specifically related to textbook physics questions with no given solution that may or may not be able to be solved.

Ellie, Bill, and Charles said what it means to understand physics is to solve a physics problem correctly.

> Understanding physics means if I have a physics problem, I can solve it. (Ellie)

> Understanding means you've solved a problem, so you've understood the problem. (Bill)

> I feel like I understand when I can actually solve a physics problem and get it right. So, for me, understanding means being able to solve a problem correctly and this is one of the major milestones indicating that I understand some physics. (Charles)

In summary, professors said what it means to understand physics is to achieve the ability to solve physics problems correctly.

4.5.2.3 Professor Subcategory: Conducting Physics Research

In this subcategory of description, professors said what it means to understand physics is to conduct physics research.

Charles said what it means to understand physics is to do research. Charles adds that doing physics research indicates mastery of a physics topic and is a prime indicator of someone's physics understanding.

> The ultimate test of what understanding means is being able to do research in a physics topic. If you're doing research, then you've mastered the topic. (Charles)

Bob said what it means to understand physics is to develop both theoretical and experimental physics research.

> Understanding means you should be able to develop and conduct physics research experiments. For example, if you're a theorist, this might be thought experiments that you make and then going through the process of applying the physics and seeing if it either works or doesn't. For real physics experiments it's measuring a particular physical parameter and seeing that it is what you expect it to be. (Bob)

Larry said a prime indicator of what it means to understand physics is to do physics research. Larry adds that research drives physics understanding because undertaking physics research helps the physicist hone their 'research toolkit'.

> A prime indicator of what it means to understand physics is research. Research really drives understanding because when you practice research, it means you develop and hone your physics research toolkit. (Larry)

In summary, professors said what it means to understand physics is to conduct physics research. For the professors, conducting physics research and developing experiments is an indicator of physics mastery and therefore understanding.

4.5.2.4 Professor Subcategory: Visualizing physics

In this subcategory of description, professors said what it means to understand physics is to achieve the ability to visualize physics. When professors visualize physics, they form a mental picture of a physics principle or process.

Charles said what it means to understand physics is to achieve the ability to form a mental picture of the physics process he is studying.

> Understanding physics means I have some mental picture of what's happening. I like to be able to have a mental picture of the process that I'm studying, and this means I understand it. (Charles)

Allan said what it means to understand physics is to develop a geometric picture for a given physics situation.

> Understanding means I can get a geometric picture of the situation, even in quantum mechanics, which is very hard to visualize. I think it's a matter of understanding the basic

principles and seeing how they lead to a kind of formalism of the subject. Yes, what it means is achieving the ability to visualize. (Allan)

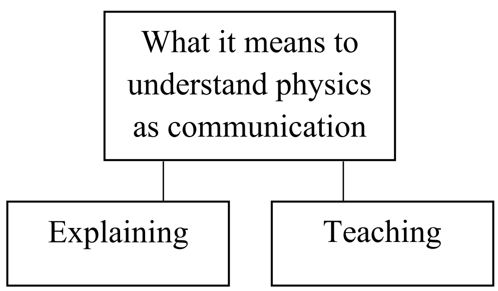
In summary, professors said what it means to understand physics is to achieve the ability to visualize physics principles and processes by using geometric or mental pictures.

4.5.3 Professor Category Three: Communication

In this category of description, professors said what it means to understand physics is to communicate physics with other people. The structure of the communication category of description can be seen in Figure 18 and contains two subcategories: (1) explaining, and (2) teaching.

Figure 18

Professors: The Structure of What it Means to Understand Physics as Communication



Professors said what it means to understand physics is to communicate physics in two ways. For the subcategory, explaining, professors said what it means to understand physics is to communicate a physics concept in more detail by providing information to make the physics concepts clearer. For the subcategory, teaching, professors said what it means to understand physics is to communicate physics through the transmission of their knowledge where information or skills are imparted to the learner.

4.5.3.1 Professor Subcategory: Explaining

In this subcategory of description, professors said what it means to understand physics is to communicate physics by explaining. Explaining was previously discussed in Section 4.3.3.1. When professors are explaining physics, they are making physics clear, plain, and understandable by describing physics and providing information about physics.

Bob said what it means to understand physics is to explain physics to someone else and Peter said explaining is a good measure of what understanding physics means.

> Understanding means if you can explain physics to someone else, then you've understood it. Sometimes when you go and try to explain something you realize that I understand that well. (Bob)

> I think I know when I have understood something when I can explain it to somebody else. I think that's really my measure of what understanding physics means. (Peter)

Blair said what it means to understand physics is to explain physics to someone else in a qualitative way.

> I mean you can understand something at a certain level when you can explain it to someone else in terms of your understanding. But if you can't explain it to someone else then you probably haven't really understood it. So being able to explain it to someone else, means understanding physics in a qualitative explanatory way. (Blair)

Riley said what it means to understand physics is to explain it. Riley added that when preparing for a test he would study in a group where the group members would explain physics to each other.

> Understanding means when I can explain physics to someone else. I always studied in groups preparing for a big test. I felt like I understood something when I could work with my peers on a problem and we could explain it to each other. I think a lot of my understanding does come down to being able to explain it to someone else. But I always feel much stronger if I can put it into words when I understand something. So that comes back to explain to others because you need words to explain to others. (Riley)

In summary, professors said what it means to understand physics is to communicate physics through explanation. By explaining physics, the professors are making their knowledge of physics concepts clear, plain, and understandable to other people.

4.5.3.2 Professor Subcategory: Teaching

In this subcategory of description, professors said what it means to understand physics is to communicate physics through teaching. Teaching was previously discussed in Section 4.3.3.2. When professors teach physics, they are involved in a process of knowledge transmission and they facilitate learning to impart their knowledge or skills to learners for the purposes of the learners. As previously stated, through teaching, the teachers' intention is to facilitate learning where "teaching is considered as deliberate actions undertaken with the intention of facilitating learning" (Taber, 2016, p. 144).

Ellie said what it means to understand physics is to teach it and to have the ability to make the teaching accessible to a wide audience.

> When I can teach physics properly then I think that's what it means, what understanding means. To be able to teach physics and make it accessible to anybody who's not in the field specifically or to teach it to a general broader audience. (Ellie)

Peter and Miley said what it means to understand physics is to teach it. Peter added that a true understanding of physics means to teach it and Miley said if she understands physics, she can teach it.

> How do you know that you truly understand physics? I think it means when you start to teach the material. (Peter)

> I find with me, if I'm teaching general relativity, I feel if I understand physics, it means I can teach it. (Miley)

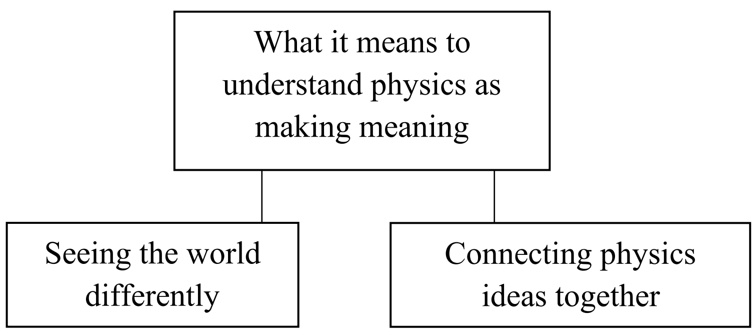
In summary, the professors said what it means to understand physics is to teach physics. Through teaching, the professors are transmitting physics knowledge to other people.

4.5.4 Professor Category Four: Making Meaning

In this category of description, professors said what it means to understand physics is making meaning. The structure of the making meaning category of description can be seen in Figure 19 and it contains two subcategories of description: (1) seeing the world differently, and (2) connecting physics ideas together.

Figure 19

Professors: The Structure of What it Means to Understand Physics as Making Meaning



Professors said what it means to understand physics is to make meaning in two ways. For the subcategory, seeing the world differently, professors said what it means to understand physics is to see the world differently by connecting physics to the real world. The term 'real world' has been previously defined in Section 4.3.4. The professors used the term 'real world' during the interviews when referring to the world outside of the classroom and laboratory. For the subcategory, connecting physics ideas together, professors said what it means to understand physics is to make connections between different physics ideas, concepts, and theories within the field of physics.

4.5.4.1 Professor Subcategory: Seeing the world differently

In this subcategory, professors said that what it means to understand physics is to see the world differently. Professors see the world differently when they connect physics to the real world. Some of the connections that professors made between physics and the real world include connecting physics to the following: washing machines, the planets and stars, cellular phones, microwave ovens, and coffee machines.

Kelly said what it means to understand physics is to connect physics with a real world problem and with everyday objects such as cellular phones, washing machines, the planets, and the stars.

> Understanding means if I can make a good connection with a real world problem or with a theory. It means to know how everything in our everyday world works. For example, washing machines, dryers, refrigerators, the planets and stars, and cell phones. (Kelly)

Paul said what it means to understand physics is to connect physics with everyday gadgets. Paul adds that by making physics connections to everyday objects he can understand how they mechanically work.

> Understanding physics means you are making connections with physics to understand electricity or the flow of water through pipes. You can connect physics to real world or everyday things that we buy like gadgets, microwave ovens, coffee machines and understand how they work and know what physics is going on. If you think of a coffee machine, it's got electricity, it's got water, it's got thermodynamics. (Paul)

In summary, professors said what it means to understand physics is to make meaning by seeing the world differently when they connect physics to the real world.

4.5.4.2 Professor Subcategory: Connecting physics ideas together

In this subcategory of description, professors said what it means to understand physics is to connect physics ideas together within the field of physics. Professors connect physics ideas together when then they link, and associate different physics ideas, concepts, and theories together. Some of the physics ideas that professors connected together include connecting all knowledge about physics together and connecting physics topics with each other.

Steve said what it means to understand physics is to connect physics with everything he knows about physics.

> Understanding physics means when I see how physics connects with everything else that I know about physics. (Steve)

Riley said what it means to understand physics is to connect physics topics to each other and to identify physics connections that had not been previously recognized.

> To understand physics means you can see how physics topics connect with each other. (Riley)

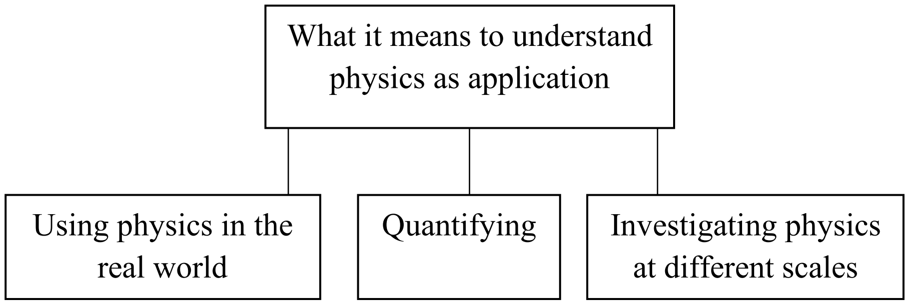
In summary, professors said what it means to understand physics is to make meaning by connecting different physics ideas, concepts, and theories together within the field of physics.

4.5.5 Professor Category Five: Application

In this category of description, professors said what it means to understand physics is to apply physics. The structure of the application category of description can be seen in Figure 20 and it contains three subcategories of description: (1) using physics in the real world, (2) quantifying, and (3) investigating physics at different scales.

Figure 20

Professors: The Structure of What it Means to Understand Physics as Application



Professors said what it means to understand physics is to apply physics in three ways. For the subcategory, using physics in the real world, professors said what it means to understand physics is to apply physics to situations outside of the classroom and the lab for some specific purpose. For the subcategory, quantifying, professors said what it means to understand physics is to apply physics by making measurements about a given phenomenon. Finally, for the subcategory, investigating physics at different scales, professors said what it means to understand physics is to apply physics by investigating how physics works at different scales such as microscopic, macroscopic, time, and energy scales.

4.5.5.1 Professor Subcategory: Using physics in the real world

In this subcategory, professors said what it means to understand physics is to use physics in the real world outside of the classroom and the lab for some specific purpose. For example, using physics to track the motion of satellites.

Jerry said what it means to understand physics is to apply what he knows about the laws of physics in the real world.

> Understanding means you're able to apply what you know about the laws of physics to real world situations and say what will happen in a particular case. Physics is not just a set of laws, you have to apply them to certain cases. (Jerry)

Andrew and Mike said what it means to understand physics is to apply physics and to use it in the real world.

> Understanding physics means when I can take something that I know or have learned and apply it in the world that I hadn't maybe considered before. (Andrew)

> I think to truly understand physics means you have to apply it or use it. You really don't understand it until you actually go out in the real world and use it. (Mike)

Jim said what it means to understand physics is to apply the physics that he has learned for some useful purpose. Jim gives the example of applying physics for the purpose of tracking satellites.

> When I apply physics means I've understood it. I learned the formulas, I applied it, and I was doing something useful with it. For example, you go to NASA and then you can use physics to describe where these satellites move in the sky and then you can use physics to track them. That's what it means. (Jim)

In summary, professors said what it means to understand physics is to apply physics by using it in situations outside of the classroom and the lab for some specific purpose. The quotes revealed that professors recognised that through applying physics, it could be used and manipulated for some specific purpose.

4.5.5.2 Professor Subcategory: Quantifying

In this subcategory of description, professors said what it means to understand physics is to apply physics by making measurements about a specific physics phenomenon. Through quantifying or making measurements, the professors are engaging in a process whereby they measure some given physics quantity and collect data about it. In this subcategory, professors used the words quantify and measure to describe what it means to understand physics. As previously stated in Section 4.4.5.2, quantify and measure are considered to have similar meanings for the purposes of my study.

Jim said what it means to understand physics is to examine something happening in nature and to quantify it by taking measurements.

> I think what understanding physics means is being able to look at something happening in nature, to quantify it, and to take measurements. (Jim)

Steve said what it means to understand physics is to take measurements about a given phenomenon and to quantify its behaviour.

> Understanding physics means the ability to observe phenomena, to make measurements that quantify the behaviour I'm seeing, and the ability to try to explain what I observe based on as few assumptions as possible. (Steve)

Finally, Bob said what it means to understand physics is to measure a physical parameter and to know what the expected behaviour of the parameter will be. For example, the parabolic path of a ball may be verified though measurement.

> Understanding means I should be able to measure things. So I think part of what understanding means is learning how to measure things and understand whether you've actually measured something or if it's just an instrumental effect that you're seeing. And for real experiments, maybe it's measuring a particular physical parameter and seeing the behaviour you expected. I mean, you can say a ball follows a parabola but unless you measure it, you don't know for sure that it really does that. (Bob)

In summary, professors said what it means to understand physics is to quantify. Through the process of quantifying physics, professors collect measurements about a given physics phenomenon to understand its behaviour.

4.5.5.3 Professor Subcategory: Investigating physics at different scales

In this subcategory of description, professors said what it means to understand physics is to apply physics by investigating different scales. These scales can include the microscopic, macroscopic, time, energy, atomic, nuclear, and sub-nuclear.

Larry said what it means to understand physics is to investigate all linked physics scales and timescales.

> Being able to understand means as fully as possible to investigate what happens to physics on all linked scales and timescales. (Larry)

Dean said what it means to understand physics is to investigate how the world works at different scales.

> Understanding just means to investigate how the world works at different scales and to be able to see the underlying processes that give rise to the things we observe every day. (Dean)

Kelly said what it means to understand physics is to investigate how the universe works at the microscopic and macroscopic scales.

> To understand the universe at the microscopic and macroscopic scale. Investigating scales make exciting questions whether small or big questions, whether at the microscopic or macroscopic level. I think that's what understanding means. (Kelly)

Steve said what it means to understand physics is to investigate different physical scales (atomic, nuclear, sub-nuclear) and to describe the physics happening at each scale.

> I mean, for most physicists, good physicists, I think understanding means to be able to go down and investigate the microscopic interactions and say this is what's happening at each scale. I think that human experience stops on the energy scale of fractions of an electron volt. But a physicist doesn't stop there, a physicist can understand physics at much higher energy scales, from the atomic scale, to the sub-nuclear, to the nuclear scale. (Steve)

In summary, professors said what it means to understand physics is to investigate physical scales. These scales include the microscopic, macroscopic, time, energy, atomic, sub-nuclear, and nuclear scales.

4.5.5 Professor Outcome Space

Table 14 describes the five categories of description (referential aspects) and the fourteen subcategories of description (structural aspects). The referential aspects describe the differences in the professors' overall conceptualizations and the structural aspects describe the variation of internal structure of the conceptualizations. For each of the categories and subcategories, a brief description is given that reflects what the focus of each of the conceptualizations refers to.

Table 14

Professor Outcome Space

	Professors **What it means to understand physics.**	
Categories of Description (Referential Aspect)	**Subcategories of Description (Structural Aspect)**	
What it means to understand physics as:		**The Focus is on:**
Feelings		The focus is on affect such as an experienced feeling. Professors conceive of what it means to understand physics as an experienced feeling.
	Positive feelings.	The focus is on positive feelings when the understanding of physics is achieved. The focus is on positive experienced feelings of triumph, excitement, euphoria, happiness, accomplishment, satisfaction, gratitude, confidence, and pride.
	Feelings of insight.	The focus is on feelings of insight. The focus is on an insight or 'aha' moment for a physics topic that helps guide the professors' reasoning.
	Feelings of intuition.	The focus is on an intuition or a 'gut feeling' for a physics topic that helps guide the professors' reasoning.
Achievement		The focus is on the achievement of a goal or ability. Professors conceive of what it means to understand physics as achieving validation of their physics knowledge through publishing peer reviewed physics papers, as achieving the ability to correctly solve physics problems, as achieving the ability to conduct physics research, and as achieving the ability to visualize physics.
	Validating through peer assessment.	The focus is on achieving validation of physics knowledge through publishing peer reviewed physics papers.
	Solving physics problems.	The focus is on achieving the ability to correctly solve physics problems.
	Conducting physics research.	The focus is on achieving the ability to conduct physics research.
	Visualizing physics.	The focus is on achieving the ability to visualize physics through a mental or geometric picture.
Communication		The focus is on communicating physics with other people. Professors conceive of what it means to understand physics as communicating physics by explaining, and teaching.

Professors What it means to understand physics.		
Categories of Description (Referential Aspect)	**Subcategories of Description (Structural Aspect)**	
What it means to understand physics as:		**The Focus is on:**
	Explaining.	The focus is on communicating physics with other people by explaining.
	Teaching.	The focus is on communicating physics with other people by teaching.
Making Meaning		The focus is on making meaning with physics.
	Seeing the world differently.	The focus is on seeing the world in a different way by linking or associating physics with the world.
	Connecting physics ideas together.	The focus is on making links between different physics concepts and theories within the field of physics.
Application		The focus is on being able to use and apply physics knowledge in real world situations for some purpose. Professors conceive of what it means to understand physics as applying physics in real world situations, as quantifying, and as investigating physics at different scales.
	Using physics in the real world.	The focus is on using and applying physics in the real for some purpose.
	Quantifying.	The focus is on quantifying or making measurements about the world so that the world can be explained.
	Investigating physics at different scales.	The focus is on using physics to investigate both the macroscopic and microscopic physical scales.

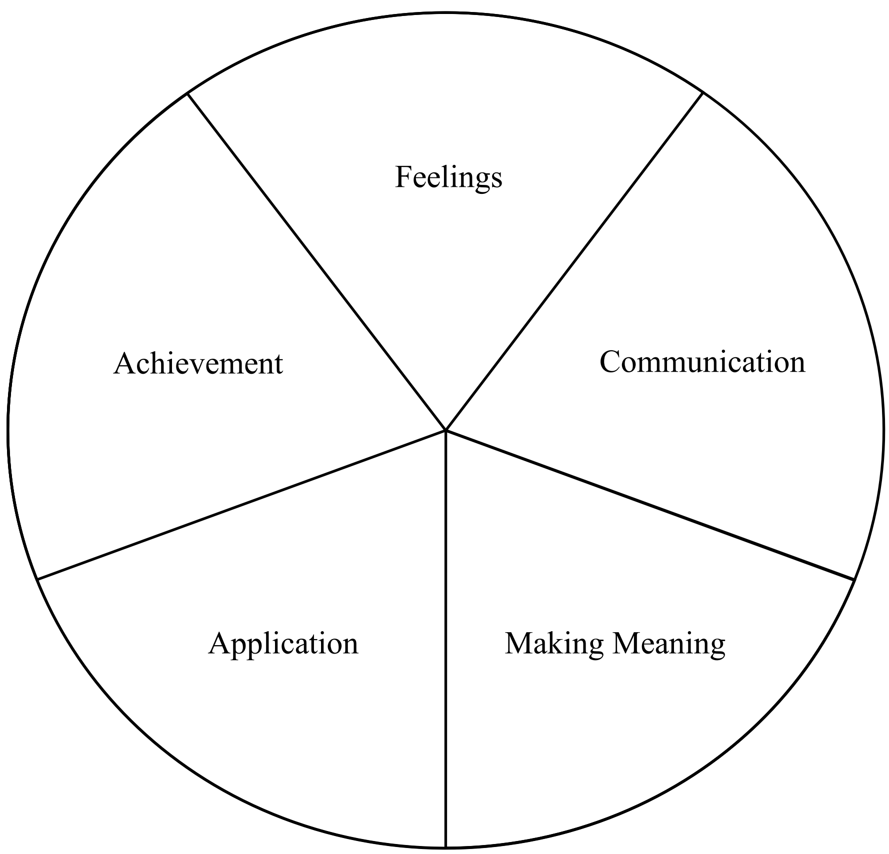
4.6 Outcome Space for the Students, Teachers, and Professors

As previously explained in Section 3.2.3.2, the students', teachers', and professors' set of related categories of description for the phenomenon, what it means to understand physics, is referred to as an 'outcome space' (Marton, 2000; Säljö, 1996; Trigwell, 2000; Walsh et al., 2007). The outcome space describes how the categories of description are internally related (Trigwell, 2000) and describes the minimum number of categories of description that explains all the variations in the data (Marton, 2000; Säljö, 1996; Trigwell, 2000; Walsh et al., 2007).

The outcome space for my study has a unique structure based on the finding that the categories of description were not hierarchical (see Figure 21). My study did not find any categories of description for what it means to understand physics that were reported by students, teachers, and professors to be inferior or superior to any other category. The categories for my study are proposed to be organized within a circle and indicate that no category of description is more important or less important than any other. The participants collectively hold a holistic view of what it means to understand physics because some of the students, teachers, and professors described all the categories of description in Figure 21 and all the students, teachers, and professors described more than one category of description. This holistic view of what it means to understand physics suggests that the five categories of description are interconnected components of a dynamic system of what it means to understand physics.

Figure 21

The Holistic Structure of the Students', Teachers', and Professors' Outcome Space



The five categories of description of the outcome space are the same for the students, teachers, and professors. What is different for the students, teachers, and professors, are the subcategories of description both numerically and substantively. The students reported twelve subcategories of description of which three were unique to the students, the teachers reported thirteen subcategories of description of which three were unique to the teachers, and the professors reported fourteen subcategories of description of which six were unique to the professors.

The students' three unique subcategories of description include: (1) 'deriving physics formulas' from the 'achievement' category of description', (2) 'conforming to classroom demands' from the 'achievement' category of description, and (3) 'doing labs' from the 'application' category of description. The teachers' three unique subcategories of description include: (1) 'using multiple modes of representation' from the 'communication' category of description, (2) 'inventing' from the 'application' category of description, and (3) 'predicting' from the 'application' category of description. The professors' six unique subcategories of description include: (1) 'feelings of intuition' from the 'feelings' category of description, (2) 'validating through peer assessment' from the 'achievement' category of description, (3) 'solving physics problems' from the 'achievement' category of description, (4) 'conducting physics research' from the 'achievement' category of description, (5) 'visualizing physics' from the 'achievement' category of description, and (6) 'investigating physics at different scales' from the 'application' category of description.

The differences between the subcategories are highlighted in Table 15 and indicate the variations in the structural aspects for the students', teachers', and professors' conceptualizations of what it means to understand physics. The subcategories of description that are unique to each group have been underlined in the table to differentiate them form each other. The differences between the subcategories, both numerically and substantively, is further examined in Section 5.1.

Table 15

Combined Outcome Space for the Students, Teachers, and Professors

What it means to understand physics.			
Categories of Description (Referential Aspect)	**Subcategories of Description (Structural Aspect)**		
What it means to understand physics as:	**Students**	**Teachers**	**Professors**
Feelings			
	Positive feelings. Feelings of insight.	Positive feelings. Feelings of insight.	Positive feelings. Feelings of insight. Feelings of intuition.
Achievement			
	Validating through assessments. Solving physics questions. Deriving physics formulas. Conforming to classroom demands.	Validating through assessments. Solving physics questions.	Validating through peer assessment. Solving physics problems. Conducting physics research. Visualizing physics.
Communication			
	Explaining. Teaching.	Explaining. Teaching. Using multiple modes of representation.	Explaining. Teaching.
Making Meaning			
	Seeing the world differently. Connecting physics ideas together.	Seeing the world differently. Connecting physics ideas together.	Seeing the world differently. Connecting physics ideas together.
Application			
	Using physics in the real world. Doing labs.	Using physics in the real world. Quantifying. Inventing. Predicting.	Using physics in the real world. Quantifying. Investigating physics at different scales.
Total subcategories	12	13	14

Note: Subcategories of description that are unique to a specific group have been underlined.

As previously discussed in Section 3.6.4, maps of conceptualization were hand drawn during the data analysis for the students, teachers, and professors to graphically represent the outcome space for each participant group as the data analysis progressed. The last iteration for these maps of conceptualization were computerized using the mind mapping electronic visualization software, 'DRAWIO' (Diagrams.net, 2020) and can be seen in Appendices X, Y, Z. Appendix X has five maps of conceptualization for each of the five student categories of description, Appendix Y has five maps of conceptualization for each of the five teacher categories of description, and Appendix Z has five maps of conceptualization for each of the five professor categories of description. According to Dahlin (2007), the outcome space produced from the participants' conceptions represent a "map of conceptions or, if you like, a map of (a certain part of) the human mind" (p. 338). Therefore, the final computerized maps of conceptualization that were drawn from the data for each of the groups represent the participants' conceptions about what it means to understand physics.

The proposed non-hierarchical outcome space for the students, teachers, and professors can be justified in two ways: (1) Justification directly from the data of my study., and (2) Justification directly from previous educational research.

(1) Justification directly from the data of my study.

The participants in my study did not describe what it means to understand physics as a hierarchy. Rather, the data suggested that the conceptions are interconnected. Within one quote and without a pause when answering my question, 'what does it mean to understand physics?', the participants reported many different conceptions suggesting an interconnected and dynamic system of what it means to understand physics. My study is not unique in this respect as Zhao (2015) also found a non-hierarchical outcome space with interconnected conceptions about learning science.

Below, I have provided an example quote from each of the students, teachers, and professors that demonstrates the holistic nature of what it means to understand physics as reported by the participants. As each interview progressed, participants provided additional information about what it means to understand physics which provided the opportunity for all variations of description to be brought to light by the participants. In other words, an individual can hold more than one conception and an individual does not prioritize one conception over the other.

In a study exploring the different ways of conceptualizing the experiences of how understanding comes about among first-year university students, Dahlin (1999) found that "a majority of subjects agreed that understanding has a holistic character [and] to understand often meant to have a sense of wholeness about something" (p. 202). As with the Dahlin study, the participants in my study described what it means to understand physics as having a wholeness being more than one thing. The following three quotes from a student, teacher, and a professor demonstrate that the participants' responses reflect such a holism. The quotes represent a holism because more than one conception was articulated by the participant without a pause when answering the question 'What does it mean to understand physics?' and these were important initial responses to my question. Furthermore, the conceptions the participants reported reflect more than one category of description from within the circular outcome space (see Figure 21).

Amelia (student) stated:

> What it means to understand physics is being able to know it yourself, apply it to different scenarios that we see, and being able to share it with others. (Amelia)

In this quote, it is clear that what it means to understand physics for Amelia (student) is to know it herself, to apply it, and to share it with others. Amelia provides three different conceptions about what it means to understand physics in one of her responses and she does not state that a conception is more or less important at anytime during her interview.

Helen (teacher) stated:

> What it means to understand physics is when you're able to communicate your knowledge to somebody else. Then I think you've gained a certain understanding about it. I think being able to apply it even when the parameters slightly change like if you understand how to do one kind of problem, to be able to do it for a different kind of problem shows that you have a certain understanding. I think there's also a feeling associated with it too. (Helen)

Helen (teacher) said what it means to understand physics is to communicate, to apply, and to experience a feeling. Helen provides three different conceptions about what it means to understand physics in one of her responses and she does not state that a conception is more or less important at anytime during her interview.

Carter (professor) stated:

> What is means to understand physics is when you can explain it to someone else, teach it to someone else, and you can find the necessary analogies and a way to have a conversation about it. Another meaning of understanding of physics is when you try to come up with ways to just visualize it in your head and say well if this is true, what happens? What's the manifestation of this physics? And does that work? (Carter)

Carter (professor) said what it means to understand physics is to explain, teach, and visualize physics. Carter provides three different conceptions about what it means to understand physics in one of his responses and he does not state that a conception is more or less important at anytime during his interview.

The illustrative quotes from Amelia, Helen, and Carter are presented above to demonstrate the holistic nature of what it means to understand to physics. The categories of description for my study are organized within a circle (see Figure 21) and this indicates that no category of description is more important or less important than any other.

(2) Justification from educational research.

According to Åkerlind (2005a), the structure of an outcome space "need not always take the form of a linear hierarchy of inclusiveness" (p. 329) and Dahlin (2007) contends that "it may be observed that not all phenomenographic outcome spaces have a hierarchical structure of dimensions of variation" (p. 336). Walsh (2000) agrees with Åkerlind and Dahlin that the outcome space need not be hierarchical and adds that "I differ from some others who think that [conceptions] must be put into a [logically related] structure" (p. 28).

When investigating Mainland Chinese students' conceptions of learning science, Zhao (2015) and Zhao and Thomas (2016) found a non-hierarchical outcome space and these students also held a holistic view of science learning where no conception was inferior or superior to another. Irving and Sayre (2015) found a non-hierarchical outcome space for their study investigating the perceptions university students have about becoming a physicist. Irving and Sayer (2015) write "The phenomenographic analysis of the interview data resulted in six distinct categories of description for students' perceptions of physicists. None of these categories is 'bad' or 'good'; we present them without value hierarchy" (p. 6). Furthermore, van Kessel (2016) examined student conceptions of evil and found an outcome space that was not hierarchical but had five related categories of description or 'themes' and several subcategories of description or "a variety of interconnected subthemes" (p. 3). Therefore, the outcome space for a phenomenographic study need not be hierarchical and there have been several recent studies, as noted above, that have presented the outcome space as non-hierarchical in the literature (Irving & Sayre, 2015; van Kessel, 2016; Zhao, 2015).

4.7 Summary

In summary, the separate data analysis of each group (high school physics students, high school physics teachers, and university physics professors revealed the same five categories of description: (1) feelings, (2) achievement, (3) communication, (4) making meaning, and (5) application. Yet, these five categories of description for each of the groups contained some differences in their subcategories. Specifically, the professors reported fourteen subcategories of description, the teachers reported thirteen subcategories of description, and the students reported twelve subcategories of description. The professors reported the greatest number of subcategories of description about what it means to understand physics whereas the high school physics students reported the least number of subcategories of description. In addition to the number of subcategories of description being different between the groups, the nature of the subcategories is also different between the groups and these differences are explored in Section 5.1.

Since the three outcome spaces that were developed from my data for the students, teachers, and professors have the same five categories of description (see Table 12, Table 13, Table 14, & Table 15), the same circular outcome space (see Figure 21) is used to represent the logical relationship between the data. For the students, teachers, and professors, the outcome space is non-hierarchical, holistic, and best represented by a circle. The categories of description have equality amongst one another, no category of description is at a lower level, and no category of description is at a higher level with relation to one another.

Chapter 5 Discussion

The purpose of my study was to determine the variations in the qualitatively different ways high school physics students, high school physics teachers, and university physics professors conceptualized about what it means to understand physics.

This chapter describes the similarities and differences (variations) between the conceptions of what it means to understand physics for high school physics students, high school physics teachers, and university physics professors. The contributions my study makes to the literature are addressed and the potential link between expertise and the variation in the subcategories of description between the three groups is examined. The implications of my study, the limitations of my study, and suggestions for future research are presented, and I discuss my development as a researcher. Finally, the chapter closes with a concluding statement for my doctoral dissertation.

5.1 Comparisons of the Students', Teachers', and Professors' Categories of Description and Subcategories of Description

The following section examines the similarities and differences between the students', teachers', and professors' categories of description and the subcategories of description. Table 15, previously discussed in Section 4.6, provides a visual representation of the categories of description and subcategories of description for the students, teachers, and professors.

The variations that exist between the participants' subcategories of description can be explained in terms of their role for a given situation, the context for a given situation, and the extent of the participant's expertise in the field of physics. For example: the role of a physics student as a learner in the context of a high school physics classroom, the role of a teacher as an educator in the context of a high school physics classroom, the role of a professor as an educator in the context of a university, and the role of a professor as a researcher in the context of a university laboratory. In terms of physics expertise, students may be considered as having a novice level of physics expertise, the teachers may be considered as having an intermediate level of physics expertise, and the professors may be considered as experts (Priest & Lindsay 1992; Dee-Lucus & Larkin 1986; Finegold & Mass, 1985; Taasoobshirazi & Carr, 2008).

5.1.1 Comparisons of the Feeling Category of Description

For the ‘feeling’ category of description, the students, teachers, and professors said that what it means to understand physics is to experience a feeling. The participants all reported experiencing positive feelings, and many participants in each of the three groups reported experiencing a feeling of insight. However, only the professors reported experiencing a feeling of intuition.

The students, teachers, and professors all said that what it means to understand physics is to experience positive feelings. For example, some of the positive feelings shared by participants included confidence, happiness, and enjoyment.

The students, teachers, and professors described what it means to understand physics as an experienced feeling of insight. This insight was reported as taking two forms, an ‘aha’ feeling and a ‘eureka’ feeling. For example, Carl (student) said, “understanding means to suddenly have an ‘aha’ moment”, Gavin (teacher) said, “understanding means to experience a ‘eureka’ moment”, and Mark (professor) said, “what it means to understand physics is to have a deep physical insight”. As previously noted in Chapter 4, Topolinski and Raber (2010) describe insight as an ‘aha’ feeling or a sudden “feeling of being right” (p. 402) and Entwistle and

Entwistle (1992) reported a university students' feeling of insight as "understanding can be the 'aha'-'eureka!' type where an insight comes in a blinding flash" (p. 8).

This sudden 'aha' feeling does not appear to be related to the level of physics expertise someone has acquired since the students, teachers, and professors all described this sudden feeling despite their varying levels of physics training and expertise. According to Gick and Lockhart (1995) and Metcalfe and Wiebe (1987), the 'aha' feeling is experienced by an individual when the solution to a problem pops into their mind surprisingly and abruptly and it may represent a common human experience.

Only the professors said that what it means to understand physics is to experience a feeling of intuition. For example, Larry (professor) said, "I guess to understand means to have an intuition", while Dean (professor) said, "what it means to understand physics is you acquire an intuition". Marton et al. (1994) state "there is such a thing as intuition, yet it's difficult to define it as pure intuition. Maybe simply, cool logic, computed by a brain of a very high level" (p. 466). Marton et al. contend that intuition is the result of a brain with a very high level of expertise such as the brain of a professor. The professors may have been the only group to conceptualize what it means to understand physics as experiencing a feeling of intuition because, as experts in the field of physics, they had developed intuition as the result of their extensive physics training and experience.

5.1.2 Comparisons of the Achievement Category of Description

For the 'achievement' category of description, the students, teachers, and professors described what it means to understand physics as the result of achieving a goal or the ability to perform a task.

All the students, teachers, and professors said that what it means to understand physics is to achieve validation of their physics knowledge through assessment. Marc (student) said, “I think understanding physics means that it’s reflected in your grade on a test”, Darren (teacher) said “that’s what I think understanding means, when I can answer the questions on a test and pass the test”, while Bob (professor) said, “understanding physics means you can publish papers”. The responses by students are consistent with Kortemeyer (2007) who reported that physics students “are motivated by their need to perform on standardized tests with mostly formula driven numerical problems and by the need to get a very good grade in a course” (p. 555). In their role as researchers, the professors consider assessment as a peer reviewed paper in the context of academia while in their roles as learners and educators the students and teachers consider assessment as a test in the context of the classroom.

Only students and the teachers said that what it means to understand physics is to achieve the ability to solve physics textbook questions, while the professors focused on solving physics problems. The professors differ from the student and teacher responses in that they describe achieving the ability to solve physics problems rather than specifically referring to solving routine physics textbook questions as in the case of the students and teachers. For example, Harry (student) said, “understanding physics means you can solve textbook physics questions”, Simon (teacher) said, “when I was in university, understanding meant I could do textbook questions on the topic”, while Ellie (professor) said, “understanding physics means if I have a problem in physics, I can solve it”. There is a difference between questions and problems and how students and teachers interpret these words compared with professors. In their role as physicists, the professors consider the solving of ‘problems’ in a context outside of the classroom while in their roles as learners and educators the students and teachers consider the solving of ‘questions’ in a context inside of the classroom. In schools, teachers and students commonly refer to physics ‘questions’ as ‘problems’ and these school ‘questions’ have a defined solution from the back of a physics textbook. However, the ‘problems’ that physicists try to solve will not be found in the back of a physics textbook, may be very difficult to solve, and may not have a defined solution. Furthermore, the physics professors’ role as physicists and researchers have different goals when solving physics problems than the goals of the students and teachers in their role as learners and educators when solving textbook physics ‘questions’.

Only the professors said that what it means to understand physics is to achieve the ability to conduct research. Bob (professor) said, “understanding means you should be able to develop and conduct physics research experiments”. To develop and conduct physics research experiments may require expert physics knowledge that the professors possess since they are “individuals with specialized knowledge of the domain” (Patel & Groen, 1991, p. 96). The students and teachers may not have the specialized physics knowledge necessary to develop and conduct research experiments, and therefore they do not share this subcategory of description with the professors. Conducting research is also outside of the role and context of the students and teachers whereas conducting research is well within the role of the physicist as research scientists.

Only the professors said that what it means to understand physics is to achieve the ability to visualize physics. Allan (professor) said “understanding means I can get a geometric picture of the situation, even in quantum mechanics, which is very hard to visualize”. Moore and Slisko (2017) state:

> Visualization is a common and important step in expert-like problem solving across multiple disciplines. Within the context of physics education, significant intervention is often required to develop visualization skills with novice problem solvers. (p. 156)

As Moore and Slisko (2017) contend, visualization is common to expert physics problem solvers, such as the professors, but it is not common to novice problem solvers. This ability to visualize has recently been reported by Kozhevnikov et al., (2010) as being very important to the process of scientific discoveries. Kozhevnikov et al. (2010) write:

> There is much historical evidence that visualization plays a central role in conceptualization processes of physics and in scientific discoveries. Research on the cognitive processes underlying physics discoveries such as Galileo's laws of motion, Maxwell's laws, Faraday's electromagnetic field theory, or Einstein's theory of relativity, has implicated the extensive use of visual/spatial reasoning in these discoveries. (p. 549)

Therefore, a physicist with much experience and expertise about physics, uses visualization as an important tool when making scientific discoveries. The novice students may not have reported the visualization subcategory because they may not have developed their visualization skills in the classroom and may not have received interventions about the benefits of visualization from their teacher to engage with. Teachers may not be aware of the "significant intervention" (Moore & Slasko, 2017, p. 156) that is required to promote visualization to students and as a result, the teachers may not have reported this subcategory of description. It is also possible that the teachers may not possess the skills to visualize physics scenarios and this may point to visualization being overlooked in teacher education programs. Furthermore, visualization may not have been described by teachers because in their roles as educators and in the context of the classroom, visualization is not something their students are assessed on from the curriculum and therefore teachers may not be concerned with teaching students about visualization.

The students were the only participants who said that what it means to understand physics is to achieve the ability to derive physics formulas. For example, Amelia (student) said, "most of what it means to understand physics is kind of that you can derive formulas". Kortemeyer (2007) asked students what they learned from deriving physics formulas and students said that “derivations are not seen as a way to connect concepts but as a way to prove that a formula is true, and solving problems boils down to plug-and-chug” (p. 552). Kortemeyer also reported that students indicated that “the derivations are presented to prove that a formula is correct” (p. 554) and students said “I’ll believe what you [teacher] tell me” (p. 554) when referring to the validity of a physics formula. Students may have been the only group to conceptualize what it means to understand physics as derivation because students, in their roles as learners, possess a novice level of physics knowledge and expertise. Students, in their roles as learners, are still learning about high school physics in the context of the classroom and may require verification of some of the formulas that they are learning about. Deriving physics formulas is one of the ways physics is taught to students in Manitoba physics classrooms. According to the Manitoba grade twelve physics curriculum, students “must derive an equation algebraically” (Manitoba Education & Training, 2005, p. 2:21) and students are required to learn how to “derive the special equations for constant acceleration” (Manitoba Education & Training, 2005, p. 4:9). The teachers may be deeply familiar with high school physics and may not need the same degree of formula verification through formula derivation as the students. The professors, with the highest level of physics expertise, have greater domain knowledge and this knowledge is better organized in comparison to novices (Chi et al., 1981), which may lead to the professors’ exclusion of formula verification as they are less dependent upon it. Both the professors and the teachers have moved past the necessity to ‘derive’ physics formulas because of their intermediate and expert physics knowledge.

Finally, only the students said that what it means to understand physics is to achieve the goal of conforming to classroom demands. For example, Alex (student) said, “what it means to understand physics is being able to follow along, listen, and keep up with the teacher”. Following along, listening, and keeping up with the teacher represents a passive student role where the role of the teacher is to transmit their physics knowledge to the students. Roth and Roychoudhury (1994) reported that "for children growing up in Western society and attending its schools, objectivism is thus the predominant or the only epistemology available and thus becomes the default epistemology" (p. 26) while Lorsbach and Tobin (1992) contend that "the epistemology that is dominant in most educational settings today is similar to objectivism" (p. 1). Kincin (2004) agrees, stating that "the objectivist epistemology continues to be the subtle enemy to encouraging meaningful learning and constructivist views of the nature of science and knowing, little seems to have changed in many classrooms" (p. 310). Therefore, it is not surprising that students, in their roles as learners and in the context of the classroom, hold conceptions of teaching and learning that reflect objectivist or transmissive teaching practices where they are passive learners. Students may have reported the conceptualization, 'conforming to classroom demands' when describing what it means to understand physics because students may be passive participators in the classroom because they "passively absorb the knowledge the professor provides" (Weaver & Qi, 2005, p. 582). Recently, Loftin et al., (2010) have reported that students "rarely raise their hands or engage in discussion…they make eye contact and sit where their presence can be observed by the instructor but are otherwise silent" (p. 120). However, it is encouraging that according to Kinchin (2004), when science students are given a choice between a constructivist classroom where the student is an active builder of understanding and an objectivist classroom where the student is a passive receiver of information, that there was an "overwhelming preference among students for a constructivist learning environment" (Kinchin, 2004, p. 301).

5.1.3 Comparisons of the Communication Category of Description

For the 'communication' category of description, the students, teachers, and professors said that what it means to understand physics is to communicate physics.

The students, teachers, and professors all said that what it means to understand physics is to explain physics. For example, Alice (student) said, "understanding physics means I'd be able to back up what I learned and explain what it is", Anne (teacher) said, "I think that's what understanding physics means, if you can explain it to somebody else", and Bob (professor) said, "understanding means if you can explain physics to someone else".

The students, teachers, and professors all said that what it means to understand physics is to teach physics. For example, Ben (student) said, "what it means to understand physics is when I could teach it to others", Gavin (teacher) said, "I think when you can teach someone a topic means you understand it.", and Ellie (professor) said, "when I can teach physics properly then I think that's what it means, what understanding means".

Since the students, teachers, and professors all reported the subcategories explain and teach, this may mean that from novice level physics students, to intermediate level physics teachers, to expert level physics professors, what it means to understand physics is to communicate physics by explaining and teaching.

The teachers were the only participants who said that what it means to understand physics is to use multiple modes of representation. For example, Miles (teacher) said "to me, understanding physics means being able to communicate it to someone else using different modes of representation, diagrams, formulas, and graphs". In this subcategory of description, teachers, in their role as educators and in the context of the physics classroom, described that understanding physics means being able to communicate physics concepts using multiple modes of representation. Dufresne et al., (1997) suggest "one goal of physics instruction should be to get students to consider and use multiple representations…if students are not fluent with a representation they are not going to consider it when faced with a difficult problem to solve" (p. 274). The teachers may have been the only group to conceptualize what it means to understand physics as communicating by multiple modes of representation because the Manitoba grade eleven physics curriculum suggests teachers use multiple modes of representation when teaching physics (Manitoba Education & Training, 2003). The Manitoba physics curriculum describes these modes of representation as visual, graphical, symbolic, and numerical. The visual mode represents a mode where physics can be seen or is visible, the numerical mode represents data such as a table of values, the graphical mode represents a graph representing some physics concept, and the symbolic mode represents some given algebraic physics formula. The Manitoba physics curriculum suggests that "to facilitate teaching and learning, it is important to understand these modes of representation and their relationship to each other" (Manitoba Education & Training, 2003, p. 2:17). The teacher quotes may have reflected some of these modes of representation where physics is represented in multiple ways.

5.1.4 Comparisons of the Making Meaning Category of Description

For the 'making meaning' category of description, the students, teachers, and professors said that what it means to understand physics is to make meaning in two ways: (1) seeing the world differently and (2) connecting physics ideas together.

The students, teachers, and professors all said that what it means to understand physics is to make meaning by seeing the world differently. For example, Amy (student) said, "understanding physics means when I connect physics happening in the real world to understand how a light bulb works, or how light refracts or reflects off an object", Bryan (teacher) said, "understanding physics means connecting physics to the real world to understand the universe", and Paul (professor) said, "understanding physics means you are making connections with physics to understand electricity or the flow of water through pipes…you can connect physics to real world or everyday things". In these illustrative quotes, the participants said that what it means to understand physics is to make meaning by seeing the world differently when they connect physics to the real world. The students, teachers, and professors all used the term 'real world' in their interviews to describe the world outside of the physics classroom and laboratory.

The students, teachers, and professors all said that what it means to understand physics is to make meaning by connecting physics ideas together within the field of physics. For example, Ben (student) said, "what it means to understand physics is to look at all of the ideas and main theories of physics and connect them together", Brody (teacher) said, "I think understanding physics means when I can connect everything I know about physics together", and Riley (professor) said, "to understand physics means you can see how physics topics connect with each other ". In each of these quotes, the participants said that what it means to understand physics is to make meaning by connecting different physics ideas, concepts, and theories together within the field of physics.

Making meaning, by connecting different physics ideas together within the field of physics, may potentially indicate that the nature of physics involves a recursive process where new knowledge is linked to prior knowledge. The Manitoba grade 11 and grade 12 physics curricula includes 'making connections' as one of the parts of the "dynamic processes in literacy learning integrated into science" (Manitoba Education & Training, 2003, p. 2:11). The physics curriculum further describes "making connections" (p. 2:11) as part of a recursive process of learning where “students move back and forth within and between exploring, making connections, creating, revising, and recreating” (p. 2:11) when they learn about physics.

5.1.5 Comparisons of the Application Category of Description

For the ‘application’ category of description, the students, teachers, and professors said that what it means to understand physics is to apply physics in a given context for a specific purpose.

The students, teachers, and professors all said that what it means to understand physics is to apply physics in situations by using physics in the real world. The students, teachers, and professors all used the term ‘real world’ in their interviews to describe the world outside of the physics classroom and laboratory. For example, Brianne (student) said, “I think understanding physics means applying it to the real world”, Brody (teacher) said, “to understand physics means that you can apply it to a situation you’ve never seen before preferably to a real world context”, and Mike (professor) said, “ I think to truly understand physics means you have to apply it or use it. You really don’t understand it until you actually go out in the real world and use it”. For this subcategory, the students, teachers, and professors all said that what it means to understand physics is to apply physics in the real world for some purpose such as the application of physics to calculate satellite orbits. Since all the groups reported this subcategory, this may mean that from novice level physics students, to intermediate level physics teachers, to expert level physics professors, what it means to understand physics is to apply it in a certain way.

The teachers and professors were the only groups who said that what it means to understand physics is to apply it by quantifying. For example, Les (teacher) said, “quantifying in a general way means understanding” and Steve (professor) said, “understanding physics means the ability to observe phenomena, to make measurements that quantify the behaviour I'm seeing". Through quantifying, the professors and the teachers, in the context of conducting research or conducting a laboratory, are making measurements about a given physics phenomenon to analyze and understand it. The students may not have reported this subcategory because in their role as students in the context of the classroom, they may not be familiar with the word 'quantify' but may be more familiar with the concept of taking measurements in the context of performing a classroom laboratory.

The students were the only group who said that what it means to understand physics is to apply it by doing labs. For example, Alex (student) said, "understanding physics means doing labs". The students in their role as learners may have been the only group to report the subcategory 'doing labs' because they are familiar with doing physics labs in the context of the classroom as part of their everyday classroom experience.

The teachers were the only group who said that what it means to understand physics is to apply it by inventing and predicting. For example, Darren (teacher) said, "understanding physics means being able to take what you know and extend it to something completely new by invention", Simon (teacher) said, "I would say understanding means to make predictions. The ability to predict where an object will be after a certain amount of time like with projectiles". Teachers said that what it means to understand physics is to apply physics by creating or designing something new through invention and teachers said that what it means to understand physics is to apply physics by predicting how the world works around them. The teachers in their role as educators in the context of the classroom, may have been the only group to report the subcategories 'inventing' and 'predicting' because they are familiar with teaching about invention and prediction in the context of the Manitoba physics curriculum. The Manitoba physics curriculum mandates physics teachers teach about physics inventions such as the following: (1) Volta's invention of the electric pile in 1800, (2) Claude Servais Mathias Pouillet's invention of the tangent galvanometer in 1837, and (3) as part of the Grade twelve Medical Physics Unit, the invention of nuclear medicine imaging techniques such as MRI, ultrasound, endoscopy, X-ray, CT scanning, PET, heavy isotopes such as Ba; nuclear medicine therapies such as brachitherapy, external beam, and the gamma knife (Manitoba Education & Training, 2005). In addition, the Manitoba physics curriculum mandates physics teachers teach about prediction as part of the "Skills and Attitudes Outcomes Overview" (Manitoba Education & Training, 2005, p. 4:7) where "students develop scientific inquiry through the development of an hypothesis/prediction, the identification and treatment of variables, and the formation of conclusions" (p. 4:7). Therefore, it is no surprise teachers identified 'invention' and 'prediction' because they are mandated to teach about 'invention' and 'prediction' to their physics students as part of the Manitoba high school physics curriculum.

The professors were the only participants who said that what it means to understand physics is to apply it by investigating physics at different scales. For example, Larry (professor) said, "being able to understand means as fully as possible to investigate what happens to physics on all linked scales and timescales". The professors, in their role as researchers in the context of the laboratory, were the only group to conceptualize what it means to understand physics as to investigate different scales. The ability to investigate physics at different scales might require physics expertise that students and teachers do not possess. Physics expertise beyond that which the students and teachers possess may be necessary to design experiments to conduct research at the microscopic, macroscopic, time, energy, atomic, sub-nuclear, and nuclear scales. Jones (2015) emphasizes the importance of understanding physics at different scales when he writes "a characteristic driving force of physicists, both young and old, is to understand the physical universe on all scales" (p. 14).

As mentioned earlier, the teachers said that what it means to understand physics is to quantify, invent, and predict while the professors said that what it means to understand physics is to quantify and investigate physics at different scales. However, the students did not report the teacher and professor subcategories of description quantify, invent, predict, and investigate physics at different scales. It may be speculated that since quantify, invent, predict, and investigate physics at different scales represent cognitive skills (Bloom & Krathwohl, 1956; Wiggins, & McTighe, 1998, 2005) requiring time and experience to develop, the reason the students did not report these categories is that they are novice physics learners and have not yet developed these cognitive skills that the teachers and professors have developed and therefore reported.

5.1.6 Summary

This section examined the similarities and differences (variations) between the students', teachers', and professors' categories of description and the subcategories of description The participants conceived of what it means to understand physics as five categories of description (feelings, communication, achievement, making meaning, and application) and the variation between these categories of description exists within the subcategories of description. The variation in the subcategories of description might be the consequence of the different roles the participants take for a given situation (ie. learner, educator, and researcher), the context of the given situation (ie. school, university, laboratory, and research), and the level of physics expertise each participant possesses (ie. novice, intermediate, and expert). Expertise is further discussed in Section 5.6.

5.2 Contributions to the Literature

This section details three contributions my study makes to the literature. First, the contribution to the literature from the categories and subcategories of description are discussed. Second, the contribution to the literature from the study's outcome space are presented. Third, I present my study's contribution to the literature by examining Zhao's (2015) innovative interpretation of variation in phenomenographic research.

5.2.1 Contribution to the Literature from the Categories and Subcategories of Description

This section highlights key findings that my study's categories of description and subcategories of description contribute to the literature and I contextualize the categories of description and the subcategories of description in relation to the previously discussed literature (Chapter 2). The only category that I report that is also reported in the phenomenographic literature is the 'application' category of description. Although the remaining four categories of description from my study have not been reported in the phenomenographic literature, some of the subcategories of description associated with these categories of description have been reported in the literature. My study is unique to the literature as it examines what it means to understand physics, rather than what has been explored previously in the literature, which was the investigation of university students' conceptions of understanding specific physics concepts, students' conceptions of understanding mechanics (Waterhouse & Prosser, 2000), and students' conceptions of understanding (Irving & Sayre, 2012). Therefore, the lack of similarity between my categories of description and the categories of description reported in the literature is not necessarily surprising.

5.2.1.1 Contribution to the Literature from the Feelings Category of Description

The category of description ‘feelings’ has not been reported in phenomenographic literature but the students’, teachers’, and professors’ subcategory ‘feelings of insight’ has been reported in the literature. The subcategory ‘feelings of insight’ is similar to Entwistle and Entwistles’ (1992) category of description ‘feelings of satisfaction’ where the authors describe the “nature of understanding” (p. 7) as one of the “aspects of the experiences of understanding” (p. 7). Entwistle and Entwistle reported that undergraduate students’ experiences of understanding in revising for degree examinations “generally had a feeling tone associated with it - there was necessarily an emotional response, at least where significant understanding had been achieved” (p. 7). For the category of description ‘feeling of satisfaction’, Entwistle and Entwistle (1992) state that the students’ experienced satisfaction when their confusion for a given topic was “replaced by insight” (p. 7). Students described their feeling of insight where “understanding can be the ‘aha-eureka!’ type where an insight comes in a blinding flash” (Entwistle & Entwistle, 1992, p. 8). For my study, I placed the ‘aha’ and ‘eureka’ feelings that the participants experienced into the subcategory called ‘feelings of insight’.

Some key findings of my study for the ‘feeling’ category of description include that: (1) intuition is an important feeling that professors experienced when they reported what it means to understand physics, and (2) all three groups said that what it means to understand physics is to have a positive emotional response. The participants all said that what it means to understand physics was to experience an emotional response or feeling.

5.2.1.2 Contributions to the Literature from the Achievement Category of Description

The category of description 'achievement' has not been reported in the literature but the students' and teachers' subcategory 'solving physics questions', and the professors' subcategories 'solving physics problems', and 'visualizing' have been reported in the literature.

The subcategories 'solve physics questions' and 'solve physics problems' are similar to Waterhouse and Prosser's (2000) category B 'understand when you can solve problems'. Waterhouse and Prosser (2000) explain that "understanding is when students know they can solve given problems" (p. 5). For my study, both the students and the teachers said that what it means to understand physics is to 'solve physics questions', but the professors said that what it means to understand physics is to 'solve physics problems'. Waterhouse and Prosser interviewed university students about their experiences of understanding mechanics, and the students reported the conception 'solving physics problems', just as the university professors in my study. In my study, the students, teachers, and professors said that what it means to understand physics is to achieve the ability to either solve physics questions or solve physics problems. As previously discussed in Section 5.1.2, there is a difference between 'questions' and 'problems' and how students and teachers interpret these words compared with professors. For my study, the students and teachers interpreted the word 'questions' as having a defined solution that may be found in the back of a physics textbook in the context of the classroom while the professors defined the word 'problems' as having no fixed solution in the context of 'problems' outside of the textbook and classroom. For the Waterhouse and Prosser (2000) study, they reported a category of description "understand when can solve problems" (Waterhouse and Prosser, 2000, p. 5) and explain this category as "understanding occurs when students know they can solve problems they are given" (p. 5). However, Waterhouse and Prosser do not explain if these 'problems' that students solve are textbook physics 'questions' from inside the classroom and with a defined solution or physics 'problems' from outside of the classroom with no defined solution.

The subcategory 'visualization' is similar to Irving and Sayre's (2012) category B 'understand when can use, visualize, and apply in different contexts'. Irving and Sayre (2012) examined university students' "conceptions of understanding" (p. 198) and explain that "understanding is when students can apply understanding in different contexts and can be applied to gain a visualization of a concept" (p. 200). A key finding for my study is that only the professors said that what it means to understand physics is to achieve the ability to visualize physics. I placed 'visualization' as a subcategory of the category 'achievement', but Irving and Sayre (2012) placed 'visualization' as being part of an 'application' category. For my study, the professors framed the ability to visualize physics as a skill achieved through their experience and physics training. The students and the teachers may have not reported 'visualization' since they have not yet attained the expertise of a physics professor.

In summary, for the category of description 'achievement' the students, teachers, and professors all said that what it means to understand physics is to achieve a goal or to achieve the ability to do something. The subcategories that have been reported in the literature for the category 'achievement' include the students' and teachers' subcategory 'solving physics questions', the professors' subcategory, 'solving physics problems', and the professors' subcategory, 'visualization'. The subcategories of description that have not been reported in the phenomenographic literature represent key findings for the category 'achievement' and include the students', teachers', and professors' subcategory 'validating through assessment', the students' subcategories 'deriving physics formulas' and 'conforming to classroom demands', and the professors' subcategory 'conducting physics research'. The category of description 'achievement' is a key finding that has not been reported in the literature.

5.2.1.3 Contributions to the Literature from the Communication Category of Description

The category of description 'communication' has not been reported in the phenomenographic literature but the students', teachers', and professors' subcategories, 'explaining', and 'teaching', have been reported in the literature.

In the communication category of description, my subcategory 'explain', is similar to Entwistle and Entwistles' (1992) category 'confidence about explaining', Waterhouse and Prosser's (2000) category D, 'understand when you can explain it to others or yourself', and Wiggins and McTighe's (2005), 'can explain', facet of understanding.

Entwistle & Entwistle (1992) examined university students' conceptions of understanding in revising for degree examinations and their category of description 'confidence about explaining' is described by a student as follows: "well, for me, it's when I could tell somebody else, if I was asked a question, and I could explain it so that I felt satisfied with the explanation" (p. 10). Waterhouse & Prosser (2000) describe category D, as "understanding is when you feel confident with explanations of objects" (p. 5) and Wiggins and McTighe (2005) describe, 'can explain', as "generalizations or principles, providing justified and systematic accounts of phenomena, facts, and data; make insightful connections and provide illuminating examples or illustrations" (p. 84). It is important to note that Entwistle and Entwistle (1992) and Waterhouse and Prosser (2000) have a category of description that includes 'explanation', but for my study I placed 'explanation' as a subcategory of the category 'communication'. The participants in my study reported ‘explain’ and ‘teach’ as utilizing the method of verbal communication with other people and therefore I put ‘explain’ and ‘teach’ into the ‘communication’ category of description.

The subcategory ‘teach’ is similar to Irving & Sayre’s (2012) category C, ‘understand when can teach someone else’. Irving and Sayre described their category C as “understanding is when you feel you can communicate your interpretation of a concept to someone else” (p. 200). For my study, I placed ‘teach’ as a subcategory of the category ‘communication’. Irving and Sayre recognize that teaching is a form of communication and they have placed ‘explain’ and ‘teach’ into separate categories of descriptions. For my study, I also separated ‘explain’ and ‘teach’ but I have placed them into their own subcategories of description within the category ‘communication’. The students, teachers, and professors all said that what it means to understand physics is to communicate physics through teaching physics to others.

In summary, for the category of description ‘communication’, the students, teachers, and professors all said that what it means to understand physics is to communicate physics to other people. The subcategories of description that have been reported in the literature for the category ‘communication’ include the students’, teachers’, and professors’ subcategories ‘explaining’ and ‘teaching’. The subcategories of description that have not been reported in the literature represent key findings for the category ‘communication’ and include the teachers’ subcategory ‘using multiple modes of representation’. The category of description ‘communication’ is a key finding that contributes to the literature.

5.2.1.4 Contributions to the Literature from the Making Meaning Category of Description

The 'making meaning' category of description has not been reported in the phenomenographic literature but the subcategory of description 'connecting physics ideas together' is similar to Waterhouse and Prosser's (2000) category E "understand when you consolidate your knowledge" (p. 5).

In Waterhouse and Prosser's (2000) category E, the word 'consolidate' means to combine a number of things into a single more effective or coherent whole. Therefore, for my study's subcategory of description, 'connecting physics ideas together', the participants are consolidating their physics knowledge or they are combining a number of different physics ideas together to form a more effective and coherent whole as in the Waterhouse and Prosser's (2000) category E, 'consolidate'. A key finding for my study is the subcategory of description, 'seeing the world differently' since it has not been reported in the literature.

5.2.1.5 Contributions to the Literature from the Application Category of Description

The 'application' category of description has been reported in the phenomenographic literature. Waterhouse and Prosser (2000) have a category of description similar to my category 'application' and label it as 'understand when you can relate to real life situations', which they explain as "apply what you know to real life objects". Additionally, Irving and Sayre (2012) have a category 'apply' in three different levels of their hierarchy for their outcome space and this 'apply' category is similar to my category of description 'application'. Irving and Sayre's three different 'apply' categories include: "category A 'understand when can use and apply', category B 'understand when can use visualize and apply in different contexts', and category E "understand when can apply mathematical description consolidate knowledge" (Irving & Sayre, 2012, p. 200). Therefore, the notion of ‘apply’ in relation to understanding physics is a finding that has been identified by earlier phenomenographic studies.

In the application category of description, my subcategory ‘using physics in the real world’ is similar to Entwistle and Entwistles’ (1992) category ‘flexibility in adapting and applying’, Waterhouse and Prosser’s (2000) category C ‘understand when you can relate to real life situations’, and Wiggins and McTighe’s (2005) facet of understanding ‘can apply’. Entwistle and Entwistle (1992) describe the category ‘flexibility in adapting and applying’ in the following way: “understanding involves being able to apply this information in a different situation than the one it was ‘learnt’ in originally” (p. 10). Waterhouse and Prosser (2000) describe category C as “understanding is when you can apply what you know to real life objects” (p. 5) and Wiggins and McTighe (2005) describe ‘can apply’ as “effectively use and adapt what we know in diverse and real contexts-we can ‘do’ the subject” (p. 84). For my study, the students, teachers, and professors, all said that what it means to understand physics is to apply it by ‘using physics in the real world’.

In summary, for the category of description ‘application’, the students, teachers, and professors all said that what it means to understand physics is to apply physics for some given purpose and the ‘application’ category has been reported in the literature (Waterhouse & Prosser 2000; Wiggins & McTighe 2005; Irving & Sayre 2012). The subcategory of description for my study that has been reported in the literature for the category ‘application’ include the students’, teachers’ and professors’ subcategory ‘using physics in the real world’. The subcategories of description that have not been reported in the literature represent key findings for the category ‘application’, and include the teachers’ and the professors’ subcategory, ‘quantifying’, the students’ subcategory, ‘doing labs’, the teachers’ subcategories, ‘inventing’ and ‘predicting’, and the professors’ subcategory ‘investigating physics at different scales’.

5.2.2 The Contribution to the Literature from the Outcome Space

My study suggested a non-hierarchical, circular, and holistic structure for the outcome space of the conceptions of what it means to understand physics, which has not been reported in the existing literature. What has been reported in the literature about university students’ conceptions of understanding physics concepts is a hierarchical outcome space where the conceptions are logically arranged from a low level to a high level (Waterhouse & Prosser, 2000; Irving & Sayre, 2012). Therefore, my non-hierarchical, circular, and holistic outcome space contributes to the literature since only hierarchical outcome spaces have been reported for studies that investigated students’ conceptions of understanding mechanics (Waterhouse & Prosser, 2000) and students’ conceptions of understanding (Irving & Sayre, 2012).

The outcome space for the phenomenon, what it means to understand physics, represents a set of related categories of description, describes how the categories are internally related, and describes the minimum number of categories that explains all the variations in the data (Marton, 2000; Säljö, 1996; Trigwell, 2000; Walsh et al., 2007). In order to contextualize the structure of my outcome space in the literature, it is vital that the reader remain aware that my study investigated what it means to understand physics, and I was unable to find a published study that also investigated what it means to understand physics. Rather, two studies have investigated university students’ conceptions about understanding mechanics (Waterhouse & Prosser, 2000) and university students’ conceptions about understanding (Irving & Sayer, 2012) which is different from investigating conceptions of what it means to understand physics. In addition, my study examined three groups (high school physics students, high school physics teachers, and university physics professors), whereas the previous studies investigated university physics students. Therefore, it could reasonably be expected that the outcome space from my study would be different from the outcome space reported by Waterhouse and Prosser (2000) and Irving and Sayer (2012). Indeed, this is the case. My outcome space is best visualized as a circular and holistic structure (see Figure 21) for the phenomenon, what it means to understand physics, whereas Waterhouse and Prosser (2000) and Irving and Sayer (2012) depicted their outcome spaces as hierarchical.

The outcome space for the studies of Waterhouse and Prosser (2000) and Irving and Sayer (2012) relied on the authors' judgment to arrange their categories of description from a low level to a high level of complexity of understanding physics concepts, yet the authors did not justify their rationale for placing a particular category into the range of either a low level, mid level, or a high level. For example, in Waterhouse and Prossers' (2000) study, category C, "understanding is when you can apply what you know to real life objects" (p. 5) is located at a lower level than category D, "understand when you can explain it to others or yourself" (p. 5). However, it could be debated that category C, 'apply', could be placed higher in the hierarchy than category D ,'explain', as Anderson and Krathwohl (2001) organize the cognitive process "Apply" (p. 67) at a higher level than the cognitive process "Explaining" (p. 66) in relation to Bloom's Taxonomy. This demonstrates that the authors Anderson and Krathwohl (2001) and Waterhouse and Prosser (2000) placed 'apply' and 'explain' in a different hierarchical order. The difference in the hierarchical ordering between Waterhouse and Prosser (2000) and Irving and Sayer (2012) were examined in Section 2.3.2.

The lack of hierarchy in my outcome space is supported through the writing of Åkerlind (2005a), who suggests “the structure of an outcome space need not always take the form of a linear hierarchy of inclusiveness; branching structures or hierarchies are also a possibility” (p. 329) and also through the writing of Dahlin (2007) who states “it may be observed that not all phenomenographic outcome spaces have a hierarchical structure of dimensions of variation” (p. 336). Furthermore, van Kessel (2016) reported her phenomenographic study about conceptions of evil with an outcome space that was not hierarchical but had five related categories of description or ‘themes’ and a number of subcategories of description or “a variety of interconnected subthemes” (p. 3). Additionally, a recent phenomenographic study about learning science in Mainland China visualized the study findings as non-hierarchical, circular, and holistic (Zhao, 2015; Zhao & Thomas, 2016).

As the outcome space for this study is non-hierarchical, holistic, and best represented by a circle, the categories of description have ‘equality’ amongst one another; no category of description is at a lower level, and no category of description is at a higher level in relation to one another. Educational research supports understanding as “multidimensional and complicated” (Wiggins & McTighe, 2005, p. 84) where aspects of understanding are overlapping and integrated. Entwistle and Entwistle (1992) add that students’ experiences of understanding in revising for degree examinations had a “feeling of wholeness” (p. 18) about it and this wholeness is represented in the holistic character for my study’s outcome space.

The students, teachers, and professors appear to think about what it means to understand physics holistically where the categories of description are intimately interconnected with each other. The participants reported what it means to understand physics is to: experience a feeling, to communicate physics to other people, to achieve a goal or the ability to do something, to make meaning, and to apply physics for some given purpose. The students, teachers, and professors reported all the categories of description and no one category was emphasized over another. Just as the hermeneutic circle is a metaphorical way of conceptualizing understanding (Maturana & Varela, 1992), the circular outcome space for my study may potentially be interpreted as a metaphor for the holistic understanding the students, teachers, and the professors conceptualized about what it means to understand physics.

The variation within the students', teachers', and professors' conceptualizations of what it means to understand physics exists between the subcategories rather than between the five categories of description that form a circular holistic outcome space. For example, the students, teachers, and professors all reported communication as one aspect of what it means to understand physics, but the methods of communication that they described varied and included 'explaining' and 'teaching'. Therefore, as an example, the variation exists in the subcategories of description for the communication category. Although the outcome space is holistic and circular, there is variation between the subcategories of description for each of the three groups (students, teachers, and professors). Åkerlind (2005a) describes the case where variation occurs in the subcategories of a phenomenographic study as follows:

> Where data are perceived as indicating variation that does not appear to form part of a logical relationship between categories, these data may be reported as representing non-critical variation within one or more ways of experiencing, or as sub-categories of a primary category of description. (p. 329)

Therefore, as Åkerlind (2005a) contends, the variation for my study occurs in the subcategories of description rather than between the categories of description.

5.2.3 Contribution to the Literature from an Innovative Interpretation of Variation in Phenomenographic Research

This section describes my study's contribution to Zhao's (2015) innovative interpretation of variation in phenomenographic research where he reported that variation exists in the study participants' subcategories of description rather than the variation existing in the categories of description.

Phenomenography is a research method that examines the qualitatively different ways people experience a phenomenon, such as what it means to understand physics, and attempts to describe the different ways the phenomenon is experienced by the group (Marton, 1986; Edwards, 2007). According to Zhao (2015), traditional phenomenographic analysis examines "the variation that exists between categories, i.e., different groups of people would conceive the same phenomenon as belonging to different categories" (p. 280). For example, Marton et al., (1993) reported that the phenomenon of learning was conceived of by students as belonging to six qualitatively different categories. These categories included: (A) Increasing one's knowledge, (B) Memorizing and reproducing, (C) Applying, (D) Understanding, (E) Seeing something in a different way, and (F) Changing as a person. (Marton et al., 1993, p. 283). Therefore, some students conceived learning as 'applying' while other students conceived of learning as 'understanding'.

However, the students, teachers, and professors for my study conceived of what it means to understand physics holistically as five categories of description (feelings, communication, achievement, making meaning, and application). There was no variation between the categories of description between the groups but there was variation in the subcategories of description. Zhao (2015) and Zhao and Thomas (2016) reported a similar holistic structure and variation within the subcategories when examining Mainland Chinese students' conceptions about learning science. Zhao reported variation in the students' subcategories of description but did not find variation in the categories of description. Zhao writes:

> The variation resides inside the categories. Different students reported different understandings of how and why they should listen to the teacher or attend to exams. Thus, my study presents a new way to look at the variation embedded in phenomenographic research. (Zhao, 2015, p. 281)

Therefore, my study adds to the literature about the innovative interpretation of the variation that exists in phenomenographic research as proposed by the Zhao (2015) study that claimed, "variation resides inside the categories" (p. 281) rather than between categories for different sets of participants.

5.3 Expertise and the Categories of Description

While gathering literature to contextualize my findings, it became apparent that the variation in the professors' subcategories of description when compared to the students' and teachers' subcategories of description could potentially be the consequence of their varying expertise, as Nickerson (1985) suggests "one way of thinking of understanding evokes the notion of expertise" (p. 222). In addition, Walsh, et al. (2007) contend that "a common view throughout the literature is that instruction should encourage students to 'think like a physicist' or result in a shift from a 'novice problem solver' to an 'expert problem solver'" (p. 1).

The professors in my study provided six unique conceptions as reported in the subcategories of description about what it means to understand physics, and these include: (1) feelings of intuition, (2) validating through peer assessment, (3) solving physics problems, (4) conducting physics research, (5) visualizing physics, (6) and investigating physics at different scales.

Nickerson (1985) contends that "one understands a concept (principle, process, or whatever) to the degree that what is in one's head regarding that concept corresponds to what is in the head of an expert in the relevant field" (p. 222). Trowbridge and McDermott (1980) explain the degree of a student's physics understanding in the following way: "we may consider as an indicator of degree of understanding the extent to which a student's understanding corresponds to that of a physicist" (p. 1020). Therefore, the degree to which a physics student understands physics concepts depends on how closely their understanding of these physics concepts corresponds to that of a physicist.

Research examining expertise suggests that it takes about five to ten years to develop in a domain (Bruning et al., 2004; Ericsson, 1996). The term 'novice' is used for individuals who have only "rudimentary competence in the domain" (Priest & Lindsay, 1992, p. 339) whereas experts are defined as individuals with advanced degrees and years of practice within their domain of expertise (Dee-Lucas & Larkin, 1986). In the literature about physics expertise, novices are typically high school students or introductory-level college physics students (Dee-Lucus & Larkin 1986; Finegold & Mass, 1985), "whereas experts are typically found to be physicists, physics professors or doctoral physics students" (Taasoobshirazi & Carr, 2008, p. 151). Based upon the literature, the high school physics students in my study may be considered novices. The high school physics teachers may also be considered novices depending upon whether they have completed physics courses at the university-level making their expertise equivalent to the university student or they may be considered to have expertise intermediate or in between novice and expert if they have completed university-level physics courses. Since university physics professors have extensive physics experience and training, they could be considered as experts.

The majority of the research on expertise in the physics literature has been examined through the following: problem solving strategies, pictorial representation (visualization) of physics problems, domain knowledge as demonstrated through solving physics problems, and metacognition (Kuo et al., 2013; Tobias & Everson 2000; Anzai, 1991; Chi et al. 1989; Davis 1989; Larkin et al., 1980; Tobias & Everson 2000).

Expertise in physics has been primarily examined through the comparison of problem-solving strategies between novices and experts (Kuo et al., 2013; Feil & Mestre; 2010; Mason & Singh, 2011; Ericsson & Smith, 1991). Novice problem solvers have been found to use a 'working backward' strategy through forming an equation that contains the goal of the problem, whereas experts work forward from a set of equations generated from the information provided in the problem (Mason & Singh, 2011; Larkin, 1985; Kuo, et al., 2013). Although my study did not examine the solving of physics problems, interestingly, the professors conceptualized a subcategory of the 'achievement' category of description as 'solving physics problems' whereas the high school students and teachers conceptualized a subcategory of description 'solving physics questions'. The high school students and teachers did not use the word 'problem' but rather used the word 'question' when providing a response to, 'What it means to understand physics?'. The difference in this word usage may demonstrate a difference in the conceptualization of physics problems between the professors, the teachers, and the students. As discussed previously in Section 5.1.2, there is a difference between 'questions' and 'problems' and how students and teachers, in their roles as learners and educators, interpret these words compared with professors, in their roles as researchers. In the context of school, the teachers and students refer to the solving of physics 'questions' that have a defined solution, while in the context outside of school, the professors refer to physics ‘problems’ that do not have a defined solution.

The utilization of a pictorial depiction (visualization) of physics problems has been reported to be a major difference between expert and novice physics problem solvers (Dhillon, 1998; Larkin et al., 1980) and research on expert-novice problem solving has indicated an importance of visual representations in physics (Larkin, 1983; Chi & Glaser, 1988; Ericsson & Smith, 1991). Only the professors in my study reported ‘visualization’ when answering the question ‘What it means to understand physics?’ and this may demonstrate the professors’ expertise with the spatial and visualization demands that are common to physics problem solvers (Larkin et al., 1980). In addition, Moore and Slisko (2017) state that “visualization is a common and important step in expert-like problem solving across multiple disciplines” (p. 156). For example, Allan (professor) said “understanding means I can get a geometric picture of the situation, even in quantum mechanics, which is very hard to visualize”.

Expertise in physics, in terms of domain specific knowledge and the organization of that knowledge, has been examined only in terms of how experts and novices categorize problems (Chi et al., 1981). Experts have been reported to focus on the principles and laws underlying problems while novices focus on the surface features of the problems when categorizing problems (Chi et al., 1981). As my study did not look at physics problem solving, I am unable to relate the professors’ domain specific knowledge directly to the physics expertise literature. However, in the category of description ‘achievement’ the professors reported a unique subcategory of description ‘conducting physics research’ and the act of conducting research may require domain specific knowledge and the ability to organize that knowledge.

Research suggests that effective metacognition is essential for efficient problem solving and for the transition from novice to expert (Tobias & Everson 2000) while Taasoobshirazi and Carr (2008) write that “metacognition has been found to be critical for successful problem solving and understanding [in science]” (p. 157). Shin et al., (2003) reported that high school astronomy students who had metacognitive skills were more likely to do well on problems that required a good conceptual understanding of physics but that metacognition was no a good predictor of their performance when answering problems that could be solved by rote memorization. In addition, metacognition is important when solving physics problems that “require an understanding of the principles and laws of physics” (Taasoobshirazi & Carr, 2008, p. 156). The professor’s expert understanding of the principles and laws of physics may be related to their conception ‘investigating physics at different scales’. For example, when answering the question, ‘What it means to understand physics?’ Steve (professor) said:

> I mean, for most physicists, good physicists, I think understanding means to be able to go down and investigate the microscopic interactions and say this is what’s happening at each scale. I think that human experience stops on the energy scale of fractions of an electron volt. But a physicist doesn’t stop there, a physicist can understand physics at much higher energy scales, at the atomic scale, at the nuclear scale, and at the sub-nuclear scale.

This quote demonstrates that the expert physics professor is able to extend their expert understanding of the principles and laws of physics to all scales, from the very small to the very big. In reflecting upon their physics knowledge, the professors “expertise emerges as a function of reflection on what one knows and what one needs to know” (Taasoobshirazi & Carr, 2008, p.157).

Expertise may be related to the outcome space that was developed for my study as Dahlin (2007) suggests that "an expert in a certain field could be understood as someone who is able to move all over this outcome space, in his or her mind" (p. 339). In addition, Dahlin (2007) writes:

> The expert is one whose understanding encompasses all the conceptions mapped out in the outcome space (and perhaps more than these). This also seems to put the expert in a favourable position for creative conceptional acts. That is, he or she would seem to have a greater potential for constituting new conceptions within the established dimensions of variation, or for going beyond these dimensions by transforming them. (Dahlin, 2007, p. 339).

According to Dahlin (2007), expertise seems to position the expert for 'creative conceptual acts'. Therefore, to help foster expert-like thinking in the physics classroom, "more attention should be placed on the importance of understanding specific strategies that foster creativity at all levels in the classroom" (Žižić, Granić, & Lukie, 2017, p. 95).

The physic professors, who have physics expertise, had the most conceptions of what it means to understand physics and thus engage with every aspect in the outcome space of what it means to understand physics, including the internal variation in the subcategories of description.

5.4 Implications of the Study

My study has potential practical implications for high school physics students, high school physics teachers, and faculties of education responsible for the training of pre-service physics teachers.

(1) My study has implications for the promotion of metacognition in the physics classroom. Metacognition is the thinking about one's thinking, and it may be defined as one's knowledge, control, and awareness of one's thinking and learning (Thomas, 2012a). Mestre (2001) states that "reflecting about one's own learning is a major component of metacognition, and does not occur naturally in the physics classroom, due to lack of opportunity and because

instructors do not emphasize its importance" (p. 47). To emphasize the importance of metacognition to high school physics students, the physics teacher could potentially have students reflect on their physics learning by asking them the research question from my study, 'What does it mean to understand physics?'. By answering this question, students are being given the opportunity to reflect on their physics learning and teachers could potentially use this moment to teach their students about metacognition. Currently in the Manitoba physics curriculum, metacognition is not an outcome for teachers to teach to students. By including metacognition into the Manitoba physics curriculum and teaching physics students about metacognition, this may be used to potentially improve physics students' learning "as there is a need to develop and enhance their adaptive metacognition so that they can learn more effectively, efficiently, and with increased understanding" (Thomas, 2012b, p. 30). When teachers ask their students the question, 'What does it mean to understand physics?', the students may experience a 'metacognitive experience' (Flavel, 1979) that further helps to develop their metacognition. A metacognitive experience is defined by Thomas (2013) as "a conscious experience that occurs when one considers one's cognitive and learning endeavours or one's metacognitive knowledge" (p. 5). According to Thomas, these metacognitive experiences are key because they can lead to the development and enhancement of students' metacognition. Finally, Lukie (2015) contends that in the physics classroom, "when students reflect on the thinking processes they attended to in designing acronyms, many should report a metacognitive experience resulting from having been stimulated by their teacher to think about acronyms in a way they had not done previously" (p. 31). Therefore, having physics students design acronyms to help them remember physics formulas is a way to promote metacognition and metacognitive experiences in the physics classroom (Lukie, 2015).

Haagen-Schützenhöfer (2017) states that physics education research “hardly effects school teaching practice… our experience shows that teachers are longing for teaching materials ready to use in class” (p. 105). To facilitate the utilization of my study’s findings, a small curriculum unit about metacognition could be written as ‘ready to use’ for the high school physics classroom and teachers could begin teaching the metacognition unit by first asking students to reflect upon the research question from my study, ‘What does it mean to understand physics?’. Students may not have previously reflected upon their thinking and the teacher could use this opportunity to teach students about the benefits of metacognition or the thinking about ones’ thinking.

(2) Faculties of education may potentially use the results of my study to inform students, pre-service physics teachers, and teachers about what expert physicists think it means to understand physics. These expert physicists’ conceptions could be potentially studied by pre-service physics teachers and teachers so that they may inform their physics students about these conceptions of experts. For example, physicists were the only participants who conceived of what it means to understand physics as ‘visualization’ and to ‘investigate physics at different scales’. Therefore, visualization techniques and investigating physics at multiple scales could be included as part of the Manitoba physics curriculum to be taught to students and pre-service teachers. The importance of physics visualization has been stated by Moore and Slisko (2017) and the importance of understanding physics at multiple scales has been stated by Jones (2015). Jones (2015) writes that “a characteristic driving force of physicists, both young and old, is to understand the physical universe on all scales, i.e. it is an intellectual pursuit” (p. 14).

(3) My study has potential to provide insights into students’ conceptions about what it means to understand physics that may potentially enable teachers and professors “to more fully

understand students' classroom behaviour, including their resistance to teachers' use of strategies that aim to challenge the transmissionist, behaviourist paradigms that so often guide classroom practice and students' learning processes" (Thomas & McRobbie, 1999, p. 668). In the 'achievement' category of description, students, in their role as learners and in the context of the classroom, reported a conception of what it means to understand physics as 'conforming to classroom demands'. For example, Alex (student) said:

> What it means to understand physics is being able to follow along, listen, and keep up with the teacher. Understanding physics means following along with all the questions, if you're following along in class and listening to the teacher and doing all these examples that are down on the board. (Alex)

Alex's conception reflects his experience with a transmissionist pedagogy and his consequent objectivist epistemology where students conform to the demands of the classroom such as following along with the teacher as physics notes are given and following along and working through problems provided by the physics teacher on the board. The 'conforming to classroom demands' conception might provide insight for physics teachers that some students conceive of learning physics as transmisionist, and that alternative pedagogies could be employed that promote a constructivist student epistemology.

(4) The subcategory 'intuition' may have implications for physics students and physics teachers. Simon and Simon (1978) state that "physicists and engineers often refer to 'physical intuition' as an essential component of skill in solving physics problems" (p. 224), where this physical intuition can be described as trustworthy knowledge "constructed from experience and perception" (p. 33). Simon and Simon interpret 'physical intuition' as "when a physical situation is described in words, a person may construct a perspicuous [clearly expressed and easily understood] representation of that situation in memory" (p. 225) and I contemplate whether the

word ‘representation’ may be related to visualization? The relationship between intuition and visualization may warrant further investigation. As “an advantage in physical intuition accounts for the superior ability of physicists to solve physics problems” (Simon & Simon, 1978, p. 230), it may be potentially beneficial to inform students and teachers about intuition and how it might be developed.

(5) An interesting result from my study is how the physics classroom is not seen by some high school physics students as the ‘real world’. The students used the exact term ‘real world’ in their interviews to describe the world outside of the physics classroom. For example, Brianne (student) said “I think understanding physics means applying it to the real world because you can only go so far in a classroom”, John (student) said “understanding physics means to be able to look at something that you’ve learned in class and make a real world connection to it”, and Amy (student) said “to understand physics means if I’m able to apply what I’ve been taught in the real world”.

According to Wieman and Perkins (2005) “students see physics as less connected to the real world, less interesting, and more as something to be memorized without understanding” (p. 37) and Lorsbach and Tobin (1992) add that students often “separate school science from their own life experience” (p. 3). In my study, students seemed to express a similar sentiment. Therefore, the results of my study suggest that a stronger link must be facilitated between the students’ ‘real world’ outside of the physics classroom and the students’ world inside of the classroom.

To create a stronger link between the students’ own life experience and the world of the classroom, contextual activities could be facilitated that include student interests that increase the engagement of students. These contextual activities “relate learning to an application in the real world" (Whitelegg & Parry,1999, p. 68) and can involve a "Large Context Problem (LCP) approach…based on the general observation that learning could be well motivated by a context with one unifying central idea capable of capturing the imagination of the students" (Stinner, 2006, p. 19). For example, teaching about electromagnetism through the context of the history and invention of the electric guitar and pickup where students build an electric guitar and pickup (Lukie, 2012; Metz & Lukie, 2013).

The physics classroom remains dominated by "the work of students doing laboratory exercises (producing 'cold discoveries')" (Roth, 2013, p.10) that are based upon "the work of scientists (who are said to do science authentically producing 'hot discoveries')" (p. 10). What is needed in the physics classroom is "teaching science in and through student-designed and directed inquiry and small-group work" (Roth, 2016, p. 301). In describing the state of physics instruction in Ontario, Roth (2013) describes the following:

> Although all the fellow physics teachers from other schools that I met while teaching high school physics used lectures, assigned textbook word problems, and used standard prescribed laboratory exercises to realize the official Ontario provincial syllabus, my students spent 70% of their time in class on designing experiments, conducting experiments, analyzing the data using sophisticated statistics software, and wrote research reports. (p. 137)

As a physics teacher I am in agreement with Roth's (2016) idea where 70% of student time is spent on designing authentic student designed experiments rather than simply producing inauthentic "cold discoveries" (Roth, 2013, p.10) based upon scientists' authentic "hot discoveries" (p.10). The challenge of bringing the outside world into the high school physics classroom might be mitigated through more contextual activities for students and having students design labs based upon their personal interests.

5.5 Limitations of the Study

There is a need for studies to be transparent when reporting their limitations. In particular, the contextual nature of qualitative research means that careful thought must be given to the potential transferability of its results to other settings (Kuper et al., 2008). Transferability depends on the authors' transparency of their study's limitations (Kuper et al. 2008) and I present these limitations in the following paragraphs before providing suggestions for future research.

(1) The high school physics student participants were recruited from high schools in Winnipeg, Manitoba. A limitation is that students were only recruited from one province in Canada and may not be a representative sample for Canadian high school students. Although, this sample of high school physics students may not reflect a representative sample of Canadian high school physics students, Gunstone (1987) suggests that "students' physics understanding is consistent across diverse samples of students" (p. 691) implying that the results of my study may potentially be transferrable to other similar settings.

(2) In Manitoba, where my study occurred, high school teachers are granted a kindergarten to grade twelve teaching certificate that permits them to teach any grade and in any subject resulting in many out-of-field teachers for a given field of teaching. This situation may potentially result in high school physics teachers who have not taken any undergraduate courses in physics and who may not have any formal physics training. In describing these types of physics teachers, the term 'out-of-field' is often used. During my data collection, I asked the teacher participants to self report as in-field or as out-of-field physics teachers. Sixty-one percent of the physics teachers identified as out-of-field and thirty-nine percent of the physics teachers reported as in-field physics teachers. Since the majority of physics teachers in my study were out-of-field teacher participants, this may reduce the transferability of the teachers' conceptions

of what it means to understand physics to jurisdictions where only in-field physics teachers teach high school physics.

(3) My study interviewed university physics professors from the province of Manitoba, and I made no distinction between physicists involved in research and physicists whose primary responsibility was teaching. However, there is the possibility that there could be a difference between the conceptions of teaching physicists and research physicists regarding what it means to understand physics.

(4) A limitation for my study is that the participants were not given the interview questions in advance. The following insight was shared by a teacher participant:

> Now I'm almost wishing I would've had these questions ahead of time because I feel like they're really juicy, like I feel like there's a lot that could be said about what it means to understand physics. (Helen)

According to Wiggins and McTighe (2005), understanding for a given topic is multidimensional and complicated and according to White and Gunstone (1992), complex concepts require time to formulate reflective responses. Therefore, it could have been beneficial to provide the participants with the study questions prior to the interview so that they could have had a period of time to reflect upon their responses to the question, 'What it means to understand physics?'. Future studies that investigate what it means to understand some other educational domain or phenomena may consider providing the participants the opportunity to read and think about the interview questions in advance.

5.6 Suggestions for Future Research

(1) For my study, I interviewed high school physics students, high school physics teachers, and university physics professors. Pre-service physics teachers and university physics

students were two populations that were not included in my study and future studies could investigate what it means to understand physics for these populations. Through examining the conceptions of what it means to understand physics from the pre-service physics teachers and university physics students, additional data could be obtained to provide a broader image of what all the populations involved in physics education think about what it means to understand physics.

(2) My dissertation has problematized the space for the research question, what it means to understand physics. By problematizing the space, researchers my begin to think about what it means to understand physics so future similar research may be undertaken to extend my study.

(3) Moore and Slisko (2017) contend that visualization is common to expert physics problem solvers and Kozhevnikov et al., (2010) suggest that visualization is important to the process of scientific discoveries. Since visualization is important to problem solving and when making discoveries, visualization requires further investigation. Physicists could be asked how visualization helps them to solve physics problems, how they apply visualization when conducting research, and professors could be asked for specific examples about how to teach visualization to students. The professor responses could be provided to classroom physics teachers so that they may discuss how expert physicists use visualization in the field of physics and the benefits of using visualization.

(4) Intuition is a potential area of future research since this conception was only reported by the physics professors. Intuition could be investigated through Jungian analytical psychology, which is the theory and approach to the practice of psychology that was developed by Carl G. Jung (Mayes, 2005, 2007, 2010; Dobson, 2008). Importantly, Dobson (2008) suggests that “long have the dominant approaches to educational psychology overlooked the unconscious

dimensions of the mind" (p. 7). Therefore, the unconscious dimensions of the mind, such as intuition, could be potentially illuminated through analytical psychology and a study that investigates the professors' personality types. According to Jung (1923), intuition is one of four paired personality types, and he distinguishes them as "thinking/feeling and intuition/sensation" (p. xvii). Future research could involve determining the professors' personality type by asking them to take the Myers-Briggs personality test (Quenk, 2009). A potential question of study may include the extent to which intuition is the result of personality type, physics training, or a combination of both.

The writings of Carl Jung could be examined to provide further insight into intuition. For example, Wolfgang Ernst Pauli (1945 Nobel prize in physics) corresponded with Carl G. Jung in a series of letters from 1932-1958 that have been compiled into a book. In writing to Jung, Pauli explains about the "value of intuition to science's empiricism" (Jung & Pauli, 2014, p. xxxiv). In Jung's Collected Works (1921/2014), Jung describes intuition as:

> In intuition, a content presents itself whole and complete, without our being able to explain or discover how this content came into existence. Intuition is a kind of instinctive apprehension, no matter of what contents. Intuitive knowledge possesses an intrinsic certainty and conviction. (par. 770, p. 453)

Therefore, physics professors could be asked to comment on Carl Jung's conception of intuition and Wolfgang Pauli's views about intuition.

5.7 Development as a Researcher

In the following section, I discuss my development as a researcher and what I have learned from the process of undertaking qualitative research for my dissertation.

(1) My development as a researcher began with my Master of Education degree. I pursued a Master of Education degree because as a high school physics, science, and

mathematics teacher, I was motivated by a desire to increase my students' 'intellectual engagement' (Willms et al., 2009) and their understanding of physics concepts including the difficult concept of electromagnetism. I designed classroom based contextual activities where grade twelve physics students made an electric guitar and pickup and I designed lessons about the history and invention of the electric guitar that contextualized the concept of electromagnetism (Lukie, 2012). Stinner (1994), suggests that there is strong evidence indicating that learning methods that are embedded in a context such as Stinners' (2006) 'Large Context Problem (LCP)' are useful and essential. Furthermore, Stinner (1994) argues that the history of science may be used to help humanize the work of scientists making it easier for students to relate to these scientists and to their work while McKinney and Michalovic (2004) add that "including the history and nature of science adds understanding to science classes" (p. 46).

My mixed methods research revealed that students were positively engaged with the contextual activities of building an electric guitar and pickup and that they were positively engaged with the lessons about the history and invention of the electric guitar. Students said the following: "I loved everything. This was the highlight of this school year. It showed me how I can use electromagnetism at home." (Lukie, 2012, p. 135), "The hands-on activity of building the guitar pickup related all of the concepts we've been learning about." (p. 135), and "Learning about the history of the guitar and how electromagnetic pickups work was very interesting, especially considering the fact that I play guitar as well." (p. 136).

The students' 'intellectual engagement' facilitated their deeper conceptual understanding of electromagnetism and according to Metz and Lukie (2013), the students' "cognitive engagement represents a mental effort that promotes deeper understanding of scientific concepts promoting [their] intellectual achievement" (p. 2). By introducing my physics classroom activities, where students built an electric guitar and pickup, I tried to tap into my students' love of music and inspire some 'romance' (Winchester, 1989, p. i) within the complicated topic of electromagnetism so that students could move their learning to a connected realm.

These contextual physics classroom activities allowed me to dwell in the zone between the Manitoba physics 'curriculum as plan' and the 'curriculum as lived' (Aoki, 2005) where "the quality of curriculum-as-lived experiences is the heart and core as to why we exist as teachers" (Aoki, 2005, p. 165). This notion of 'curriculum as lived' is further supported by Roth (2013) who reports the benefits of a "planned, enacted, and living science curriculum" (p. 137). The students inside of my physics classroom were very interested about the electric guitar, its history, and music, and in turn became very interested about Faraday's law of electromagnetic induction as a result of engaging with contextual activities.

Building off of my M.Ed. research, I pursued a Ph.D. to continue my research with high school physics students, but to now include high school physics teachers and university physics professors and to investigate about their conceptions of what it means to understand physics.

Now that my dissertation has been written, I am reminded of Constantine P. Cavafy's poem 'Ithaca' (see Appendix AA) and the long journey Odysseus took to reach his island home. Just as Odysseus' journey to Ithaca provided him with adventure and knowledge, my Ph.D. has also given me a wonderful journey and has provided me with much wisdom and rich experiences. Ithaca symbolizes the end of Odysseus' journey and the completion of my dissertation symbolizes the end of my current academic journey.

(2) For my dissertation research, my data collection resulted in seventy-three participants and 43.5 hours of recorded interview data to transcribe. As I was teaching full time during the

data analysis stage, I learned how to effectively manage my time by adhering to a strict research and teaching schedule.

(3) With the large amount of transcribed data that I had to analyze, I learned the importance of a well-structured electronic database such as the Excel spreadsheet program. I used Excel to organize and store my data and data analysis (see Section 3.6.4) in a matrix of findings.

(4) As I read the seventy-three transcribed interviews, I learned that multiple readings of a transcript are necessary to ensure that I fully grasped the perspectives each of the participants shared with me during the interviews. I learned that for each subsequent reading of a transcript, I discovered further and sometimes new insights into what the participant described to me. In addition, I learned that if I read a transcript months later after my initial reading, that sometimes additional insights about the data came to me that were fruitful.

(5) I discovered that there is no 'how to' manual or 'do it yourself (DIY)' guide for conducting phenomenographic research. As a result, I gathered as much literature about phenomenography that I could, I read it, and then I attempted to make sense of this literature for myself. The phenomenographic literature frustrated me as a researcher because this literature described "divergent interpretations of theory, variation in the naming of the parts of a conception, and insufficient or inconsistent definitions and applications of the [what/how and referential/structural] frameworks" (Harris, 2011, p. 115).

(6) I learned about phenomenography and how it may be applied to qualitative data to organize participants' experiences of what it means to understand physics through categories and subcategories of description based upon their conceptions of this phenomenon.

5.8 Conclusion

To date, no published studies describe students', teachers', and professors' conceptions of what it means to understand physics and my study begins to fill this gap in the literature. There are studies that have examined university students' conceptions of understanding physics concepts (see Section 2.3.2), conceptions of understanding mechanics (Waterhouse & Prosser, 2000), and conceptions of understanding (Irving & Sayre, 2012), but these studies are different from my study because investigating conceptions of understanding for a given physics concept and investigating conceptions of understanding is not the same as investigating conceptions about what it means to understand physics. In my study five conceptions of what it means to understand physics emerged from the data: (1) feelings, (2), achievement, (3) communication, (4) making meaning, and (5) application. Additionally, twenty-two subcategories of description emerged from the data. The professors reported the greatest number of subcategories of description about what it means to understand physics, the students reported the least number of subcategories of description, and the frequency of these subcategories of description may be potentially related to the level of the participants' physics expertise.

The outcome space for this phenomenographic study is non-hierarchical, circular, and holistic where the variation between the categories of description lies in the subcategories of description. The circular outcome space may also suggest that the process of understanding is circular, as is illustrated by the paradox of knowledge, "the more one learns, the more one comes to realize how profound one's ignorance really is" (Nickerson, 1985, p. 221). Furthermore, Kerwin (1993) contends that:

> It requires understanding, sometimes a great deal, to be aware of what we do not know. The better we understand something the better we understand how little we know about

> it, and how much we have to learn. Awareness of ignorance occasions inquiry, and fuels it. (p. 172)

Thus, the learner is constantly in the process of understanding something and understanding can be thought of as circular. This circular understanding process is described by Gadamer (2006) in terms of Heidegger's hermeneutic circle where "constantly understanding understands itself" (p. 268).

The potential value in my study arises through providing high school physics students, high school physics teachers, and pre-service physics teachers with the conceptions of expert physics professors regarding what it means to understand physics. This opportunity facilitates these groups' familiar 'horizons' of thinking about physics to be moved toward the formation of new meanings about physics with the integration of the professors' conceptions about what it means to understand physics or the 'fusion of horizons (*Horizontverschmelzung*)' (Gadamer, 2006).

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Appendix A: Interview Protocol

Part 1. Introduction to the Interview

The purpose of my research is to determine your conceptions of understanding physics by asking you to respond to a series of questions. The interview should only take about thirty minutes. I will be audio recording the interview and I appreciate your willingness to allow me to do so with your signed informed consent. The audio recording will be kept secure and confidential. Once the interview has been transcribed, and after the data has been analyzed, the audio recording will be erased. There is no right or wrong answer to the questions. Consider this interview as simply a conversation between us where you have the opportunity to tell me what you think about the topic of what it means to understand physics.

Part 2. Interview Questions

(a) Student Interview Questions

(1) Do you have any questions before we begin?
(2) What grade you are in?
(3) Do you like studying physics?
(4) What physics topics have you enjoyed studying and why?
(5) What physics topics haven't you enjoyed studying and why?
(6) How do you know when you have understood something and tell me the characteristics about that?
Probe
- Tell me more about that.
- Is there a feeling associated with it?

(7) Tell me about the last time when you didn't understand something and tell me the characteristics about that.
Probe
- Tell me more about that.
- Is there a feeling associated with it?

(8) Describe to me what sorts of things have you understood in general?
Probes:
- Why do you think you've understood them?
- What process did you use to get to that understanding?

(9) What do you think you consider it means to understand physics?
Probe
- Tell me a bit more about that.

(10) Do you think you understand physics well?
Probe
- What sort of things do you do to understand physics?
- Why was this helpful to your understanding?

(11) Can you give me an example of some physics topic you understand well?
Probes:

- How do you know you understand the topic you just described?
- What did you do to achieve this understanding?
- Why did you do it that way?

(12) Can you give me an example of some physics topic you didn't understand well?
Probes:
- How do you know you didn't understand the topic you just described?

(13) Do you think physics is easy or difficult to understand?
Probes:
- Can you describe more about what you have just said?

(14) Do you think understanding physics is similar to other types of understanding?
Probes:
- Can you describe more about what you have just said?
- Why do you think this understanding is similar?

(15) I'd like to start finishing up now. Earlier I asked you what understanding physics means to you. At that stage, the question came out of the blue, and since then we've been talking about some specific examples of your understandings of physics. Now that you've had a chance to think about it, I'd just like to step back for a moment and ask you to summarise for me what understanding physics means to you.

(16) Before we finish, is there anything you would like to add that you haven't already mentioned?
Probe:
- Is there anything else you'd like to say?

(17) Thank you for agreeing to be interviewed. Once the data has been analyzed you will be contacted about how you may access the research results.

(b) Teacher Interview Questions

(1) Do you have any questions before we begin?

(2) Can you tell me a little about your current teaching position?
Probes:
- How long you have been teaching physics for?
- Did you specifically go into teaching to be a physics teacher?
- Tell me a little bit about your educational background and what degrees you have?
- What university physics courses have you taken?

(3) Do you like teaching physics and can you describe why?

(4) What physics topics have you enjoyed teaching and why?

(5) What physics topics haven't you enjoyed teaching and why?

(6) How do you know when you have understood something and tell me the characteristics about that?
Probe
- Tell me more about that.
- Is there a feeling associated with it?

(7) Tell me about the last time when you didn't understand something and tell me the characteristics about that.

Probe
- Tell me more about that.
- Is there a feeling associated with it?

(8) Describe to me what sorts of things have you understood in general?
Probes:
- Why do you think you've understood them?
- What process did you use to get to that understanding?

(9) What do you think you consider it means to understand physics?
Probe
- Tell me a bit more about that.

(10) Do you think you understand physics well?
Probe
- What sort of things do you do to understand physics?
- Why was this helpful to your understanding?

(11) Can you give me an example of some physics topic you understand well?
Probes:
- How do you know you understand the topic you just described?
- What did you do to achieve this understanding?
- Why did you do it that way?

(12) Can you give me an example of some physics topic you didn't understand well?
Probes:
- How do you know you didn't understand the topic you just described?

(13) Do you think physics is easy or difficult to understand?
Probes:
- Can you describe more about what you have just said?

(14) Do you think understanding physics is similar to other types of understanding?
Probes:
- Can you describe more about what you have just said?
- Why do you think this understanding is similar?

(15) I'd like to start finishing up now. Earlier I asked you what understanding physics means to you. At that stage, the question came out of the blue, and since then we've been talking about some specific examples of your understandings of physics. Now that you've had a chance to think about it, I'd just like to step back for a moment and ask you to summarise for me what understanding physics means to you.

(16) Before we finish, is there anything you would like to add that you haven't already mentioned?
Probe:
- Is there anything else you'd like to say?

(17) Thank you for agreeing to be interviewed. Once the data has been analyzed you will be contacted about how you may access the research results.

(c) Professor Interview Questions

(1) Do you have any questions before we begin?

(2) Can you tell me about your current teaching position?

Probes:

- What undergraduate physics courses you have taught?
- What are your current research interests?

(3) Do you like teaching physics and can you describe why?
(4) What physics topics have you enjoyed teaching and why?
(5) What physics topics haven't you enjoyed teaching and why?
(6) How do you know when you have understood something and tell me the characteristics about that?
Probe

- Tell me more about that.
- Is there a feeling associated with it?

(7) Tell me about the last time when you didn't understand something and tell me the characteristics about that.
Probe

- Tell me more about that.
- Is there a feeling associated with it?

(8) Describe to me what sorts of things have you understood in general?
Probes:

- Why do you think you've understood them?
- What process did you use to get to that understanding?

(9) What do you think you consider it means to understand physics?
Probe

- Tell me a bit more about that.

(10) Do you think you understand physics well?
Probe

- What sort of things do you do to understand physics?
- Why was this helpful to your understanding?

(11) Can you give me an example of some physics topic you understand well?
Probes:

- How do you know you understand the topic you just described?
- What did you do to achieve this understanding?
- Why did you do it that way?

(13) Can you give me an example of some physics topic you didn't understand well?
Probes:

- How do you know you didn't understand the topic you just described?

(13) Do you think physics is easy or difficult to understand?
Probes:

- Can you describe more about what you have just said?

(14) Do you think understanding physics is similar to other types of understanding?
Probes:

- Can you describe more about what you have just said?
- Why do you think this understanding is similar?

(15) I'd like to start finishing up now. Earlier I asked you what understanding physics means to you. At that stage, the question came out of the blue, and since then we've been talking

about some specific examples of your understandings of physics. Now that you've had a chance to think about it, I'd just like to step back for a moment and ask you to summarise for me what understanding physics means to you.

(16) Before we finish, is there anything you would like to add that you haven't already mentioned?

Probe:

- Is there anything else you'd like to say?

(17) Thank you for agreeing to be interviewed. Once the data has been analyzed you will be contacted about how you may access the research results.

Appendix B: Student Information Letter

UNIVERSITY OF
ALBERTA

Department of Secondary Education
551 Education South
Edmonton, Alberta, T6G 2G5, Canada
Phone: (780) 492-3674
Fax: (780) 492-7622
Email: educ.sec@ualberta.ca

Student Information Letter

May 04, 2016

Dear Student,

I would like to invite you to take part in an educational research study entitled, **A Phenomenographic Study Mapping the Qualitatively Different Ways in Which Secondary Physics Students, Teachers, & University Physics Professors Conceptualize Various Aspects of Understanding Physics.** This study is being undertaken to fulfill the partial degree requirements for my doctorate in secondary science education at the University of Alberta. You are being invited to participate because you are a grade twelve high school physics student and I am interested in learning what your conceptions are about what you think it means to understand physics.

The purpose of this study is to close the gap between secondary physics students', secondary physics teachers', and university physics professors' conceptions of what it means to understand physics are so that students' learning might be enhanced. The findings from this study will inform science education and teacher education programs. There is very limited scholarship on secondary physics students', teachers', and professors' conceptions of what it means to understand physics and this study will begin to fill this gap. Thus, your willingness to participate would be most appreciated.

Your participation in this study is purely voluntary and you are under no obligation to agree to participate in this study. Your full participation in the study would involve you, over the period of your involvement in grade twelve physics in the current academic year, being interviewed once by Michael Lukie, about what you think it means to understand physics for no longer than thirty minutes. If you are uncomfortable with being audio recorded, you may choose not to participate. If you decide to participate with the interview, you would be contacted by e-mail regarding your availability and willingness to be interviewed. The interview would be between you and I and the interviews would be audio recorded. The interview will be scheduled at a time of mutual convenience and will take place somewhere at your school that is suitable, convenient and agreed upon by both parties and your school. In addition, you are not obliged to answer any specific question during the recorded interview process even if you participate in the study. Even if your teacher has agreed to be part of the study you are not obliged to participate, and your current course standing will not be affected in any way.

You will be able to opt out of the study at any point up until one month after the data has been collected, simply by informing Michael Lukie or your teacher that you do not wish to continue to participate. In the event you withdraw your participation, any data that has been collected from you will be removed from the data set.

Results of the study will be presented at academic and professional conferences and may appear in academic and professional journals. Research reports might include direct quotes made by you but your name will not be used. All identifying information (e.g., your name) will be omitted whenever the results are made public to ensure your privacy, anonymity, and confidentiality. The plan for this study has been reviewed for its adherence to ethical guidelines by a Research Ethics Board at the University of Alberta. For questions regarding participant rights and ethical conduct of research, contact the Research Ethics Office at (780) 492-2615.

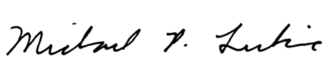
Only I will have access to the data that will be stored securely at all times at the University of Winnipeg in a locked filing cabinet or safe. Only I will transcribe your recorded verbal audio data and only I will analyse the data. You will not be identified through the transcription or data entry process. Once data has been digitized (within one month of collection) all identification will be removed, and names will be replaced with pseudonyms and codes. Only my supervisor, Professor Gregory P. Thomas, will have access to the digitized, anonymous data. The data used in the study will be securely stored for a minimum of five years and will then be destroyed.

Two copies of the letter of assent/consent will be provided. One copy should be signed and returned, and the other copy should be kept for your records. If you are under the age of eighteen, although you may give your assent to participate in the study, your parent/guardian must still provide their consent for your participation.

If you have any questions regarding the study, you may contact Michael Lukie at (204) 290-8282 (mlukie@ualberta.ca) or his supervisor, Professor Greg Thomas at (780) 492-5671 (gthomas1@ualberta.ca). If you have any questions or concerns regarding how this study is being conducted, you may contact the Research Ethics Office at (780) 492-2615. This office has no affiliation with the study investigators.

Thank you very much for considering this request.

Sincerely,



Michael Lukie, Ph.D. Candidate (University of Alberta).

Appendix C: Student Letter of Assent

UNIVERSITY OF
ALBERTA

Department of Secondary Education
551 Education South
Edmonton, Alberta, T6G 2G5, Canada
Phone: (780) 492-3674
Fax: (780) 492-7622
Email: educ.sec@ualberta.ca

Student Letter of Assent (for students under 18)

Please sign your name below to indicate your willingness to take part in the study described above.

I____, have received and had explained

to me by Michael Lukie of the Faculty of Education, University of Alberta, an attached information letter asking me to consent to participate in the research study, **A Phenomenographic Study Mapping the Qualitatively Different Ways in Which Secondary Physics Students, Teachers, & University Physics Professors Conceptualize Various Aspects of Understanding Physics**, conducted by Michael Lukie.

In agreeing to take part in this study, I understand that:

- I have been asked to participate in a research study.
- I understand the benefits and risks involved in participating in the research study.
- I have had the opportunity to ask questions and discuss the study.
- I am under no obligation to participate.
- The interview will be audio recorded.
- Even after giving my assent to take part, I may discontinue my participation without penalty at anytime. I may withdraw information that was already collected by contacting Michael Lukie or my teacher within one month of the collection of that data.
- Information that I provide will be treated as confidential. Direct quotes from me may be used in research reports (i.e., presentations and publications), but my name and other identifying information will be changed or omitted.
- Research reports will be used for academic and professional presentations (e.g. conferences, workshops) as well as academic and professional publications. They will also be used to inform physics education practices.
- I am under no obligation to participate in this study and that I can withdraw from the study after which any information or data that directly link to me as an individual will be excluded from the study.

I hereby agree to being interviewed once by Michael Lukie about my views of what it means to understand physics for no longer than thirty minutes. The interview will be scheduled at a time of mutual convenience and will take place somewhere at my school that is suitable, convenient and agreed upon by both parties and my school. I am not obliged to answer any specific question during the recorded interview process.

Print Name: ____________________________________E-mail: ______________________

Signature: ______________________________________ _______/_______/_______

Date (Day/Month/Year)

Appendix D: Student Letter of Consent

UNIVERSITY OF
ALBERTA

Department of Secondary Education
551 Education South
Edmonton, Alberta, T6G 2G5, Canada
Phone: (780) 492-3674
Fax: (780) 492-7622
Email: educ.sec@ualberta.ca

Student Letter of Consent (For students over 18)

Please sign your name below to indicate your willingness to take part in the study described above.

I____, have received and had explained to me by Michael Lukie of the Faculty of Education, University of Alberta, an attached information letter asking me to consent to participate in the research study, **A Phenomenographic Study Mapping the Qualitatively Different Ways in Which Secondary Physics Students, Teachers, & University Physics Professors Conceptualize Various Aspects of Understanding Physics**, conducted by Michael Lukie.

In agreeing to take part in this study, I understand that:

- I have been asked to participate in a research study.
- I understand the benefits and risks involved in participating in the research study.
- I have had the opportunity to ask questions and discuss the study.
- I am under no obligation to participate.
- The interview will be audio recorded.
- Even after giving my consent to take part, I may discontinue my participation without penalty at anytime. I may withdraw information that was already collected by contacting Michael Lukie or my teacher within one month of the collection of that data.
- Information that I provide will be treated as confidential. Direct quotes from me may be used in research reports (i.e., presentations and publications), but my name and other identifying information will be changed or omitted.
- Research reports will be used for academic and professional presentations (e.g. conferences, workshops) as well as academic and professional publications. They will also be used to inform physics education practices.
- I am under no obligation to participate in this study and that I can withdraw from the study after which any information or data that directly link to me as an individual will be excluded from the study.

I hereby agree to being interviewed once by Michael Lukie about my views of what it means to understand physics for no longer than thirty minutes. The interview will be scheduled at a time of mutual convenience and will take place somewhere at my school that is suitable, convenient and agreed upon by both parties and my school. I am not obliged to answer any specific question during the recorded interview process.

Print Name: ____________________________________E-mail: ______________________

Signature: ____ _______/_______/_______

Date (Day/Month/Year)

Appendix E: Parent/Guardian Information Letter

UNIVERSITY OF

ALBERTA

Department of Secondary Education
551 Education South
Edmonton, Alberta, T6G 2G5, Canada
Phone: (780) 492-3674
Fax: (780) 492-7622
Email: educ.sec@ualberta.ca

Parent/Guardian Information Letter

May 04, 2016

Dear Parent/Guardian,

I would like to invite your son/daughter to take part in an educational research study entitled, **A Phenomenographic Study Mapping the Qualitatively Different Ways in Which Secondary Physics Students, Teachers, & University Physics Professors Conceptualize Various Aspects of Understanding Physics.** I am seeking your consent for your son/daughter to participate because his/her grade twelve physics teacher, Mr./Mrs./Ms. xxxx, has agreed to participate in the study and has given me permission to speak to his/her class to seek your son/daughter's involvement.

The object of this study is to close the gap between secondary physics students', secondary physics teachers', and university physics professors' conceptions of what it means to understand physics are so that physics learning might be enhanced. The findings from this study will inform science education and teacher education programs. There is very limited scholarship on secondary physics students', teachers' and professors' conceptions of what it means to understand physics and this study will begin to fill this gap. Thus, your willingness to consent for your son/daughter to participate would be most appreciated.

Please note that you are under no obligation to agree to have your son/daughter participate in this research study. Your son/daughter's full participation in the study would involve being interviewed once by Michael Lukie about what your son/daughter thinks it means to understand physics for no longer than thirty minutes. If your son/daughter decides to participate with the interview, he/she would be contacted by e-mail regarding availability and willingness to be interviewed. The interview would be audio recorded and would be between myself and your son/daughter. The interview will be scheduled at a time of mutual convenience and will take place somewhere at the school that is suitable, convenient and agreed upon by both parties and the school. In addition, your son/daughter is not obliged to answer any specific question during the recorded interview process even if he/she participates in the study. Even if your son/daughter's teacher has agreed to be part of the study he/she is not obliged to participate, and your son/daughter's course mark will not be affected in any way.

Your son/daughter will be able to opt out of the study at any point up until one month after the data has been collected, simply by informing Michael Lukie or his/her teacher that he/she does not wish to continue to participate. In the event that you or your son/daughter withdraws consent for participation, any data that has been collected from him/her will be removed from the data set.

Results of the study will be presented at academic and professional conferences and may appear in academic and professional journals. The findings from this study will inform science education and teacher education programs and will also be used to inform physics teaching practices. Research reports might include direct quotes made by your son/daughter, but their name will not be used. Other identifying information (e.g., name, school, class and/or teacher) will also be omitted whenever the results are made public. This will help ensure son/daughter's privacy, anonymity, and confidentiality. The plan for this study has been reviewed for its adherence to ethical guidelines by a Research Ethics Board at the University of Alberta. For questions regarding participant rights and ethical conduct of research, contact the Research Ethics Office at (780) 492-2615.

Only Michael Lukie will have access to the data that will be stored securely at all times at the University of Winnipeg in a locked filing cabinet or safe. Only Michael Lukie will transcribe your son/daughter's recorded verbal audio data and only he will analyse the data. Your son/daughter will not be identified through the transcription or data entry process. Once data has been digitized (within one month of collection) all identification will be removed, and names will be replaced with pseudonyms and codes. Aside from me, only my supervisor, Professor Gregory P. Thomas, will have access to the digitized, anonymous data. The data used in the study will be securely stored for a minimum of five years and will then be destroyed.

Two copies of the letter of consent will be provided. One copy should be signed and returned, and the other copy should be kept for your records.

If you have any questions regarding the study, you may contact Michael Lukie at (204) 290-8282 (mlukie@ualberta.ca) or his supervisor, Professor Gregory P. Thomas at (780) 492-5671 (gthomas1@ualberta.ca). If you have any questions or concerns regarding how this study is being conducted, you may contact the Research Ethics Office at (780) 492-2615. This office has no affiliation with the study investigators.

Thank you very much for considering this request.

Sincerely,

Michael Lukie, Ph.D. Candidate (University of Alberta).

Appendix F: Parent/Guardian Letter of Consent

UNIVERSITY OF
ALBERTA

Department of Secondary Education
551 Education South
Edmonton, Alberta, T6G 2G5, Canada
Phone: (780) 492-3674
Fax: (780) 492-7622
Email: educ.sec@ualberta.ca

Parent/Guardian Letter of Consent

Please sign your name below to indicate your willingness to have your son/daughter take part in the study described above.

I____, have read the accompanying information letter and give my informed consent for my son/daughter to participate in the research study,

A Phenomenographic Study Mapping the Qualitatively Different Ways in Which Secondary Physics Students, Teachers, & University Physics Professors Conceptualize Various Aspects of Understanding Physics, conducted by Michael Lukie.

I consent to my son/daughter being interviewed once by the researcher about what it means to understand physics.

In agreeing for my son/daughter to take part in this study, I understand that:

- They are under no obligation to participate.
- Even after giving my consent for my son/daughter to take part, he/she may discontinue his/her participation without penalty at anytime. He/she may withdraw information that was already collected by contacting Michael Lukie or his/her teacher within one month of the collection of that data.
- Information that is provided will be treated as confidential. Direct quotes from my son/daughter may be used in research reports (i.e., presentations and publications), but his/her name and other identifying information will be changed or omitted.
- Research reports will be used for academic and professional presentations (e.g. conferences, workshops) as well as academic and professional publications. They will also be used to inform teaching practices.

I understand that I am under no obligation to consent to my son/daughter participating in this study and that I and/or my son/daughter can withdraw consent from the study after which any information or data that is directly linked to them as an individual will be excluded from the study.

The plan for this study has been reviewed for its adherence to ethical guidelines by a Research Ethics Board at the University of Alberta. For questions regarding participant rights and ethical conduct of research, contact the Research Ethics Office at (780) 492-2615.

Print Name: ____________________________________E-mail: ______________________

Print Son/Daughter's Name: _________________________

Signature: ______________________________________ _______/_______/_______

Date (Day/Month/Year)

Appendix G: Teacher Information Letter

UNIVERSITY OF
ALBERTA

Department of Secondary Education
551 Education South
Edmonton, Alberta, T6G 2G5, Canada
Phone: (780) 492-3674
Fax: (780) 492-7622
Email: educ.sec@ualberta.ca

Teacher Information Letter

May 04, 2016

Dear Teacher,

I would like to invite you to take part in an educational research study entitled, **A Phenomenographic Study Mapping the Qualitatively Different Ways in Which Secondary Physics Students, Teachers, & University Physics Professors Conceptualize Various Aspects of Understanding Physics.** This study is being undertaken to fulfill the partial degree requirements for my doctorate in secondary science education at the University of Alberta. You are being invited to participate because you are a grade twelve high school physics teacher and I am interested in learning what your conceptions are about what you think it means to understand physics.

The object of this study is to close the gap between secondary physics students', secondary physics teachers', and university physics professors' conceptions of what it means to understand physics are so that learning might be enhanced. The findings from this study will inform science education and teacher education programs. There is very limited scholarship on secondary physics students', teachers' and professors' conceptions of what it means to understand physics and this study will begin to fill this gap. Thus, your willingness to participate would be most appreciated.

What this means for physics teaching is that if the conceptions students have about what it means to understand physics are different to the conceptions their teacher has, there is the potential for a gap between the understanding of the student and the teacher. By examining both students' conceptions of what it means to understand physics and physics teachers' understanding of what it means to understand physics, pedagogical practices might be developed by the teacher so that student understanding of physics may be enhanced. If a physics teacher can identify how their conceptions of understanding physics compare with those of their students, the physics teacher might be able to align their pedagogy towards enhancing the understanding of their students.

Since I am also interested in the conceptions your students have about what it means to understand physics, I would request access to your students as research participants. Should you decide to participate, I would also request the opportunity to present the study to you and your students so that I may provide some information about the study to your students and seek their participation. Once the initial participation has been requested at the information session, you are being asked to collect the names of your students who agree to participate in the study, pass these names on to the researcher, and distribute parent/guardian information letters and assent/consent forms to your students.

Your participation in this study is purely voluntary and you are under no obligation to agree to participate in this study. Your full participation in the study would involve you:
(a) Being interviewed once by Michael Lukie about what you think it means to understand physics for no longer than thirty minutes.
(b) Allowing Michael Lukie to speak to your grade twelve physics students about the nature of the study where your students will be initially asked to participate. Collect the names of your students who agree to participate in the study, pass these names on to the researcher, and distribute parent/guardian information letters and assent/consent forms to your students.

If you decide to participate with the interview, you would be contacted by e-mail regarding your availability and willingness to be interviewed. The interview would be between you and I and the interview would be audio recorded. The interview will be scheduled at a time of mutual convenience and will take place somewhere that is suitable, convenient and agreed upon by both parties. In addition, you are not obliged to answer any specific questions during the recorded interview process even if you participate in the study.

You will be able to opt out of the study at any point up until one month after the data has been collected, simply by informing me that you do not wish to continue to participate. In the event you withdraw your participation, any data that has been collected from you will be removed from the data set. There will be no adverse repercussions to your employment if you choose to withdraw your participation. If any of your students choose to opt out of the study, the researcher has indicated in the student information letter that students may contact the researcher directly or you, their teacher. In this event, please forward the student's name to me and their participation will be removed and any data that has been collected from them will be removed from the data set.

Results of the study will be presented at academic and professional conferences and may appear in academic and professional journals. Research reports might include direct quotes made by you but your name will not be used. All identifying information (e.g., your name) will be omitted whenever the results are made public to ensure your privacy, anonymity, and confidentiality. The plan for this study has been reviewed for its adherence to ethical guidelines by a Research Ethics Board at the University of Alberta. For questions regarding participant rights and ethical conduct of research, contact the Research Ethics Office at (780) 492-2615.

Only I will have access to the data that will be stored securely at all times at the University of Winnipeg in a locked filing cabinet or safe. Only I will transcribe your recorded verbal audio data and only I will analyse the data. You will not be identified through the transcription or data entry process. Once data has been digitized (within one month of collection) all identification will be removed, and names will be replaced with pseudonyms and codes. Aside from me, only my supervisor, Professor Gregory P. Thomas, will have access to the digitized, anonymous data. The data used in the study will be securely stored for a minimum of five years and will then be destroyed.

Two copies of the letter of consent will be provided. One copy should be signed and returned, and the other copy should be kept for your records. If you have any questions regarding the study, you may contact Michael Lukie at (204) 290-8282 (mlukie@ualberta.ca) or his supervisor, Professor Gregory P. Thomas at (780) 492-5671 (gthomas1@ualberta.ca). If you have any questions or concerns regarding how this study is being conducted, you may contact the Research Ethics Office at (780) 492-2615. This office has no affiliation with the study investigators.

Thank you very much for considering this request.
Sincerely,

Michael Lukie, Ph.D. Candidate (University of Alberta).

Appendix H: Teacher Letter of Consent

UNIVERSITY OF
ALBERTA

Department of Secondary Education
551 Education South
Edmonton, Alberta, T6G 2G5, Canada
Phone: (780) 492-3674
Fax: (780) 492-7622
Email: educ.sec@ualberta.ca

Teacher Letter of Consent

Please sign your name below to indicate your willingness to take part in the study described above.

I____, have received and had explained

to me by Michael Lukie of the Faculty of Education, University of Alberta, an attached information letter asking me to consent to participate in the research study, **A Phenomenographic Study Mapping the Qualitatively Different Ways in Which Secondary Physics Students, Teachers, & University Physics Professors Conceptualize Various Aspects of Understanding Physics**, conducted by Michael Lukie.

In agreeing to take part in this study, I understand that:

- I have been asked to participate in a research study.
- I understand the benefits and risks involved in participating in the research study.
- I have had the opportunity to ask questions and discuss the study.
- I am under no obligation to participate.
- The interview will be audio recorded.
- Even after giving my consent to take part, I may discontinue my participation without penalty at anytime. I may withdraw information that was already collected by contacting Michael Lukie within one month of the collection of that data.
- Information that I provide will be treated as confidential. Direct quotes from me may be used in research reports (i.e., presentations and publications), but my name and other identifying information will be changed or omitted.
- Research reports will be used for academic and professional presentations (e.g. conferences, workshops) as well as academic and professional publications. They will also be used to inform physics education practices.
- I am under no obligation to participate in this study and that I can withdraw from the study after which any information or data that directly link to me as an individual will be excluded from the study.

I hereby agree to (please check your choices):

☐ (a) Being interviewed once by Michael Lukie about what I think it means to understand physics for no longer than thirty minutes.

☐ (b) Allowing Michael Lukie to speak to my grade twelve physics students about the nature of the study where my students will be initially asked to participate. Collect the names of my students who agree to participate in the study, pass these names on to the researcher, and distribute parent/guardian information letters and assent/consent forms to my students.

The interview will be scheduled at a time of mutual convenience and will take place somewhere that is suitable, convenient and agreed upon by both parties. I am not obliged to answer any specific question during the recorded interview process.

Print Name: ______________________________________E-mail: ______________________

Signature: ____ _______/_______/_______

Date: (Day/Month/Year)

Appendix I: Professor Information Letter

UNIVERSITY OF

ALBERTA

Department of Secondary Education
551 Education South
Edmonton, Alberta, T6G 2G5, Canada
Phone: (780) 492-3674
Fax: (780) 492-7622
Email: educ.sec@ualberta.ca

Professor Information Letter

May 04, 2016

Dear Professor,

I would like to invite you to take part in an educational research study entitled, **A Phenomenographic Study Mapping the Qualitatively Different Ways in Which Secondary Physics Students, Teachers, & University Physics Professors Conceptualize Various Aspects of Understanding Physics.** This study is being undertaken to fulfill the partial degree requirements for my doctorate in secondary science education at the University of Alberta. You are being invited to participate because you are a university physics professor and I am interested in learning what your conceptions are about what you think it means to understand physics.

The object of this study is to close the gap between secondary physics students', secondary physics teachers', and university physics professors' conceptions of what it means to understand physics are so that physics learning might be enhanced. The findings from this study will have theoretical and pedagogical applications that can inform science education and teacher education programs. There is very limited scholarship on secondary physics students', teachers' and professors' conceptions of what it means to understand physics and this study will begin to fill this gap. Thus, your willingness to participate would be most appreciated.

Physics professors are being included in this study so that physics teachers can be informed about what professional physicists consider physics understanding to be. Professional physicists and then their students, are those on the cutting edge of constructing physics understanding and their ideas about what it means to understand physics are important. By exploring what physics students think, what physics teachers think, and what physicists think about what it means to understand physics, physics teachers may potentially be able to consider whether they can incorporate some of these ideas into their own understandings that they might then communicate to their students. Informing physics teachers about what their understandings of physics are also means providing them with alternative views, those derived from physicists. Providing a reference point beyond their own expertise and experience might assist physics teachers to contextualize what they are teaching students about what it means to understand physics that extends past their own existing understandings. Teachers need to be provided with insights beyond what they themselves might hold.

Your participation in this study is purely voluntary and you are under no obligation to agree to participate in this study. Your full participation in the study would involve you being interviewed once by Michael Lukie about what you think it means to understand physics for no longer than thirty minutes. If you are uncomfortable with being audio recorded, you may choose not to participate. If you decide to participate with the interview, you would be contacted by e-mail regarding your availability and willingness to be interviewed. The interview would be between you and me and the interview would be audio recorded. The interview will be scheduled at a time of mutual convenience and will take place somewhere that is suitable, convenient and agreed upon by both parties. In addition, you are not obliged to answer any specific question during the recorded interview process even if you agree to participate in the study.

You will be able to opt out of the study at any point up until one month after the data has been collected, simply by informing me that you do not wish to continue to participate. In the event you withdraw your participation, any data that has been collected from you will be removed from the data set.

Results of the study will be presented at academic and professional conferences and may appear in academic and professional journals. Research reports might include direct quotes made by you, but your name will not be used. All identifying information (e.g., your name) will be omitted whenever the results are made public to ensure your privacy, anonymity, and confidentiality. The plan for this study has been reviewed for its adherence to ethical guidelines by a Research Ethics Board at the University of Alberta. For questions regarding participant rights and ethical conduct of research, contact the Research Ethics Office at (780) 492-2615.

Only I will have access to the data that will be stored securely at all times at the University of Winnipeg in a locked filing cabinet or safe. Only I will transcribe your recorded verbal audio data and only I will analyse the data. You will not be identified through the transcription or data entry process. Once data has been digitized (within one month of collection) all identification will be removed, and names will be replaced with pseudonyms and codes. Aside from me, only my supervisor, Professor Gregory P. Thomas, will have access to the digitized, anonymous data. The data used in the study will be securely stored for a minimum of five years and will then be destroyed.

Two copies of the letter of consent will be provided. One copy should be signed and returned, and the other copy should be kept for your records.
If you have any questions regarding the study, you may contact Michael Lukie at (204) 290-8282 (mlukie@ualberta.ca) or his supervisor, Professor Gregory P. Thomas at (780) 492-5671 (gthomas1@ualberta.ca). If you have any questions or concerns regarding how this study is being conducted, you may contact the Research Ethics Office at (780) 492-2615. This office has no affiliation with the study investigators.
Thank you very much for considering this request.
Sincerely,

Michael Lukie, Ph.D. Candidate (University of Alberta).

Appendix J: Professor Letter of Consent

UNIVERSITY OF
ALBERTA

Department of Secondary Education
551 Education South
Edmonton, Alberta, T6G 2G5, Canada
Phone: (780) 492-3674
Fax: (780) 492-7622
Email: educ.sec@ualberta.ca

Professor Letter of Consent

Please sign your name below to indicate your willingness to take part in the study described above.

I____, have received and had explained

to me by Michael Lukie of the Faculty of Education, University of Alberta, an attached information letter asking me to consent to participate in the research study, **A Phenomenographic Study Mapping the Qualitatively Different Ways in Which Secondary Physics Students, Teachers, & University Physics Professors Conceptualize Various Aspects of Understanding Physics**, conducted by Michael Lukie.

In agreeing to take part in this study, I understand that:

- I have been asked to participate in a research study.
- I understand the benefits and risks involved in participating in the research study.
- I have had the opportunity to ask questions and discuss the study.
- I am under no obligation to participate.
- The interview will be audio recorded.
- Even after giving my consent to take part, I may discontinue my participation without penalty at anytime. I may withdraw information that was already collected by contacting Michael Lukie within one month of the collection of that data.
- Information that I provide will be treated as confidential. Direct quotes from me may be used in research reports (i.e., presentations and publications), but my name and other identifying information will be changed or omitted.
- Research reports will be used for academic and professional presentations (e.g. conferences, workshops) as well as academic and professional publications. They will also be used to inform physics education practices.
- I am under no obligation to participate in this study and that I can withdraw from the study after which any information or data that directly link to me as an individual will be excluded from the study.

I hereby agree to being interviewed once by Michael Lukie about my views of what it means to understand physics for no longer than thirty minutes. The interview will be scheduled at a time of mutual convenience and will take place somewhere that is suitable, convenient and agreed upon by both parties. I am not obliged to answer any specific question during the recorded interview process.

Print Name: ______________________________________E-mail: _______________________

Signature: ____ _______/_______/_______
Date (Day/Month/Year)

Appendix K: School Superintendent Information Letter

UNIVERSITY OF ALBERTA

Department of Secondary Education
551 Education South
Edmonton, Alberta, T6G 2G5, Canada
Phone: (780) 492-3674
Fax: (780) 492-7622
Email: educ.sec@ualberta.ca

School Superintendent Information Letter

May 24, 2016
Dear School Superintendent,

I would like to invite your school division to take part in an educational research study entitled, **A Phenomenographic Study Mapping the Qualitatively Different Ways in Which Secondary Physics Students, Teachers, & University Physics Professors Conceptualize Various Aspects of Understanding Physics.** This study is being undertaken to fulfill the partial degree requirements for my doctorate in secondary science education at the University of Alberta. Your school division is being asked to participate because your school division has grade twelve high school physics students/teachers and I am interested in learning what their conceptions are about what they think it means to understand physics.

The object of this study is to close the gap between secondary physics students', secondary physics teachers', and university physics professors' conceptions of what it means to understand physics are so that learning might eventually be enhanced. The findings from this study will have theoretical and pedagogical applications that can inform science education and teacher education programs. There is very limited scholarship on secondary student conceptions of what it means to understand physics and this study will begin to fill this gap. Thus, your feedback and willingness to participate would be most appreciated.

What this means for physics teaching is that if the conceptions students have about what it means to understand physics are different to the conceptions their teacher has, there is the potential for a gap between the understanding of the student and the teacher. By examining both student conceptions of what it means to understand physics and physics teachers' understanding of what it means to understand physics, pedagogical practices might be developed by the teacher so that student understanding of physics may be enhanced. If a physics teacher can identify how their conceptions of understanding physics compare with those of their students, the physics teacher might be able to align their pedagogy more towards enhancing the understanding of their students. The ultimate goal of teaching physics is to maximize students' conceptual understanding of physics topics. Rather than provide students with facts to memorize or problems to practice in the hope that understanding develops, the teacher may first consider developing the understanding of their students by first being aware of how students understand what it means to understand physics.

Since I am interested in both students' and teachers' conceptions about what it means to understand physics, I am requesting access to students and teachers in your school division. The only students who will be asked to participate are those whose teacher's have agreed to participate. If you decide to participate, I will request the opportunity to present the study to one or more of your schools' grade twelve physics classes so that I may provide some information about the study to them. Your participation in this study is purely voluntary and you are under no obligation to agree to participate in this study. Your full participation in the study would involve some of your school division's grade twelve physics teachers and students being interviewed once by Michael Lukie about what they think it means to understand physics for no longer than thirty minutes. If the participants are uncomfortable with being audio recorded, they may choose not to participate. If they decide to participate with the interview, they would be contacted by e-mail regarding their availability and willingness to be interviewed. The interview would be between the participants and myself and the interview would be audio recorded. The interview will be scheduled at a time of mutual convenience and will take place somewhere at the school that is suitable, convenient and agreed upon by both parties. In addition, the participants are not obliged to answer any specific question during the recorded interview process even if they participate in the study.

The participants will be able to opt out of the study at any point up until one month after the data has been collected, simply by informing me that they do not wish to continue to participate. In the event the participants withdraw their participation, any data that has been collected from them will be removed from the data set. If students choose to opt out of the study, the researcher has indicated in both the student and teacher information letter that the student may contact the researcher directly and/or his/her teacher. In this event, the teacher will provide the student's name to the researcher and the student's participation will be removed and any data that has been collected from them will be removed from the data set.

Results of the study will be presented at academic and professional conferences and may appear in academic and professional journals. Research reports might include direct quotes made by the participants, but their name will not be used. All identifying information (e.g., name) will be omitted whenever the results are made public to ensure privacy, anonymity, and confidentiality. The plan for this study has been reviewed for its adherence to ethical guidelines by a Research Ethics Board at the University of Alberta. For questions regarding participant rights and ethical conduct of research, contact the Research Ethics Office at (780) 492-2615.

Only I will have access to the data that will be stored securely at all times at the University of Winnipeg in a locked filing cabinet and/or safe and only I will transcribe the recorded interview into verbal audio data. The participants will not be identified through the transcription or data entry process. Once data has been digitized (within one month of collection) all identification will be removed, and names will be replaced with pseudonyms and codes. Only my supervisor, Dr. Gregory P. Thomas, will have access to the digitized, anonymous data. The data used in the study will be securely stored for a minimum of five years and will then be destroyed.

Two copies of the letter of consent will be provided. One copy should be signed and returned, and the other copy should be kept for your records. In addition, you have been provided with copies of the student, teacher, and parent/guardian letters of information and assent/consent forms for your records.

The ethics for this study was approved by the University of Alberta Research Ethics Board on May 24, 2016 and was assigned the study number Pro00061042. If you have any questions regarding the study, you may contact Michael Lukie at (204) 786-9206 (mlukie@ualberta.ca) or his supervisor, Dr. Gregory P. Thomas at (780) 492-5671 (gthomas1@ualberta.ca). If you have any questions or concerns regarding how this study is being conducted, you may contact the Research Ethics Office at (780) 492-2615. This office has no affiliation with the study investigators.

Thank you very much for considering this request.
Sincerely,

Michael Lukie, Ph.D. Candidate (University of Alberta).

Appendix L: School Superintendent Letter of Consent

UNIVERSITY OF ALBERTA

Department of Secondary Education
551 Education South
Edmonton, Alberta, T6G 2G5, Canada
Phone: (780) 492-3674
Fax: (780) 492-7622
Email: educ.sec@ualberta.ca

School Superintendent Letter of Consent

Please sign your name below to indicate your willingness to have your school division take part in the study described above.

I____, have received and had explained to me by Michael Lukie of the Faculty of Education, University of Alberta, an attached information letter asking grade twelve physics teachers, and grade twelve physics students from my school division to consent to participate in the research study, **A Phenomenographic Study Mapping the Qualitatively Different Ways in Which Secondary Physics Students, Teachers, & University Physics Professors Conceptualize Various Aspects of Understanding Physics**, conducted by Michael Lukie.

In agreeing to take part in this study, I understand that:

- Grade twelve physics students and grade twelve physics teachers will be asked to participate in a research study. The only students who will be asked to participate are those whose teacher's have agreed to participate.
- I understand the benefits and risks involved in the school division participating in the research study.
- I have had the opportunity to ask questions and discuss the study.
- I am under no obligation to participate.
- The participant interviews will be audio recorded.
- Even after giving consent to take part, participants may discontinue their participation without penalty at any time. Participants may withdraw information that was already collected by contacting Michael Lukie within one month of the collection of that data.
- Information provide by participants will be treated as confidential. Direct quotes from participants may be used in research reports (i.e., presentations and publications), but the participant's name and other identifying information will be changed or omitted.
- Research reports will be used for academic and professional presentations (e.g. conferences, workshops) as well as academic and professional publications. They will also be used to inform physics education practices.
- Participants are under no obligation to participate in this study and can withdraw from the study after which any information or data that directly links them as an individual will be excluded from the study.

I hereby agree to Michael Lukie interviewing grade twelve high school students and teachers about their views of what it means to understand physics for no longer than thirty minutes. The interview will be scheduled at a time of mutual convenience and will take place at school somewhere that is suitable, convenient and agreed upon by both parties. Participants are not obliged to answer any specific question during the recorded interview process.

Print Name: ______________________________________E-mail: ______________________

Signature: ____ _______/_______/_______

Date: (Day/Month/Year)

Appendix M: University of Alberta Ethics Approval

UNIVERSITY OF
ALBERTA

Ethics Application has been Approved

ID:	Pro00061042
Title:	A Phenomenographic Study Mapping the Qualitatively Different Ways in Which Secondary Physics Students, Secondary Physics Teachers, and University Physics Professors Conceptualize About What it Means to Understand Physics
Study Investigator:	Michael Lukie
Description:	This is to inform you that the above study has been approved. Click on the link(s) above to navigate to the HERO workspace. **Note**: Please be reminded that the REMO system works best with Internet Explorer or Firefox. Please do not reply to this message. This is a system-generated email that cannot receive replies.

University of Alberta
Edmonton Alberta
Canada T6G 2E1

Appendix N: University of Alberta Notification of Ethics Approval

Notification of Approval

Date:	May 24, 2016
Study ID:	Pro00061042
Principal Investigator:	Michael Lukie
Study Supervisor:	Gregory Thomas
Study Title:	A Phenomenographic Study Mapping the Qualitatively Different Ways in Which Secondary Physics Students, Secondary Physics Teachers, and University Physics Professors Conceptualize About What it Means to Understand Physics.
Approval Expiry Date:	Tuesday, May 23, 2017

	Approval Date	Approved Document
Approved Consent Form:	5/24/2016	8. Teacher Information Letter April 28 2016.pdf
	5/24/2016	6. Professor Information Letter April 28 2016.pdf
	5/24/2016	1. Student Information Letter April 28 2016.pdf
	5/24/2016	4. Parent Information Letter April 28 2016.pdf
	5/24/2016	9. Teacher Letter of Consent April 28 2016.pdf
	5/24/2016	5. Parent Letter of Consent April 28 2016.pdf
	5/24/2016	3. Student Letter of Consent April 28 2016.pdf
	5/24/2016	7. Professor Letter of Consent April 28 2016.pdf

Thank you for submitting the above study to the Research Ethics Board 1. Your application has been reviewed and approved on behalf of the committee.

A renewal report must be submitted next year prior to the expiry of this approval if your study still requires ethics approval. If you do not renew on or before the renewal expiry date, you will have to re-submit an ethics application.

Approval by the Research Ethics Board does not encompass authorization to access the staff, students, facilities or resources of local institutions for the purposes of the research.

Sincerely,

Anne Malena, PhD
Chair, Research Ethics Board 1

Note: This correspondence includes an electronic signature (validation and approval via an online system).

Appendix O: University of Winnipeg Ethics Approval

THE UNIVERSITY OF WINNIPEG

June 29, 2016

Michael Lukie
Instructor
Collegiate Division
The University of Winnipeg

Dear Mr. Lukie,

Re: "A Phenomenographic Study Mapping the Qualitatively Different Ways in Which Secondary Physics Students, Secondary Physics Teachers, and University Physics Professors Conceptualize About What it Means to Understand Physics"

As advised by the Chair of the University Human Research Ethics Board (UHREB), I am writing to grant permission for you to contact students and teachers at The University of Winnipeg – Collegiate Division for the purpose of inviting them to participate in this study.

The University appreciates the value of investigating the ways in which students and instructors understand physics, leading to scholarship that will ultimately inform science education and teacher education programs. We wish you the best as you proceed with this important study.

Sincerely,

Jino Distasio
Vice-President, Research and Innovation

cc: Catherine Taylor, Chair, UHREB

515 Portage Avenue, Winnipeg, Manitoba, Canada R3B 2E9 | uwinnipeg.ca | DISCOVER · ACHIEVE · BELONG

Appendix P: Sample Data Catalog of Students' Interviews

A	B	C	D	E	F	G	H	
Student	Intervie	Conception	Page		Page		Page	
1	20							
		Solve Questions	2	I can answer the questions and like, not just one certain question, when it's put into different scenarios.	4	I come up with my own questions I guess where like, **[00:07:00]** if I was trying to help someone, I could take a question that you taught us and put it into a different type of – use different like formulas or whatever and try to create my own question.		
		Teach others	2	And . . . I can teach a certain concept to someone.	4	we can teach it to someone else and I think that's like where the most understanding comes from, so . . . **[00:07:30]**	7	and being able to shar someone younger thai the gist of it all.
		Remember formulas	2	I can remember like the . . . **[00:03:00]** what are they called, the formulas.				
		Derive formulas	4	Most of it's kind of memory, because formulas, wouldn't it be? Oh, you can derive formulas.				
		Apply	7	So it basically means being able to know it yourself and apply it to different scenarios that we see				
Student	Intervie	Conception	Page		Page		Page	
2	21							
		Good on test	2	After I take a test or something I'll be able to do it, like weeks after.	2	I'll take the test and I'll kind of get it, **[00:03:00]** but then as soon as like pen leaves paper it's like "Ooh".		
		Apply	4	Basically that I could take it, like take what I've learned and see myself using it **[00:06:00]**.	4	Hm-mm. Like an application.	4	I don't know. It's just lik
		Explain to others	4	Like talking to other people about it? It's like I'd be able to back up what I learned, you know? And like explain what it is.				
		Talk to others	4	Hm-mm. Basically a conversation about that, yeah. (that = physics)				
		Understand that physics is like blocks of a building	9	**[00:16:30]** To take something and like break it down into smaller pieces and like rebuild it, you know.				
Student	Intervie	Conception	Page		Page		Page	
3	22							
		Solve questions	2	When I can do a question and not look at the answer key.	4	To understand Physics is to be able to not have any issues when you have a problem, I guess. I don't know. **[00:06:30]**		
		Apply	4	I can apply it to real life scenarios. Like, **[00:07:00]** –	5	Like, well, like satellites for example. How, like how many times it revolves around the earth, like that.	8	So, understanding Ph apply it to real life scen about certain topics, I
		Understand the process	9	Yeah. To develop an understanding of how the process works.	9	When you see the process, you understand it more.		
Student	Intervie	Conception	Page		Page			
4	25							
		Why something is happening	4	Yeah. Probably, **[00:05:30]** like, understanding why something's happening would probably be, like, a really good understanding of it.	4	Yeah, for, like, really smart people, they're looking probably more at why things are happening or, you know		
		Use correct formula	4	But in Grade: 12 it would just be, like, knowing what to do and, like you know, you have a formula, you know what to do with the formula.				
		Prove why things happen	4	proving why things happen and stuff like that.	8	But once you get, in a way higher level. It'd be why things are happening, proving that things happen for, you know, whatever reason and that **[00:13:30]** –		
		What to do and why you are doing it	8	Yeah. Well, I'd say that it's on, in Grade: 12 it would be just understanding what to do and, kind of, why you're doing what you're doing.				
		Understand the real world	8	Yeah, I mean, why would the car slow down, you're like, oh friction, right, like, something like that. And then what's happening while it's slowing down. So, you understand that it's slowing therefore the number will be smaller, you know, something like that.				
Student	Intervie	Conception	Page		Page		Page	
5	26							

Appendix Q: Sample Data Catalog of Teachers' Interviews

Teacher	Interview	Conception	Page		Page		Page
1	1						
		Apply	8	Well, when I can transfer it to a different situation and get it right. So, like projectile motion, if I can transfer that to a new situation and then I see that I got it right, then yes, I'm happy about that. Or if I can see, what is it, similarities between one and the other.			
		How matter and energy work	11	Understand – well, I think it has to do with how matter – yeah, how things work in the world, matter and energy of different kinds.	11	So I think the basic concepts of understanding how matter and energy work	11
		Quantify/measure	11	And then also how to quantify it in some way.	11	and then trying to quantify it in some way that's meaningful.	11
		Make connections	11	And then – well – and then also connecting it to things that you would see every day, you know, how can you connect it to the traffic? How can you connect it to collisions of cars? How you connect it to the tides, you know, the tides, the ocean tides? How do you connect it to people swimming under water, that kind of thing?			
		Understand the real world	12	But I think it's mostly understanding things in the world and how they interact in terms of motion and force and energy, and energy including light and heat and all that stuff too, you know. So – and then – yeah, so – yeah. And understanding – then also understanding electronics and fields and stuff like that as well.	17	But it still comes back to understanding how things work in the world	
		Interact with physics	17	About understanding. How I understand physics. I think the more you interact with it and the more then you think about the interaction, the easier it gets.			

Teacher	Interview	Conception	Page		Page		Page
2	2						
		Apply	4	I think when you can apply it to new situations. So if you have some understanding of theories, the equations, the whatever it is, and then something completely different comes along and somehow you can take what you've learned and apply it. Or maybe even better yet, use it in a real life situation where it works. I'm not sure if that makes sense.	9	Like yeah I would say understanding through application	18
		Teach others	8	One I think is – my number one would be having to teach it. Having to teach it made me have to understand it in a way that I could explain it to somebody else and I think that is a higher			
		Explain to others	8	like a certain level to being able to explain something so that someone else understands it rather than just saying, "Well I think I have a good grasp of it" because you have to put it into words. And then you also have to understand it at a level where whatever questions or whatever part of it the person might not understand, you understand it in such a way that you can explain it either again or in a different way. So that – like let's say you're talking about a certain concept that has like eight building blocks, there are seven other steps that you have to be very clear on too because any one of those could be a problem for a student.	18	I feel to me that if you understand a problem, you could explain the why of it and I think that I'm getting better as I get older of not – like I used to love kids who got the right answer and the fact is the right answer could just be a good guess.	
		Understand the big picture	8	So I think you have to not just understand the big picture, you have to understand all of the little pictures that go into it too.			
		Identify nature of physics in a problem/recognition	9	On one level I would say that for – if I'm thinking about my students, being able to recognize the nature of physics in a particular problem. So I think that's often one of the hardest things because as a teacher I compartmentalize my lessons. So I'll teach about kinematics, I do lessons about kinematics, they have questions about kinematics. When they're all jumbled together things can look very similar, so I think a good understanding is being able to look at a problem and figure out what physics are at play.	9	Right. And one of the things I did on the last test was I had little stories. So there was a dude on a cliff and he dropped a ball, he threw a ball, he rolled a ball of the edge, he jumped off and then threw it or he just walked towards the edge. So there were five different scenarios. So they had to figure out what was the motion. Because they all sounded exactly the same but if he rolls a ball off the edge it's a certain kind of projectile motion, if he jumps off it's a different kind of projectile motion. So I think recognition of the nature of the problem. Then ideally if they continue on, their understanding of physics will change because they'll recognize a problem that physics or how physics applies to a problem, and then being able to solve it.	10
		Innovate/invent	9	But maybe down the road they help develop – like they design cars at Honda. What's his face, he was doing rocket science at – one of the former students was helping with the Canadarm, **like that's where – when you actually understand physics is that you have all your physics and then you use it to develop, you use it to innovate, you use it to change the world. Is that too**	9	but almost understanding through innovation almost.	19
		To understand changes with more physics knowledge	10	But I think as you become more of a master of physics that meaning would change I think.			

Appendix R: Sample Data Catalog of Professors' Interviews

A	B	C	D	E	F	G
Professor	**Interview**	**Conception**	**Page**		**Page**	
1	7					
		Make models	4	In general, the biggest discovery for me was that you cannot understand nature because of lack of your senses but what you can do is make the best possible models to explain what you see around you. So if the model works, you go with it, but you expect it to be overturned very easily with more elegant and more consistent description of phenomenon but to say that you understand that phenomenon, that is absolutely false. But you can get the best description so far to the best of your abilities and then wait for either yourself or somebody else to come up with better a description that will describe more – more elements of the concept with more elegant way, but I just figured out that understanding it fully from human point of view and three dimensional creatures point of view because of possible higher dimensions you are really incapable of envisioning it.	4	you can just attempt to make the best model that describ you're looking at, to the best of ability of physics –
		Can't fully understand	4	you cannot understand nature fully and be content with it,	11	
		Understand the real world	5	Yes, actually – understanding physics would be understanding the nature because physics means really understanding nature, that's all about nature, how nature works and because nature presents us with so many – so many challenges, once you think you got it then you find out how many more questions are opened actually and then you make better model and you say okay this one	6	So for me, understanding physics is understanding natur as petty little humans with boxed minds to leap out of that something and we just open more questions that –
		Predict	6	well if you predict something with that theory and you get it in observations, that's sufficient. Sometimes that's just pure sufficient but if you really want deeper understanding when more elegant idea comes that all the planets are actually moving in almost circular orbits and then all those epicycles that are complex really disappear, then you relax.		
Professor	**Interview**	**Conception**	**Page**		**Page**	
2	9					
		Explain to others	4	when you can tell it to somebody else		
		Teach others	4	teach it to someone else		
		Can make an analogy	5	and you can find the necessary analogies and the way to have the conversation, that is a very good indicator of understanding it.		
		Identify contradictions	5	The other one I think is when you, yourself try to come up with ways that, you know, it might go wrong so you come up with even just mental tests that you don't have to necessarily go and try in the lab, but just experiments in your head and say well if this is true, what happens? What's the manifestation of this physics? And does that work? And then double checking it from a different [realm], I better end up in the same spot, you know?		
		Understand physics at different scales	5	Yeah, so think about it from one end, think about it from a different point of view, do they match? They better. Checking things in their limit is another nice way to do it, you know, okay as I let this get big, whatever big is the number of atoms gets large, what happens and when the atoms get small what happens? And then if you see that those are consistent with what you know are the limits, the limit exclusions and you feel like you have a very good handle on –	10	So one thing you can do is – in your mind is you can leap things, you know like electrons and neutrons and quarks you go through this scale of larger and larger sizes and yc some molecules in biology and so on and so forth and sol back [unintelligible 00:27:36] skills and then what's intere the small scale physics starts showing up again at the ver you know, when you start asking questions like why is the matter than anti-matter? And that's a – that's a universe s it's linked to the –
		Understand the process	6	I think it means, from that point of view, that anything you look at, you can see what are the processes involved in that. It could be anything, it could be the ink drying on the paper or the ink coming out of the pen to get onto the paper, there's physics in absolutely – in absolutely everything.	7	Absolutely everywhere. You can think about absolutely e because it worked, the ink did go on the paper, therefore nature is, so that's the acceptance part and then I can st questions and figuring out what it is, what's going on. If I w
		Understand	10	I think it's all those things but also – I guess it is to know and understand how – on top of that, how the fundamental forces and fundamental processes sort of fit in both in the – in terms of their interaction but also with respect to scale. That's a nice thing that we sort of left out.		

Appendix S: Matrix of Students' Conceptions

	A	B	C	D	E	F	G	H	I	J	K
1	Student										
2	1.20	2.21	3.22	4.25	5.26	6.27	7.28	8.30	9.31	10.32	11.34
3	Solve Questions	Good on test	Solve questions	Why something is happening	Use correct formula	Teach others	Derive formulas	Solve questions	Make connections	Solve questions	Teach others
4	Teach others	Apply	Apply	Use correct formula	Understand in different ways	Make inferences	Check your answer	Make connections	Question a question	Apply	Apply
5	Remember formulas	Explain to others	Understand the process	Prove why things happen	Understand the real world	Apply	Apply	Develop a formula	Talk to others	Understand the steps to get correct answer	Solve questions
6	Derive formulas	Talk to others	Feeling /Insight	What to do and why you are doing it	Feeling /Insight	Make models	Understand through math	Apply	Understand that physics is like blocks of a building	Have interest	Understand the real world
7	Apply	Understand that physics is like blocks of a building		Understand the real world		Bring all physics theories together in a web	Feeling /Insight	Can't fully understand	Solve questions		Do classroom physics labs
8	Feeling /Insight	Feeling /Insight				Feeling /Insight		Understand the real world	Bring all physics theories together in a web		
9								Feeling /Insight	Feeling /Insight		
10											
11											
12											
13											
14											

	L	M	N	O	P	Q	R	S	T	U	V
1											
2	12.35	13.37	14.38	15.39	16.40	17.41	18.49	19.52	20.69	21.70	22.71
3	Apply	Good on test	Solve questions	Explain to others	Solve questions	Question initial understandning	Solve questions	Understand the formula	Solve questions	Get good marks	Good on test
4	Do classroom physics labs	Solve questions	Teach others	Apply	Derive formulas	Question everyday phenomenon	Get good marks	Can provide physics examples	Get the right answer	Teach others	Understand the real world
5	Solve questions	Understand the real world	Explain to others	Can't fully understand	Make connections	Have more questions	Not falling back in class	Solve questions	Understand the real world	Understand that physics is like blocks of a	Explain to others
6	Teach others	Get good marks	Apply	Solve questions	Understand the formula	Ask more complicated questions	Can follow along in class	Apply	Get good marks	Understand the real world	Explain in simple terms
7	Explain to others		Understand the real world	Create my own solutions	Understand the basic math leading to a theory	Understand the real world	To listen to the teacher	Derive formulas	Answer questions in class	Good on test	To understand that science constantly changes
8	Compare to real life		Talk to others	Solve questions in a different way	Understand physics from start to finish	Apply	Do classroom physics labs	Understand basic physics foundations	Ask questions in class	Feeling /Insight	Dispute unscientific claims
9	Compare to other topics		Feeling /Insight	Get good marks	Feeling /Insight	Gain interest					Understand the scientific method
10				Have interest		Feeling /Insight					Feeling /Insight
11				Talk to others							
12				Teach others							
13				Have confidence							
14				Feeling /Insight							

Appendix T: Matrix of Teachers' Conceptions

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
1	Teacher																						
2	T1.I1	T2.I2	T3.I3	T4.I4	T5.I5	T6.I6	T7.I8	T8.I16	T9.I9	T10.I23	T11.I29	T12.I33	T13.I36	T14.I51	T15.I53	T16.I54	T17.I55	T18.I58	T19.I59	T20.I63	T21.I64	T22.I66	T23.I72
3	Apply	Apply	Apply	Explain to others	Explain to others	Explain to others	Explain to others	Apply	Understand the real world	Explain to others	Explain to others	Convey the concepts from multiple approaches	Different levels of understanding	Explain to others	Teach others	Solve questions	Solve questions	Understand the formula	Solve questions	Apply	Explain to others	Make connections	Explain to others
4	How matter and energy work	Teach others	Understand the real world	Talk to others	Understand the real world	Understand the real world	Teach others	Solve questions	Explain to others	Apply	Understand the real world	Describe a problem in deifferent ways	Definitional level of understanding	Apply	Breakdown into simple terms	Solve conceptual questions	Predict	Apply	Can't fully understand	Explain to others	Teach others	Apply	Understand the real world
5	Quantify/measure	Explain to others	Make connections	Apply	Apply	Solve questions	Apply	Understand the real world	Breakdown into simple terms	Tie things together	Demonstrate what you know	Explain to others	Good on test	Solve questions	Can't fully understand	Describe physics qualitatively	Apply	Predict	Understand the real world	Understand the real world	Make connections	Have an intuition	Feeling /Insight
6	Make connections	Understand the big picture	Teach others	Understand the real world	Feeling /Insight	Have conceptual understanding	Understand the big picture	View things in a different way	Apply	Understand the real world	Represent physics in different modes of understanding	Apply	Can make an analogy	Understand the big picture	Get good marks	Understand the formula	Understand the real world	Use a model	Feeling /Insight	Solve questions	Apply	Explain to others	
7	Understand the real world	Identify nature of physics in a problem/recognition	Explain to others	Solve questions		Apply	Have interest in physics	Feeling /Insight	Solve questions	Understand the big picture	Teach others	Understand the real world	Represent physics in different modes of understanding	Understand the formula	Get correct answer	Apply	Desire to discover	Understand the big picture		Feeling /Insight	Good on test	Identify contradictions	
8	Interact with physics	Innovate/invent	Feeling /Insight	Feeling /Insight		Think critically about a system	Feeling /Insight		Talk to others	Make connections	Feeling /Insight	Understand the process	Quantify/measure	Feeling /Insight	Understand the real world	Predict	Feeling /Insight	Explain to others			Feeling /Insight	Feeling /Insight	
9	Feeling /Insight	To understand changes with more physics knowledge				Feeling /Insight			Get a physics degree	Feeling /Insight		Feeling /Insight	Apply		Predict	Recognize patterns		Feeling /Insight					
10		To manipulate equations							Publish papers				Understand the big picture		How science works	Quantify/measure							
11		Feeling /Insight							Feeling /Insight				Innovate/invent		Understand the physics curriculum	Understand the big picture							
12													Understand models		Feeling /Insight	Feeling /Insight							
13													Feeling /Insight										

Appendix U: Matrix of Professors' Conceptions

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Professor													
2	P1.I7	P2.I9	P3.I10	P4.I11	P5.I12	P6.I13	P7.I14	P8.I15	P9.I17	P10.I18	P11.I24	P12.I42	P13.I43	P14.I44
3	Make models	Explain to others	When experiment matches theory	Have an intuition	Make connections	To conceptualize	Get answer in multiple ways	Explain to others	Apply	Teach others	Can't fully understand	Explain to others	Solve questions	Understand the structure of space and time
4	Can't fully understand	Teach others	Understand the real world	Explain to others	Explain to others	Make models	Benchmark a solution	Solve questions	Teach others	Explain to others	To know if solution is reasonable	Predict	Do research/experiment	Can't fully understand
5	Understand the real world	Can make an analogy	Apply	Can make an analogy	Predict	Visualize	Can't fully understand	Apply	Explain to others	Solve questions	Have confidence in a model	Different levels of understanding	Teach others	To fit knowledge into a logically consistent framework
6	Predict	Identify contradictions	Can't fully understand	Solve questions	Feeling /Insight/Intuition	Abstract	Have confidence in a model	Understand mathematics	Different levels of understanding	Apply	Different levels of understanding	Understand the big picture	Explain to others	Have an intuition
7	Feeling /Insight/Intuition	Understand physics at different scales	Teach others	Visualize		Generalize	Have a deep physical insight	Quantify/measure	Feeling /Insight/Intuition	Make connections	Understand the real world	Make connections	Visualize	Feeling /Insight/Intuition
8		Understand the process	Feeling /Insight/Intuition	Predict		Understand the real world	Understand limitations of physics	Do research/experiment		Feeling /Insight/Intuition	Understand your assumptions	Feeling /Insight/Intuition	Feeling /Insight/Intuition	
9		Understand fundamental forces		Understand the real world		Solve questions	Predict	Make thought experiments			Understand the big picture			
10		Feeling /Insight/Intuition		Understand physics at different scales		Feeling /Insight/Intuition	Understand the physics of a problem.	Different levels of understanding			Solve questions			
11				Apply			Understand what is not in the textbook	To be an expert			Predict			
12				Feeling /Insight/Intuition			To be an expert	Feeling /Insight/Intuition			Not to rely on your everyday experience			
13							Feeling /Insight/Intuition				Breakdown into simple terms			
14											To understand a particular theory			
15											Feeling /Insight/Intuition			

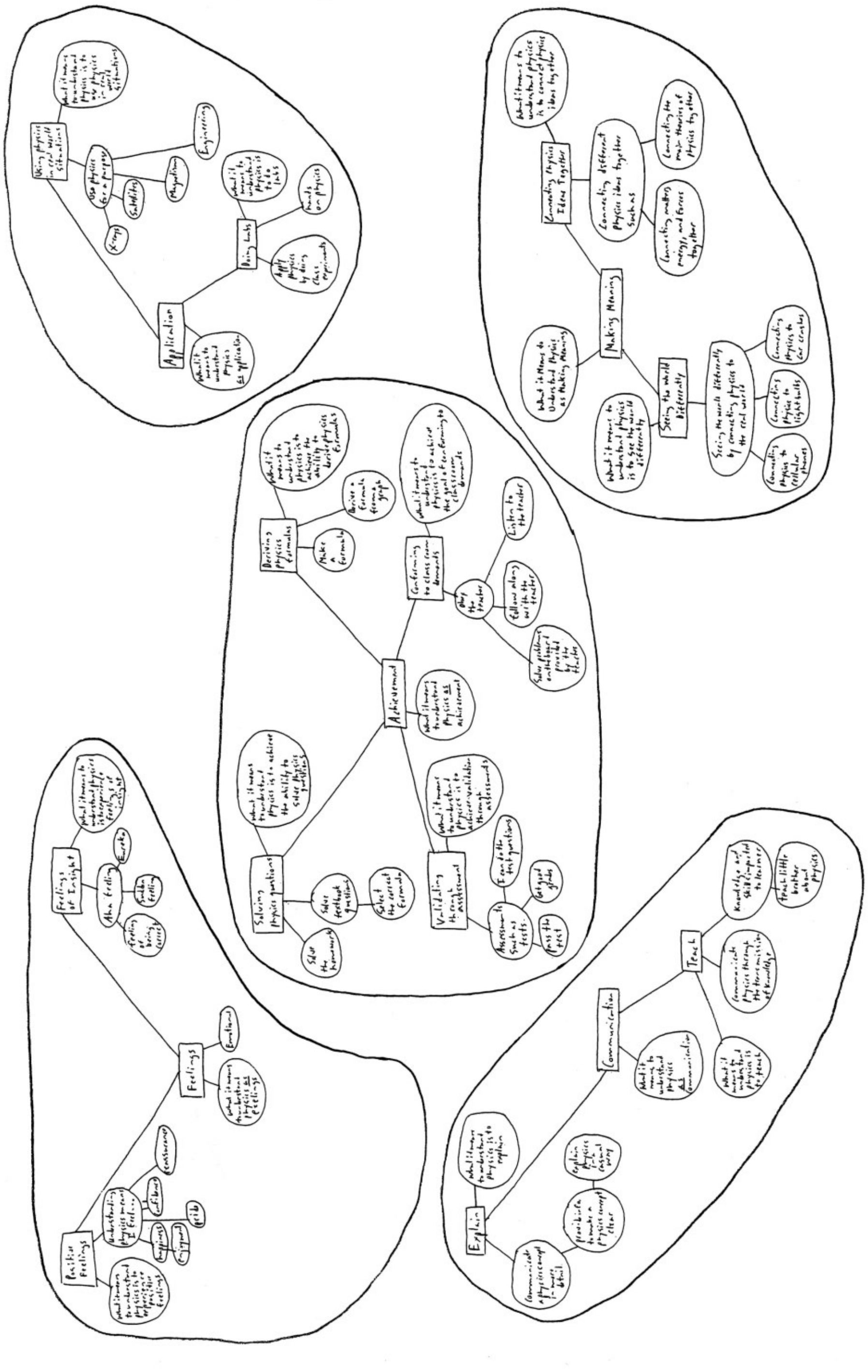
	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
1														
2	P15.I45	P16.I46	P17.I47	P18.I48	P19.I50	P20.I56	P21.I57	P22.I60	P23.I61	P24.I62	P25.I65	P26.I67	P27.I68	P28.I73
3	Explain to others	Get an a-ha moment	Derive equations	Make connections	Make connections	Explain to others	Do research/experiment	Understand the real world	Breakdown into simple terms	Apply	Teach others	Predict	To believe that physics works	Explain to others
4	Teach others	Different levels of understanding	Predict	Understand the real world	Quantify/measure	Make connections	Make connections	Publish papers	Explain to others	Teach others	Explain to others	Understand the real world	When challenging problems make sense	Apply
5	Understand the real world	Understand the real world	Make connections	Understand physics at different scales	Explain to others	To understand all the bits and pieces	Can't fully understand	Feeling /Insight/Intuition	Quantify/measure	Understand the real world	Solve questions	Rewording the question	Can make an analogy	Transfer
6	Make connections	Feeling /Insight/Intuition	Have insights	Apply	To fit knowledge into a logically consistent framework	Feeling /Insight/Intuition	Predict		Predict	Predict	Get answer in multiple ways	Apply	Recognize patterns	Feel comfortable with basic tools
7	Feeling /Insight/Intuition		Understand the formula	Make models	Teach others		Understand the real world		Solve questions	Can't fully understand	Understand the real world	Feeling /Insight/Intuition	Understand the big picture	Build up layers of complexity
8			Understand the real world	Feeling /Insight/Intuition	Understand physics at different scales		Have an intuition		Publish papers	To be skeptical	Feeling /Insight/Intuition		Visualize	Feeling /Insight/Intuition
9			Quantify/measure		Feeling /Insight/Intuition		Understand physics at different scales		Have an intuition	Feeling /Insight/Intuition			Represent physics in different ways	
10			Apply				Generalize		Understand the real world				Explain to others	
11			Feeling /Insight/Intuition				Breakdown into simple terms		Can make an analogy				Have an intuition	
12							Make models		Feeling /Insight/Intuition				Understand the real world	
13							Feeling /Insight/Intuition						Apply	
14													How to ask questions	
15													Feeling /Insight/Intuition	

Appendix V: Matrix of Students', Teachers', and Professors' Conceptions

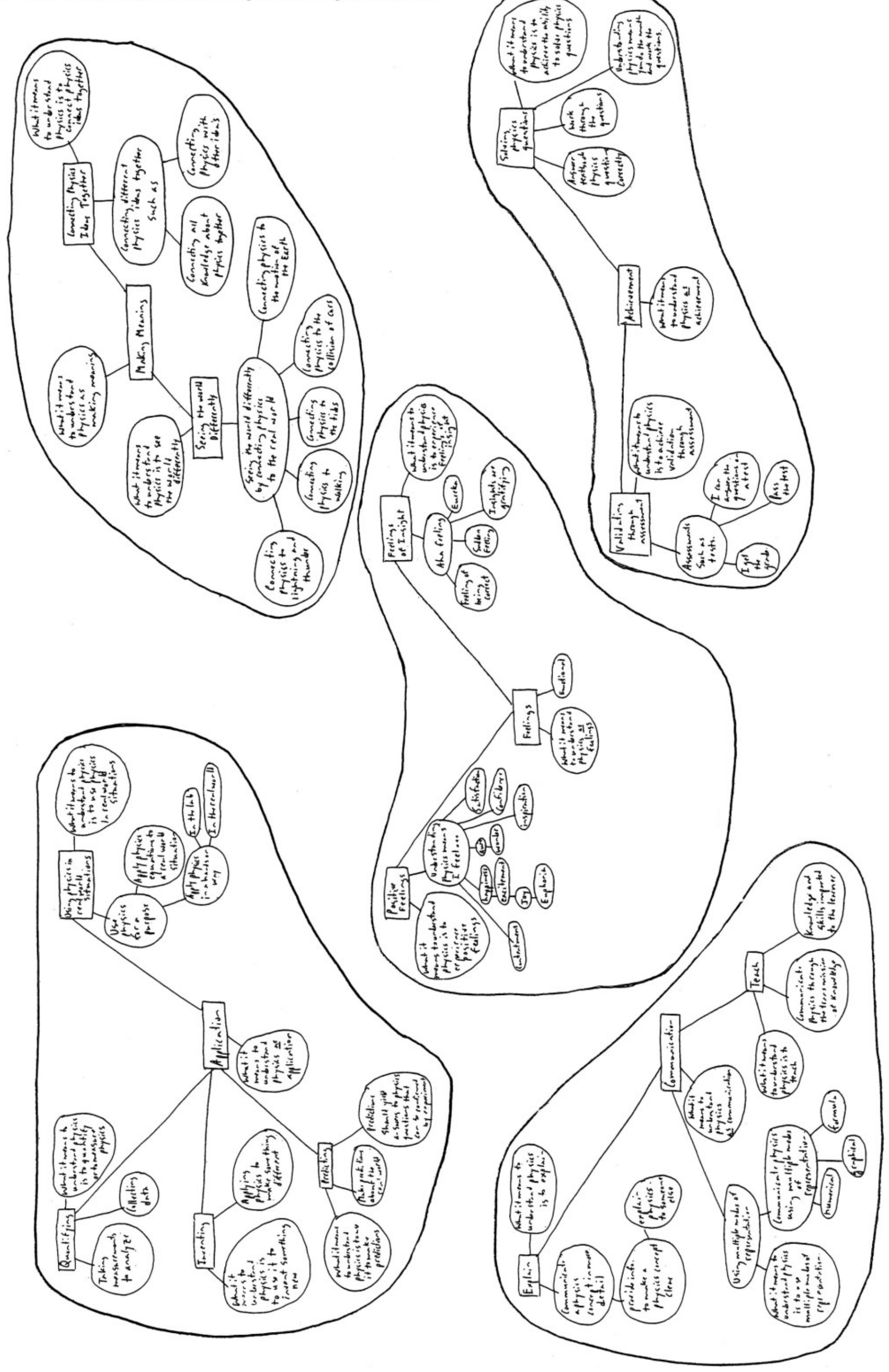
G	H	I
Professor Conceptions	Teacher Conceptions	Student Conception
Comprehend the real world	Apply	Solve Questions
Explain to others	Explain to others	Apply
Apply	Comprehend the real world	Comprehend the real world
Predict	Solve questions	Teach others
Teach others	Understand the big picture	Explain to others
Make connections	Teach others	Get good marks
Solve questions	Make connections	Good on test
Can't fully understand	Predict	Talk to others
Different levels of understandning	Know the formula	Derive formulas
Have an intuition	Innovate/invent	Do classroom physics labs
Know physics at different scales	Talk to others	Understand that physics is like blocks of a building
Quantify/measure	Good on test	Use correct formula
Make models	Quantify/measure	Make connections
Can make an analogy	Can't fully understand	Understand the formula
Do research/experiment	Breakdown into simple terms	Bring all physics theories together in a web
Visualize	Get good marks/receiving high marks	Feeling/Insight
Know the big picture	Can make an analogy	
Breakdown into simple terms	Represent physics in different modes of understandning	
Publish papers	Get correct answer	
Generalize	Feeling/Insight	
To be an expert		
Feeling/Insight/Intuition		

Appendix W: Maps of Conceptualization for the Students, Teachers, and Professors

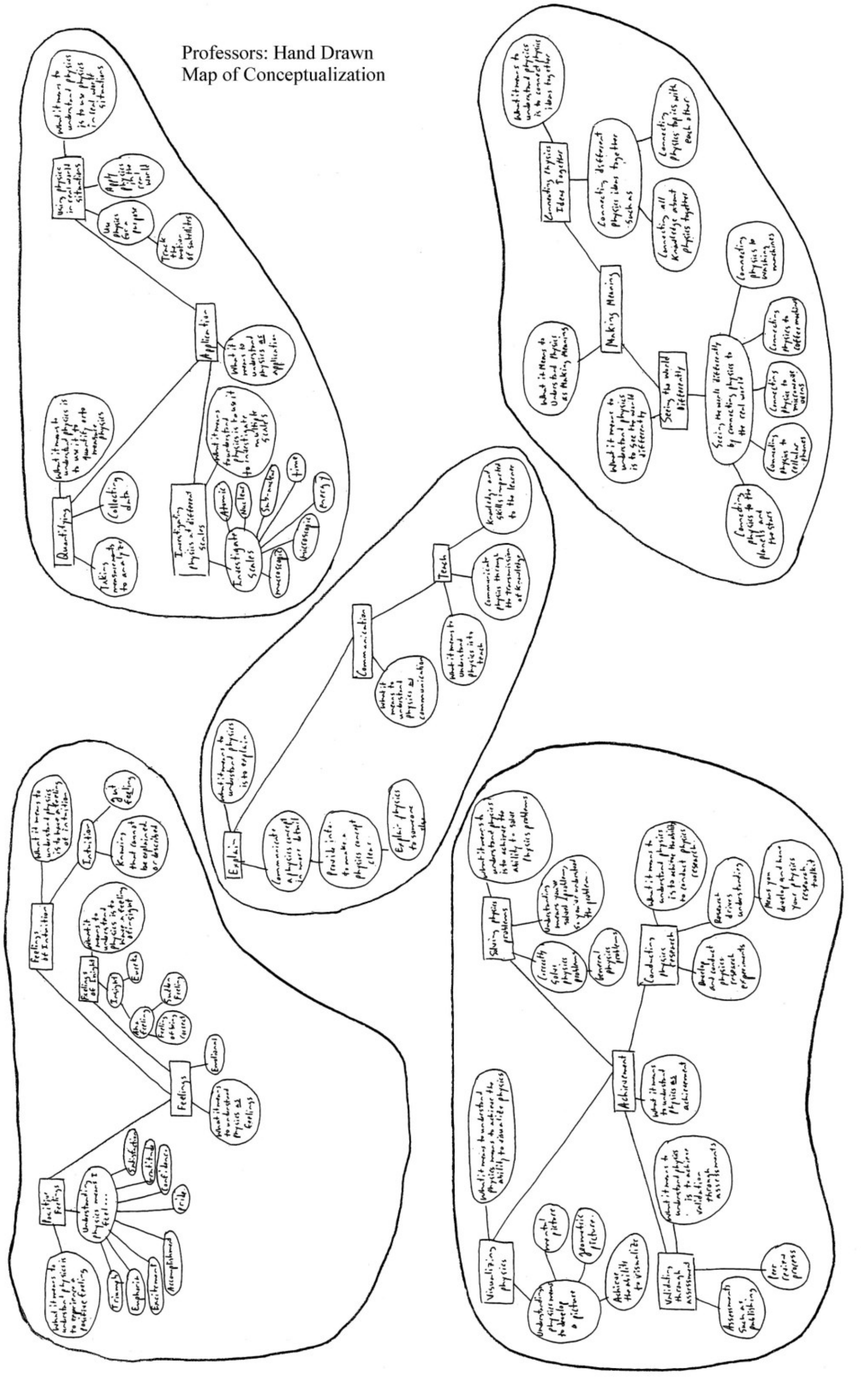
Students: Hand Drawn Map of Conceptualization



Teachers: Hand Drawn Map of Conceptualization

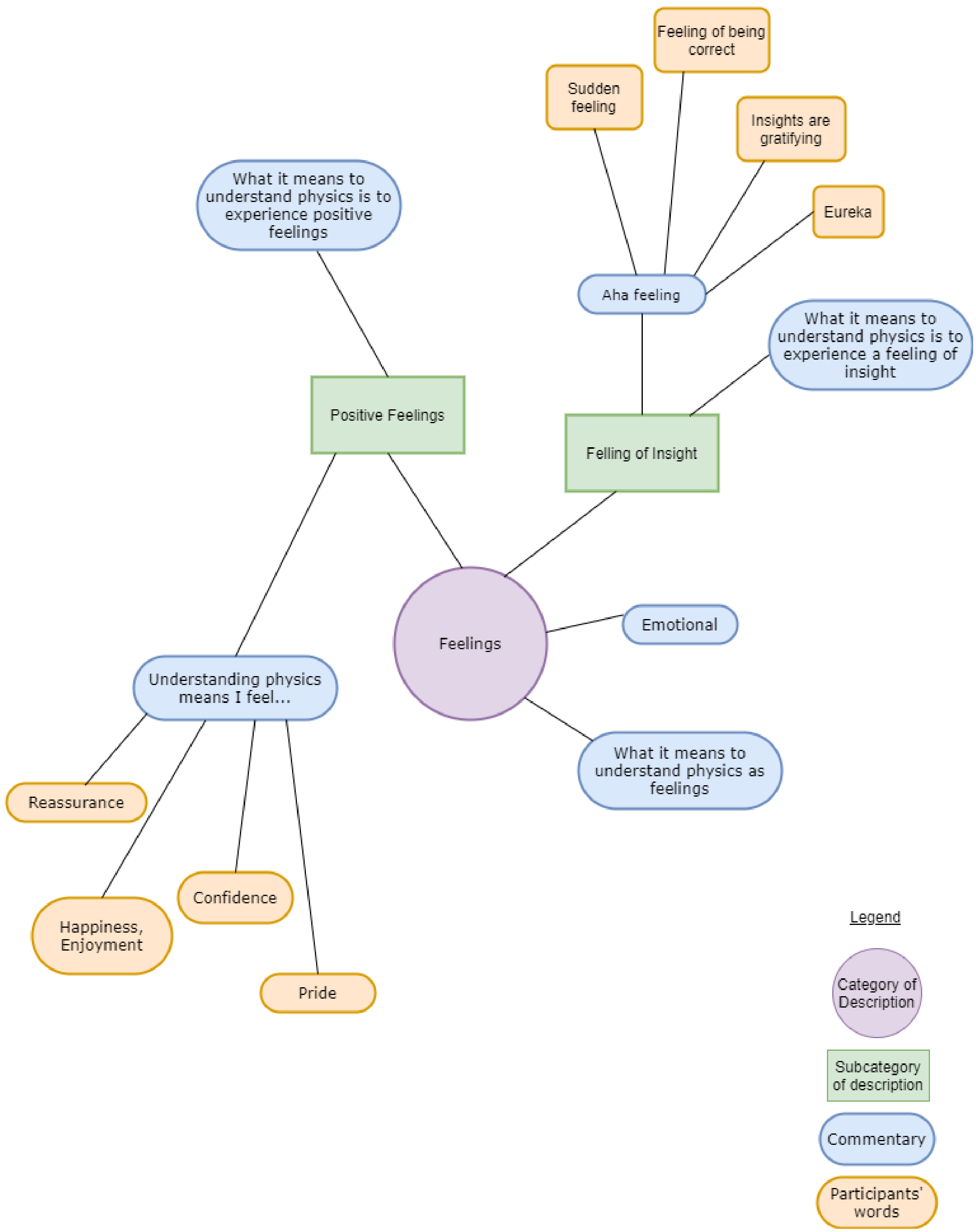


Professors: Hand Drawn
Map of Conceptualization

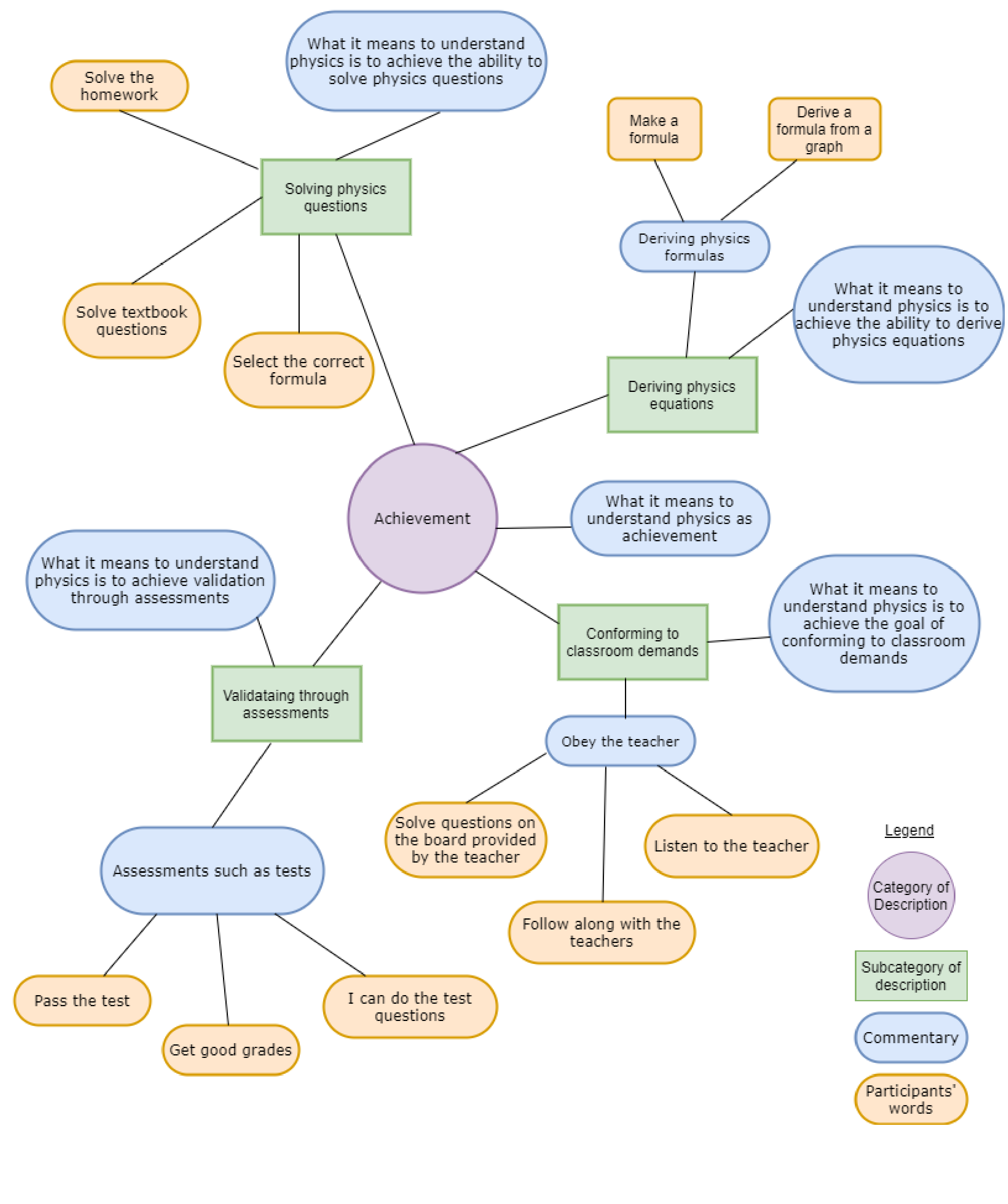


Appendix X: Student Maps of Conceptualization

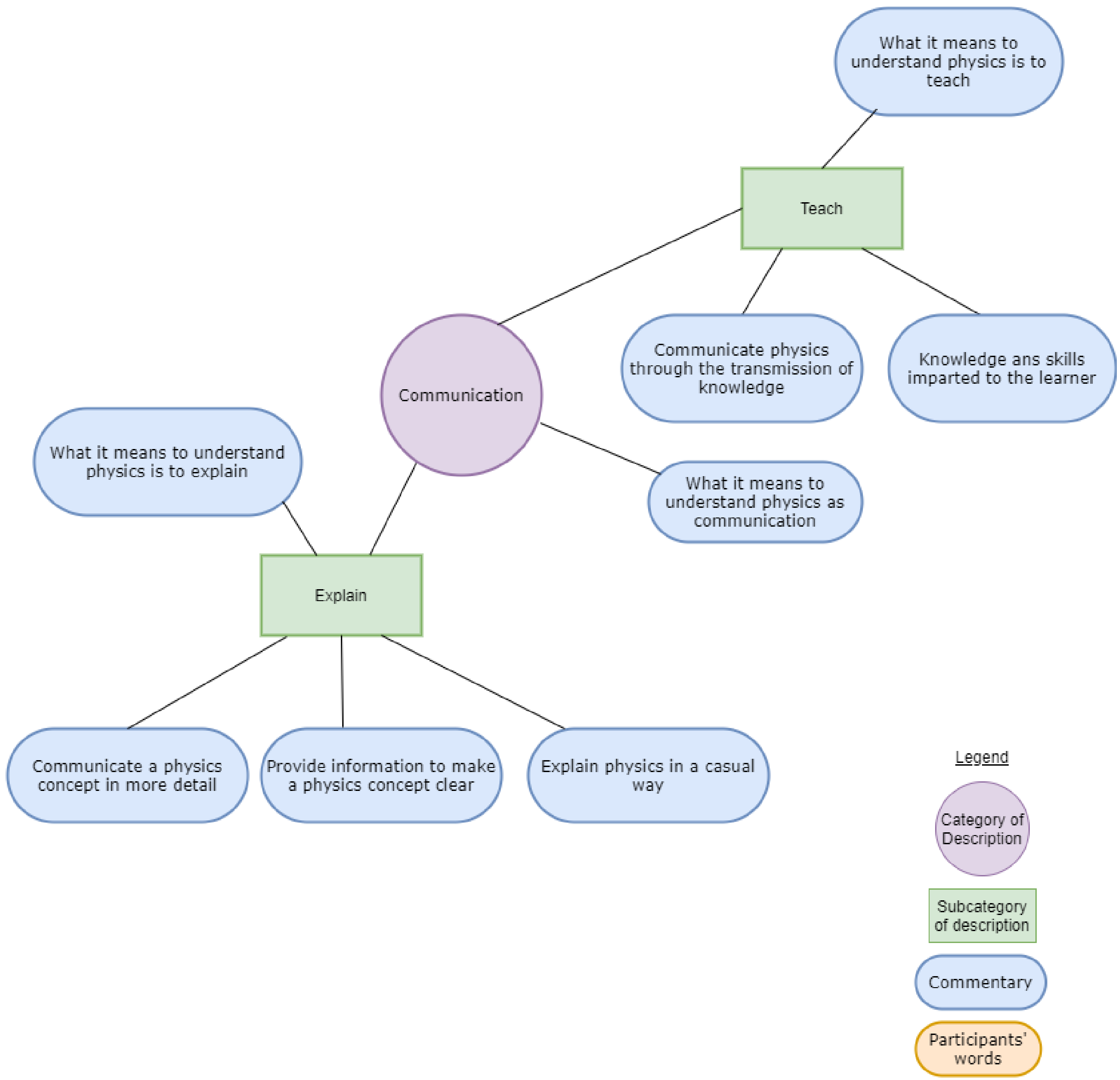
Student Category of Description: Feelings



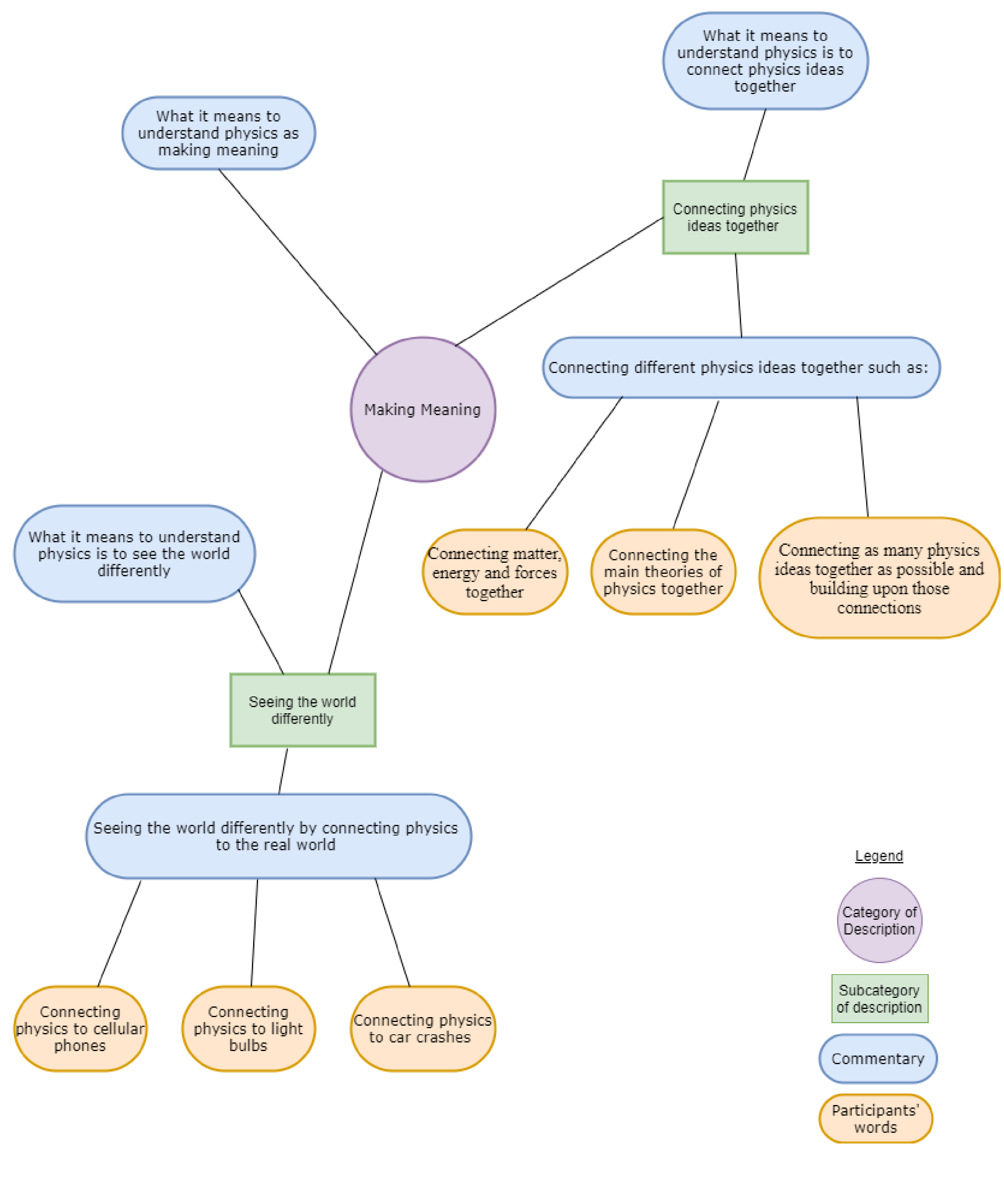
Student Category of Description: Achievement



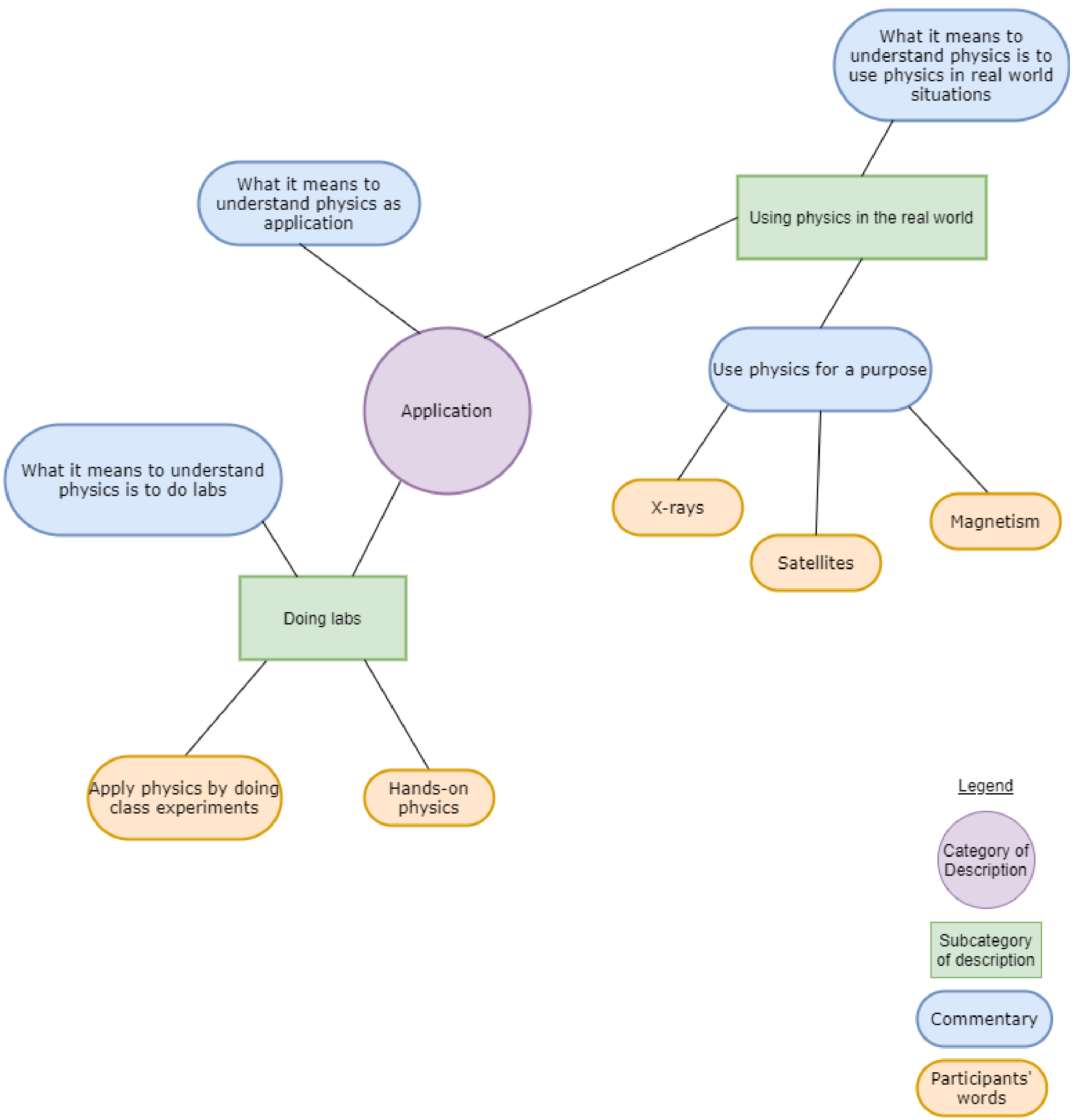
Student Category of Description: Communication



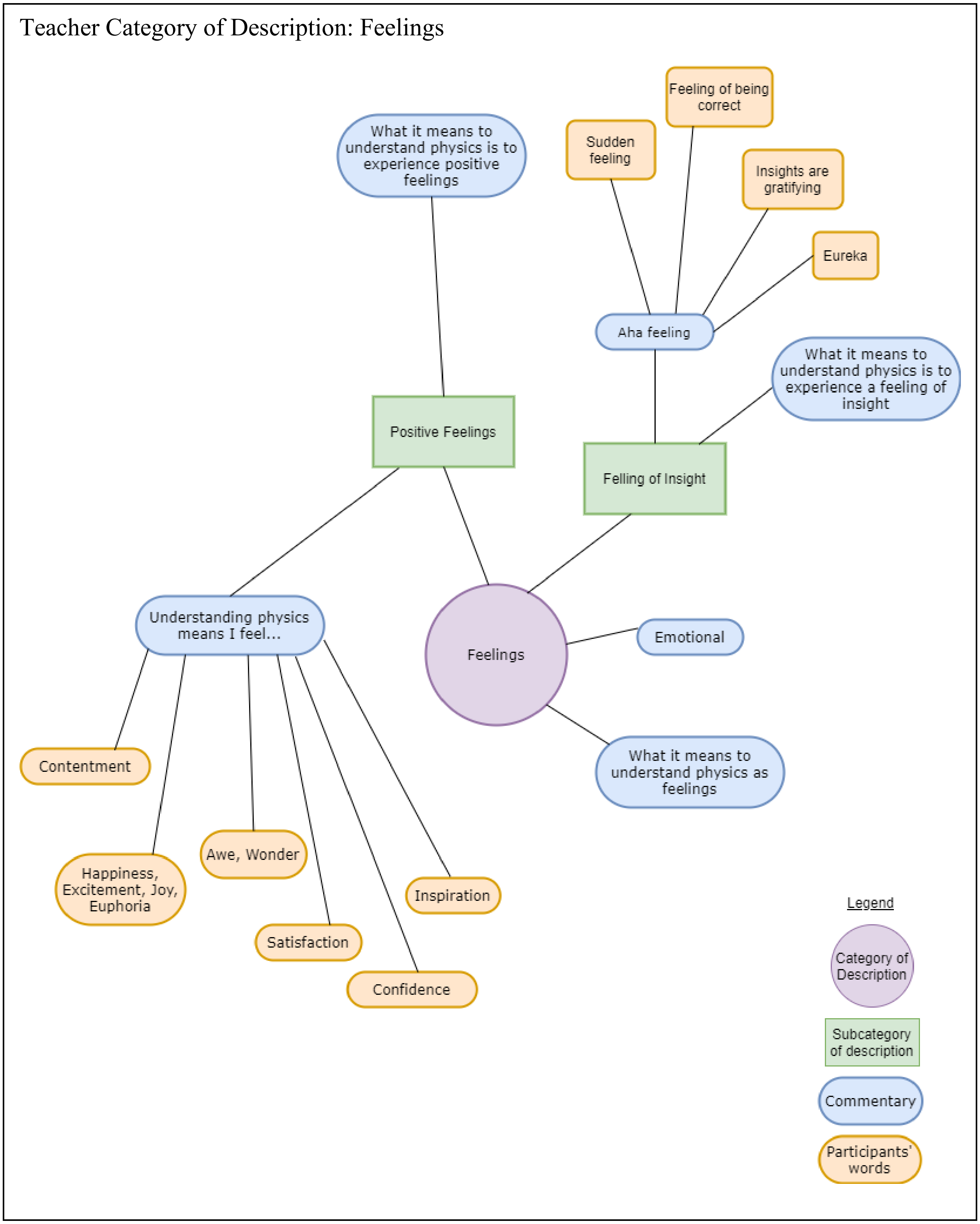
Student Category of Description: Making Meaning



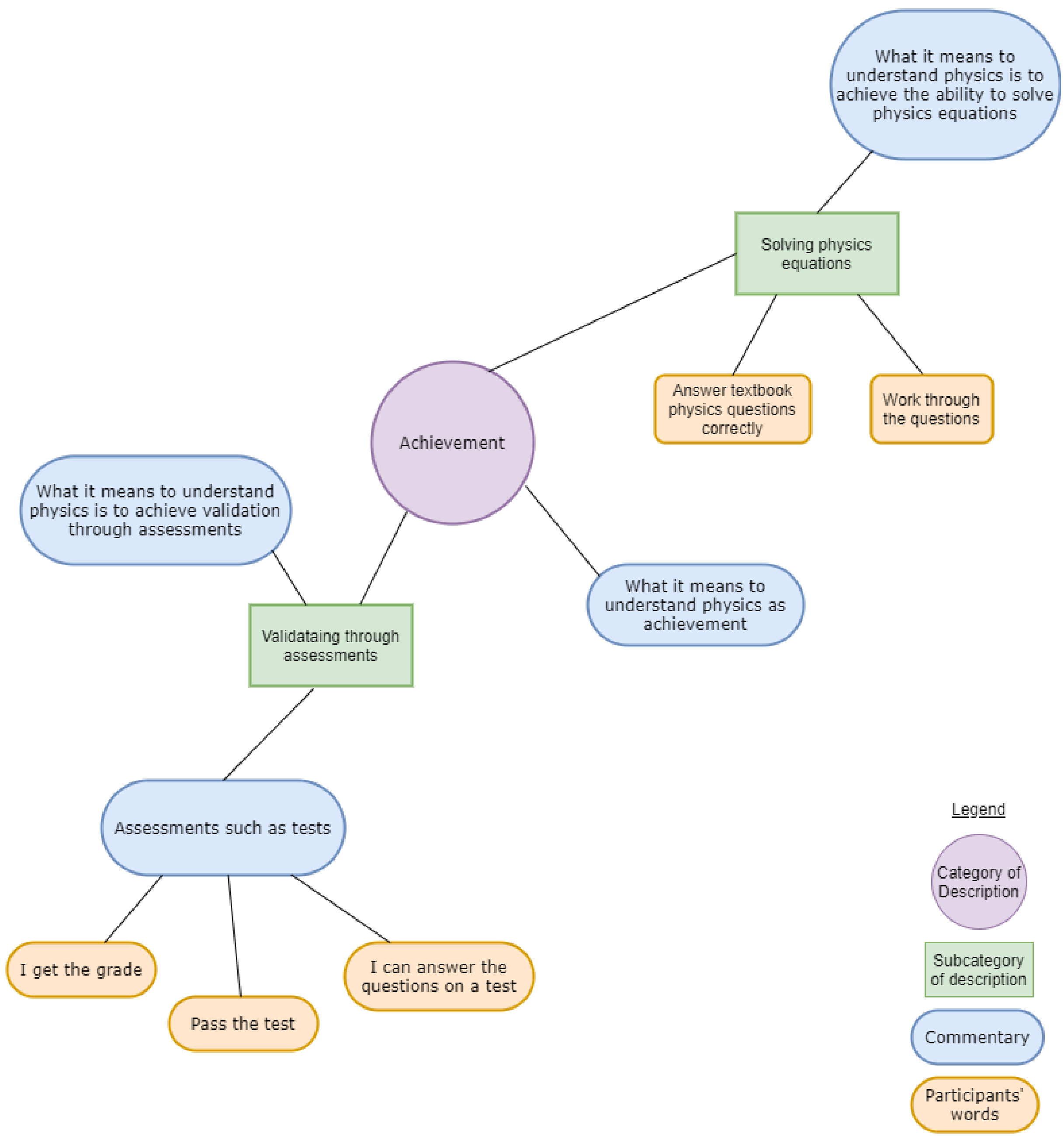
Student Category of Description: Application



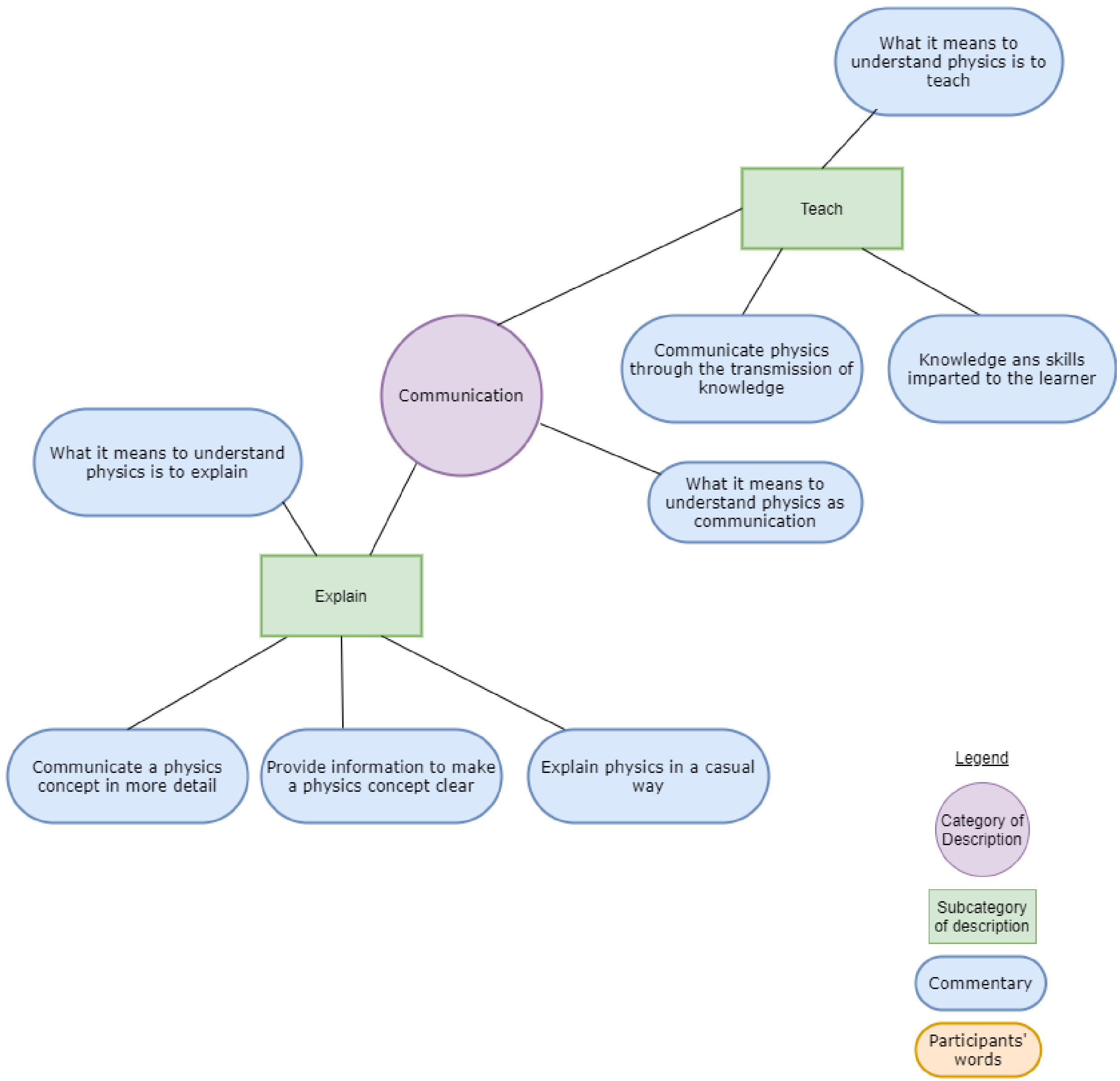
Appendix Y: Teacher Maps of Conceptualization



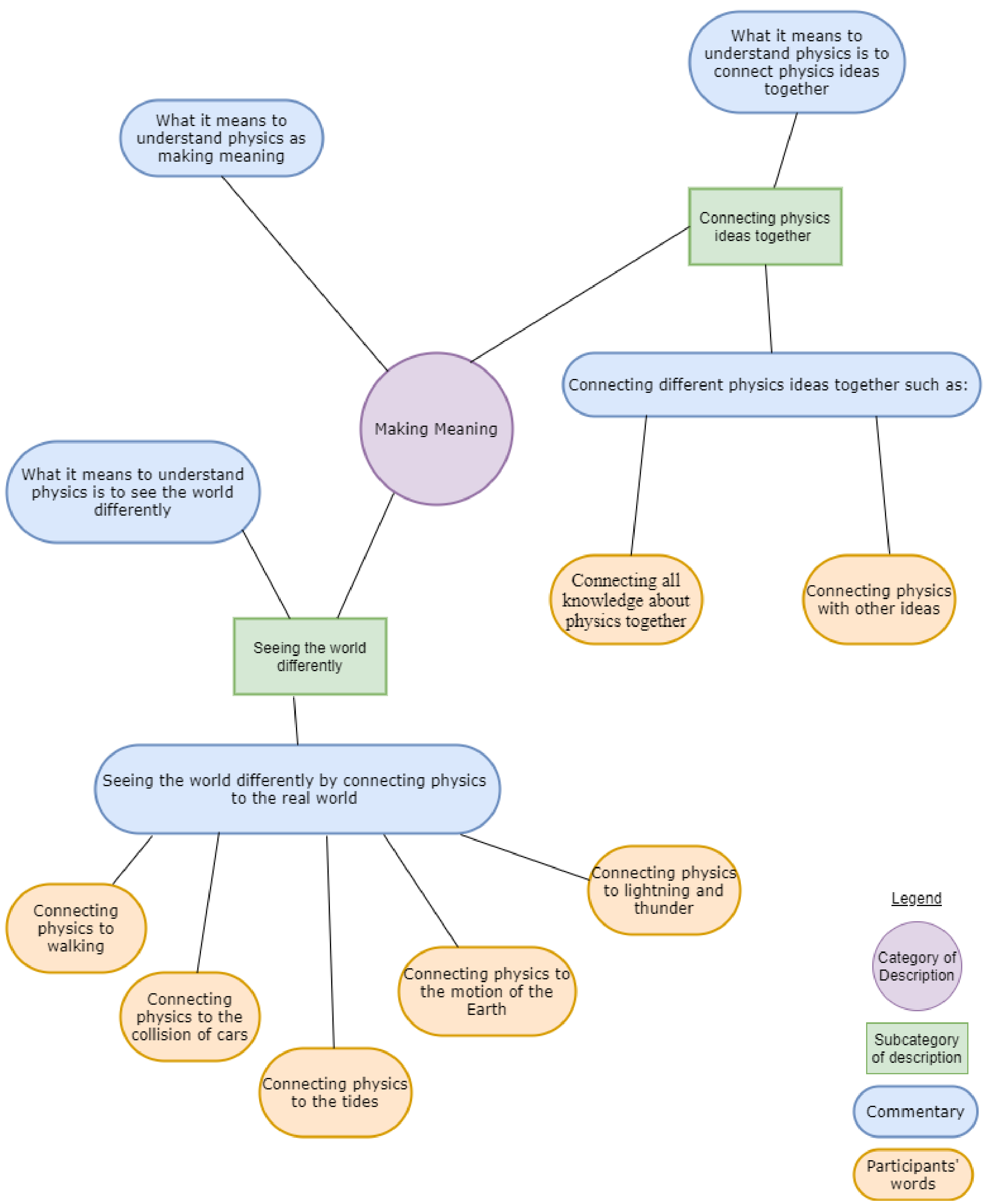
Teacher Category of Description: Achievement



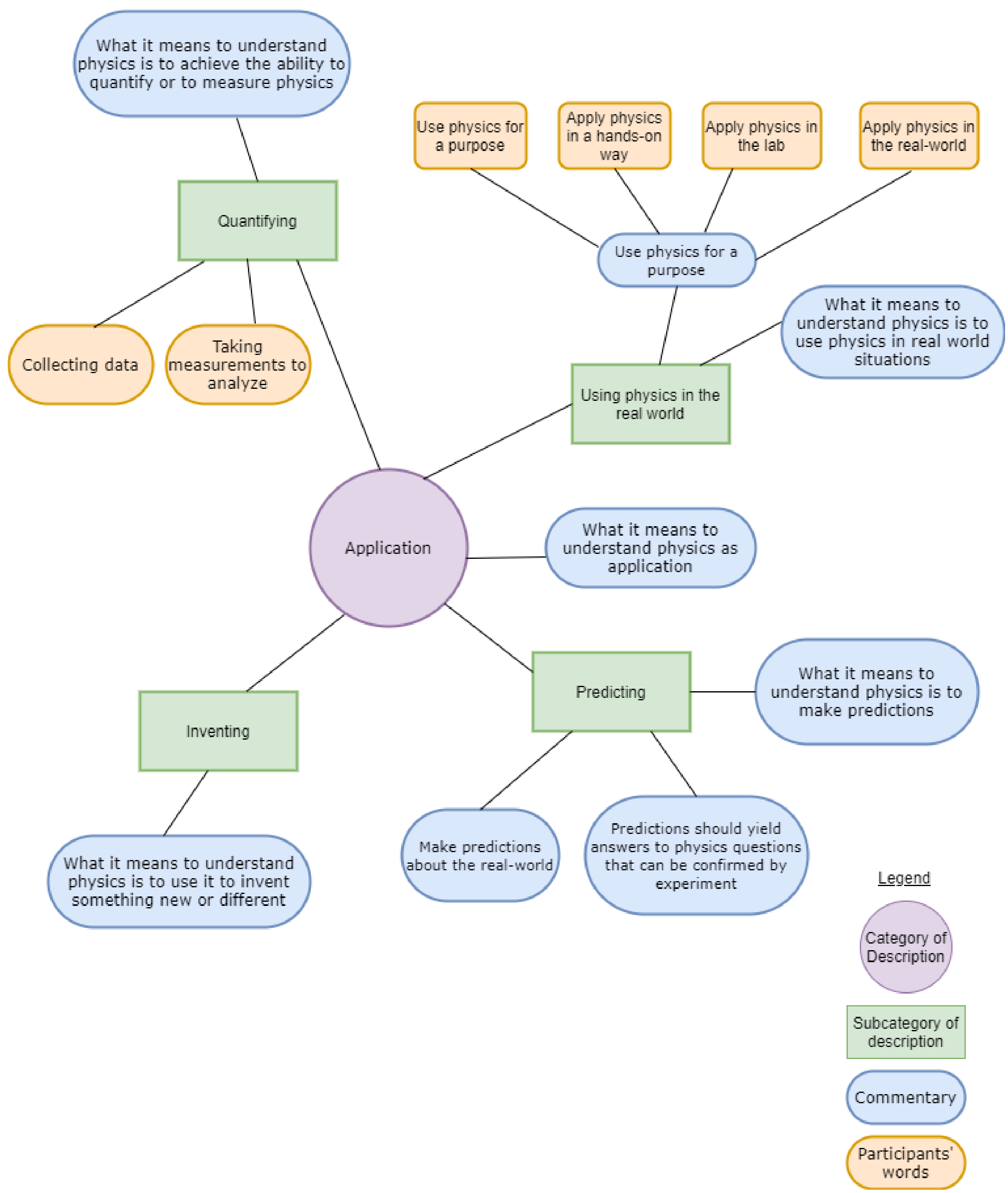
Teacher Category of Description: Communication



Teacher Category of Description: Making Meaning

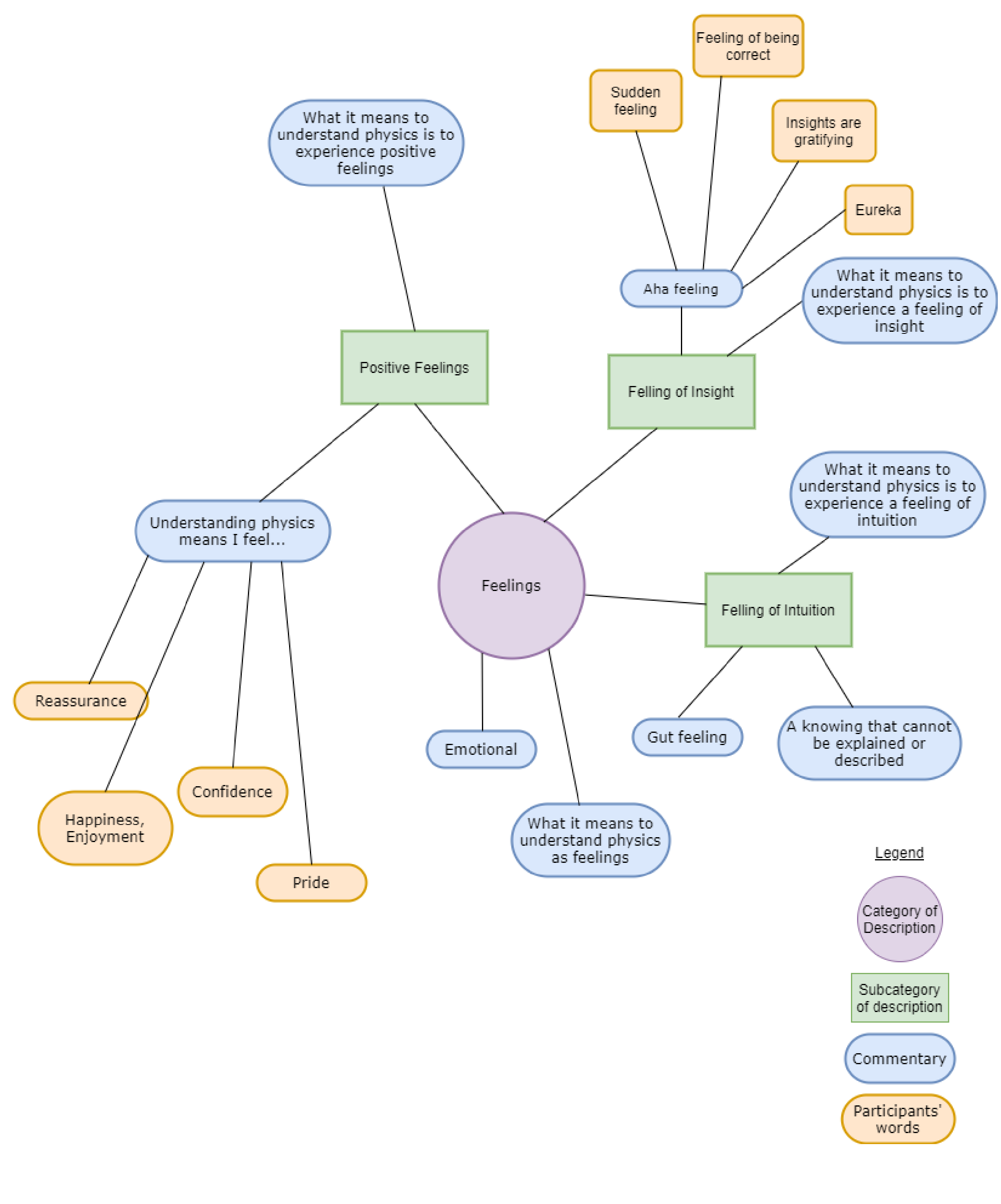


Teacher Category of Description: Application

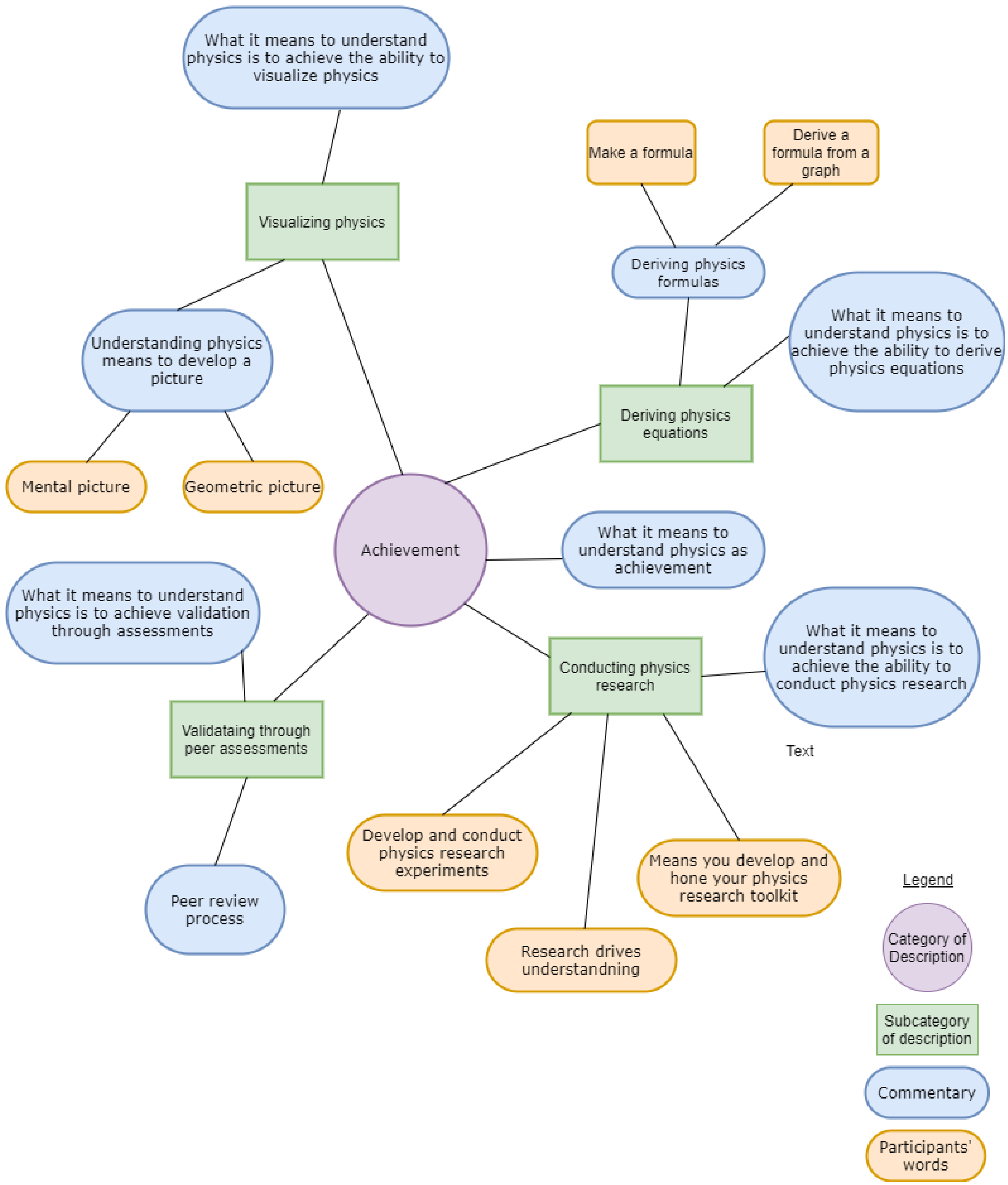


Appendix Z: Professor Maps of Conceptualization

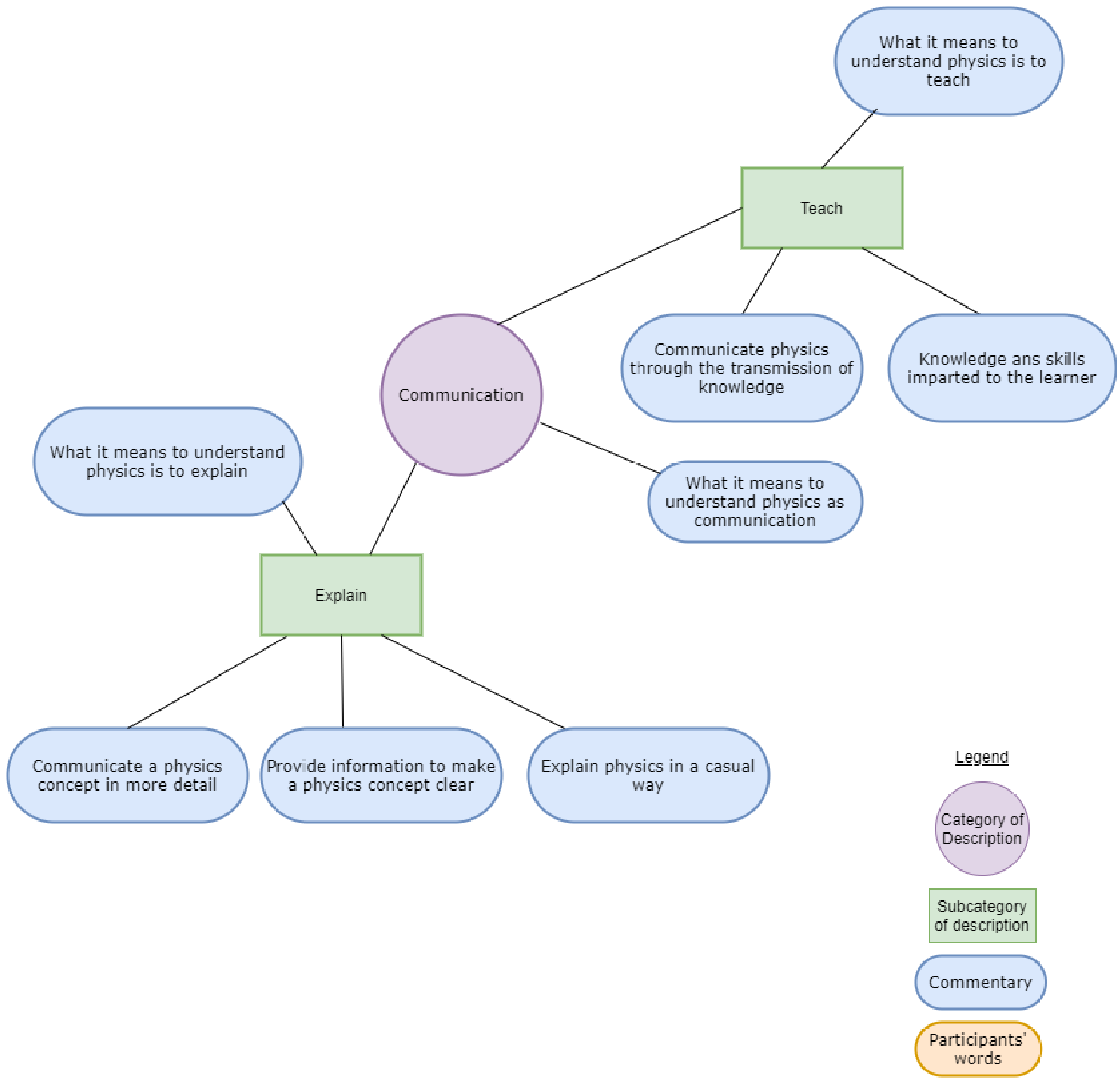
Professor Category of Description: Feelings



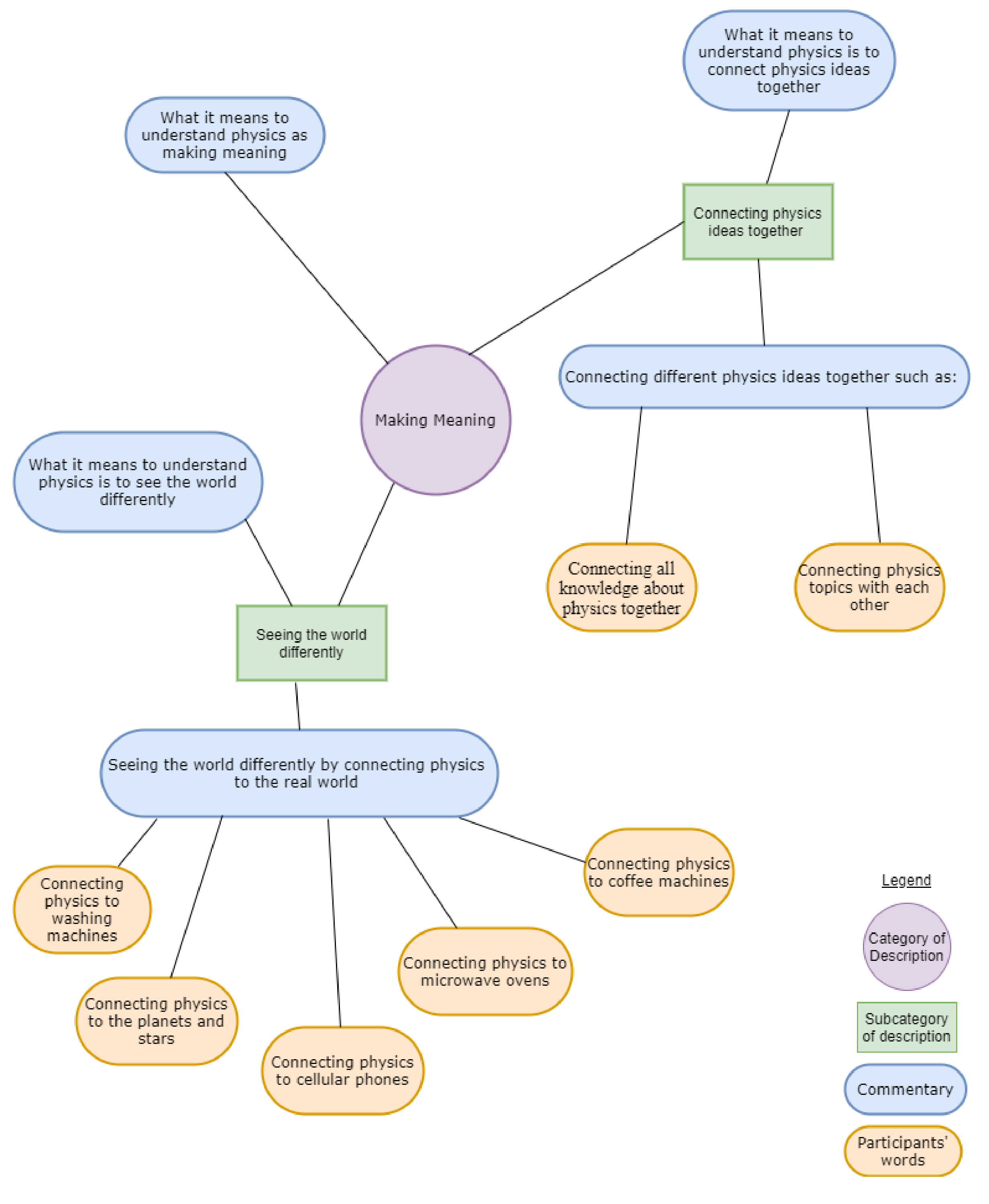
Professor Category of Description: Achievement



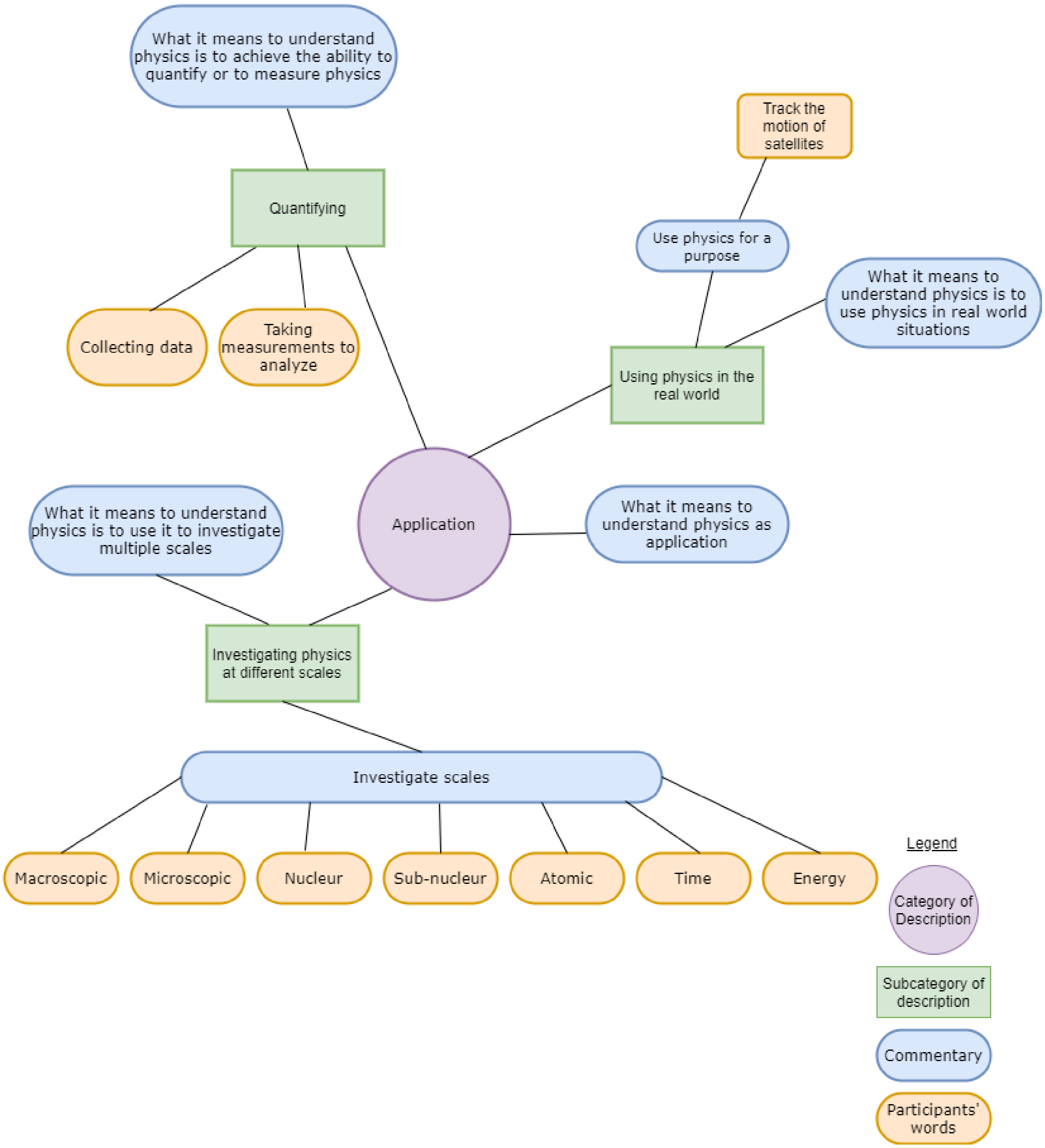
Professor Category of Description: Communication



Professor Category of Description: Making Meaning



Professor Category of Description: Application



Appendix AA: Ithaca (Constantine P. Cavafy)

Ithaca

When you set out on the journey to Ithaca,
pray that the road be long,
full of adventures, full of discovery.
The Laestrygonians and the Cyclopes,
the raging Poseidon do not fear:
you'll never find the likes of these on your way,
if lofty be your thoughts, if rare emotion
touches your spirit and your body.
The Laestrygonians and the Cyclopes,
the fierce Poseidon you'll not encounter,
unless you carry them along within your soul,
unless your soul raises them before you.

Pray that the road be long;
that there be many a summer morning,
when with what delight, what joy,
you'll enter into harbours yet unseen;
that you may stop at Phoenician emporia
and acquire all the fine wares,
mother-of-pearl and coral, amber and ebony,
and sensuous perfumes of every kind,
as many sensuous perfumes as you can;
that you may visit many an Egyptian city,
to learn and learn again from their scholars.

Always keep Ithaca in your mind.
To arrive there is your final destination.
But do not rush the journey in the least.
Better it last for many years;
and once you're old, cast anchor on the isle,
rich with all you've gained along the way,
expecting not that Ithaca will give you wealth.

Ithaca gave you the wondrous journey.
Without her you'd never have set out.
But she has nothing to give you anymore.
If then you find her poor, Ithaca has not deceived you.
As wise as you've become, with such experience, by now
you will have come to know what Ithacas really mean. (Cavafy, Hirst, & Mackridge, 2007, p. 37)