

How Does a Grade 8 Science Teacher Learn to Teach Quantum Mechanics?: An  
Exploratory Case Study

by

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B.A. Engineering Physics, Istanbul Technical University, 2000

M.A. Curriculum and Instruction, Yildiz Technical University, 2007

A Dissertation Submitted in Partial Fulfillment  
of the Requirements for the Degree of

DOCTOR OF PHILOSOPHY

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University of Victoria

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**Supervisory Committee**

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**Departmental Member**

## **Abstract**

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In 2016 the Ministry of Education in British Columbia (BC), Canada introduced the topics of quantum mechanics (QM) into the Grade 8 science curriculum. Science teachers with or without QM background are expected to learn and teach QM. Stemming from a constructivist theoretical framework, this in-depth exploratory case study explores the processes of learning and teaching the topics of QM by asking: “How does a Grade 8 science teacher learn to teach QM?” The purpose was to understand the teacher’s QM learning process, the development of pedagogical content knowledge (PCK) in QM and teacher’s views of the nature of science (NOS). The data was collected through multiple sources and analyzed by using thematic analysis. The themes were identified under five main categories: 1) the development of PCK in QM is complex, 2) the student-centered approach mandated in the redesigned curriculum may be limiting, 3) the nature of learning QM is not different than learning other subjects, 4) middle school science education is inconsistent with the current level of scientific knowledge, and 5) the development of informed views of NOS requires an accumulation and synthesis of prior knowledge in history and philosophy of science (HPS). The study proposes two previously unexplored integral aspects of PCK framework, since: the ‘allotted time’ in

learning and teaching a subject and ‘pre-PCK’ change the nature of PCK development. The term pre-PCK was coined referring to the specific content oriented and student-centered activities that take place before the class with the goal of establishing an effective basis for the PCK development. The insights emerging from the study would be of interest to other Grade 8 science teachers in BC, pre-service teacher program coordinators at the universities, and the Ministry of Education in BC to provide institutional support. This study would also contribute to closing the knowledge and communication gaps between the fields of science, science education practice and science education research.

*Keywords:* quantum mechanics, physics, science education, pedagogical content knowledge (PCK), pre-PCK, nature of science (NOS), history and philosophy of science (HPS), constructivism, exploratory case study, BC’s redesigned curriculum, Grade 8 science curriculum

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**Dedication**

To all my relations

## Chapter 1

Paradigm shifts change the underlying assumptions and transform modes of thinking in society (Cambridge English Dictionary, 2016). The emergence of this dissertation is inter-connected with a paradigm shift that took place in the 20<sup>th</sup> century which disrupted the status quo and changed the direction of exploration in the field of science, fundamentally altering the preconceived views of reality. With this paradigm shift not only the field of physics was transformed, but also the understanding of science and perspectives in philosophy of science, along with the taken-for-granted assumptions in everyday life. This paradigm shift is quantum mechanics (QM).

As a branch of physics, QM provides scientific explanations for micro-scales, namely atomic phenomenon, and promotes different perspectives understanding natural phenomena in a counterintuitive framework. For instance, in the QM framework, two separate particles can be interconnected despite the distance. When Einstein first discovered this bizarre QM phenomenon, he was not able to identify the reasons why two particles that are kilometres or light years apart were able to communicate with each other instantaneously, and he called it ‘spooky action at a distance’—known as quantum entanglement and still keeps its mystery. Quantum entanglement is used in creating quantum computers, that bring the notions of speed and power of classical computers to another dimensions by enabling entanglement of multiple bits of information simultaneously. While science and technology go hand in hand, the making of quantum computers shows that scientists do not necessarily need to know the reasons behind a scientific phenomenon in order to harness scientific knowledge and create cutting-edge

technology. Therefore, the concepts of QM not only provide accelerated technological advancements such as lasers, smart-phones, magnetic resonance imaging (MRI), and global positioning system (GPS), but also drastically alter our understanding of nature and disrupted classical views of science (Newton, 2009).

The paradigm shift of QM had its first appearance in the middle school science curriculum in British Columbia (BC), Canada in 2016 with the Ministry of Education redesigning the science curriculum to incorporate some topics of QM into Grade 8 science classes (BC's New Curriculum, 2015). One of the big ideas in Science 8 curriculum is identified as "energy can be transferred as both a particle and a wave" referring to the light as electromagnetic energy and the dual nature of light (BC's New Curriculum: Big Ideas, 2015). In the QM realm, the dual nature of light implies that light is made of particles and also is a wave. The concept of dual nature is also valid for any quantum particles indicating that matter can inhabit in two natures as a form of co-existence, such as being fire and water simultaneously.

Given the likely lack of QM background of Grade 8 science teachers, it seems timely to explore the possibilities of this transition from teachers' perspectives. I was not able to locate any research regarding the process of middle school science teachers learning and teaching QM and the impact of these processes on teachers' views of NOS. The insights emerging from this study would contribute to an unexplored area of science education literature and potentially have practical implications for an effective science education practice.

The research question that guided the study was: "How does a Grade 8 science teacher learn to teach QM?" The purpose of this in-depth exploratory case study was to

shed light on this transition by exploring a Grade 8 science teacher's pedagogical content knowledge (PCK) and her views of the nature of science (NOS) while she was learning and teaching topics of QM. Shulman's (1986; 1987) teacher knowledge framework including the domain of PCK, was utilized in order to understand the participant's personal blend of pedagogy and content knowledge developed particularly for the topics of QM. Abd-El-Khalick (2012) lays out the ten aspects of the views of NOS as the latest and inclusive version of NOS, which was utilized for the analysis of this data as a complementary framework in order to explore the participant's views of NOS. Stemming from the research question, this study was designed to illuminate how a Grade 8 science teacher engages with the concepts of QM. In particular, how she learned and developed PCK in conceptual understanding of QM, and cultivated her views of NOS.

### **Background**

I was schooled in the traditional way. The teacher stood at the front and spoke or wrote on the blackboard, the students sat in desks, organized into neat rows, and watched or listened passively. Knowledge was extrinsic, transmitted from teacher to student, just as in Bobbitt's (1915; 2004) factory model of education. The primary mode of thinking was deductive and linear, all in service of the pursuit of the single right answer.

This made for a world that I could understand—well-ordered, definite, and predictable. I trusted science. Because of its machine-like approach there were no surprises; it all made sense which created a feeling of safety. Science was the one and only reliable agent that could never disappoint or allow room for hesitation. It was solid. It was true. This machine-like mind-set was promoted, supported, and enhanced, since understanding the laws of nature had helped humankind to survive in the real world. To

me, this was a good thing. The way that I saw it, science was the most useful tool to understand the world around us and I was happy to be able tap into that understanding.

I was in middle school when I first learned about photosynthesis and the chemical reaction cycle that takes place in plants. After the school, I went for a walk on my usual trail, which was lined with trees on one side and hedges on the other. However, this time the way I see the world was different. This time the greenness around me meant something new; I knew what the plants secretly doing. During photosynthesis the plants were using what they had—water and carbon dioxide—and turning them into sugar and oxygen; producing their own food. I could see that the soil was moist and there was sunlight. The plants were definitely photosynthesizing! Six molecules of carbon dioxide and six molecules of water blended with sunlight was enough to produce sugar and oxygen. This invisible smart world of plants was truly astonishing.

I was amazed that the plants were functioning perfectly for their own survival without human intellect, which up until that very moment I had thought the grandest of all. And not only were the plants surviving on their own, they were also producing oxygen for humans. Contrary to what I had believed, the so-called primitive plants did not seem to need us at all and there was so much more going on beyond my perception.

As I continued walking between the green plants and reflecting on the pure genius of the common plant, at first I felt myself like a God who is aware of everything beyond the visible—the photosynthesis reaction; how the leaves extract carbon dioxide from the air and so on. Then I felt ignorant as I realized how little I really knew about the workings of nature. There must be so much more that human beings do not know, I thought. The possibility of vast knowledge beyond what anyone knew made me think

that perhaps I was walking on a planet out of science fiction. Those plants were brilliant creatures and I was just a poor human, not able to understand the miraculous laws of this amazing planet. I was suddenly like Alice in a strange Wonderland.

I had always had a strong interest in science. My family still tells the story of how I thought my uncle about gravity and electric currents when I was four. I was excited even then about the invisible world, but as I was walking on the trail that day, my thinking regarding the invisible world was different; this time I had made the connection between the invisible world and the representation of it through chemical reactions. In my mind, this was the day that I became a true scientist in the pursuit of unveiling the works of nature. Theory came alive for me, and my curiosity for the unseen world and the possibility of understanding nature through the marriage of theory and practice would give me the power to understand the phenomenon of the invisible world.

### **Quantum mechanics.**

Because of my interest in understanding nature I decided to study physics. Later I found out that studying physics at the university meant studying advanced mathematics, so the awe I had towards the clockwork nature of the world turned into awe for the power of mathematical expressions. I liked the idea that the mechanisms of nature were hidden beneath complex looking mathematical equations expressing themselves in Greek letters. These years in university confirmed to me that the background of the simple mathematical formulas that I had learned in high school were elegant and powerful.

I was introduced to QM after I had been taught the mathematical formulations needed to operate the QM problems during the first two years of my study. Although I was able to take in what was being taught, and successfully pass the courses, I realize in

retrospect that I had been given almost no conceptual or philosophical understanding regarding the QM concepts. The classroom discussions were mainly based on how to solve QM mathematical equations. Therefore, at university, physics for me all of a sudden equated itself with mathematics.

However, this understanding was against the nature of physics. Physics by definition is etymologically derived from the Greek word *physis*, which means nature (Chambers Dictionary of Etymology, 2008, p. 790). Until the 17<sup>th</sup> century the field of physics was called the philosophy of nature (Stanford Encyclopaedia of Philosophy, 2015). In ancient Greece this field of science first emerged as a discussion of nature; it was not overwhelmingly mathematical, as it has become today. As Eisenbud (1971) a theoretical physicist explained:

There are two complementary methods . . . to communicate physics. In the first of these, the “formal method” the manipulatory skills relating to the subject matter of interest are emphasized. . . techniques required to solve the standard problems . . . In the second, the “conceptual method” physical meanings are investigated carefully with little attention to technique. Once the basic concepts are clearly understood, or so it is assumed, manipulative skills will take care of themselves. . . The conceptual method produces philosophical wranglers who can tear subtle ideas to shreds but who are unable, perhaps, to draw a fresh conclusion from even the most fruitful stock of ideas (p. vii).

Eisenbud suggests that in order to communicate physics, first the basic concepts must be understood, and then mathematical formalism can be built on the conceptual framework.

In my QM learning experience, I was given the mathematical skills before I had understood the concepts of QM. Because of my personal interest in all things scientific, I began to read about various subjects in the *Science and Technology Journal*. As I read the journal, I began to understand the power of making sense of the abstract with the help of storytelling and images, which animated the mathematical formalism that I had learned in my university classes. What had been dry, almost dead mathematical formulas completely detached from the world as I knew it, became exciting, appealing to the sense of amazement that I had experienced when I first realized that the plants that I had seen every day were in the process of photosynthesis. However, I imagine that not all the students were fortunate enough to come upon the missing pieces.

The impact of learning QM is difficult to describe. The framework was fundamentally different than all the other things I had learned so far not only in my studies, but also in the rest of my life. The science that I had initially learned, that had comforted me with its sense of certainty of being right, had seemed intuitive in the way that it just made sense. However, QM was counter-intuitive with its probabilistic nature, with the notions of non-locality and dual nature of matter. It did not make sense with my everyday life experiences. Particles going through walls? Being at two different places at the same time? It all seemed unbelievable... I was once again Alice in Wonderland, but a fundamentally different wonderland.

For the first time, I was facing the counter-intuitive elements of science where results can be observed, but the reasons are unknown. This time I was not confident like I was when I first learned about photosynthesis, logically accepting the amazing photosynthesis cycle. Instead, my first reaction to the QM concepts was “no way!” I

found it ridiculous and disturbing. QM was far from the common sense that I had grown up, and to my astonishment it demonstrated that there are multiple realities to make sense of the world. But the mindboggling part was that while there was both the mystery and counter-intuitiveness, QM was surprisingly accurate within the scientific framework. QM was not science fiction, not a fairy tale; it was a scientifically proven framework, which confronted the reality that we have become used to.

### **The nature of science.**

My view regarding the nature of science had completely transformed after I had learned QM, on multiple levels. First, I had learned that there was no one single answer in investigating the natural phenomena and that there are also waves of probabilities that indicate that there can be more than one answer at the same time. The second lesson that the concepts of QM taught me was that without understanding the reasons we were still able to go through the scientific inquiry and get scientific answers, such as with the QM concept of entanglement. Considering the predominantly law-driven nature of classical mechanics, QM had unveiled the theory-driven nature of science in the sense that natural phenomena could be understood not only by observation that lead to laws of nature, but also by inference that lead to theories of nature.

Thirdly, I learned that there exists a reality that does not make sense compared to our immediate reality. Therefore, I needed to respect the fact that the reality that the universe has to offer us is under no obligation to make sense to human beings. From my perspective, the change in my views of nature of science with the QM paradigm shift brought an end to the arrogance towards human intellect that I had held. Human ego up until that point seemed to have the power to dictate the idea that everything around us has

to align with our sense perception or mental capacity. Consequently this influenced the sense we make of the world, causing us to stay in zone of intellectual comfort. However, I came to realize that not everything, not even science, has to align with human common sense.

Fourth, in studying QM I learned about thought experiments for the first time, where hypothetically a cat can be dead and alive at the same time. This cannot be understood in the real world, but only on the conceptual level. In my experience, these thought experiments could be as useful as laboratory experiments; in addition I realized that thought experiments could have the power to enable access to further areas of knowledge either what we are conscious of not knowing or what we are unconscious of not knowing.

The traditional way of seeing the progression of science is linear like the building blocks of a skyscraper; however, as Kuhn (1996) argues, scientific progress can be viewed as more like discovering a whole new world of scientific laws as in living in a desert and thinking that the desert is all there is, and suddenly coming across the ocean—a fundamentally different aspect of reality. From a traditional view of nature of science, science can be viewed as a product, which it has as its goal to reach the perfect science level through linear cumulative generation of solutions, where everything is understood and there is no more need for scientific investigation. However, after learning the QM paradigm shift, my view of NOS changed to an understanding that science is an ongoing activity punctuated by changes in worldviews, rather than linearly piled up scientific facts.

A paradigm shift in the field of physics might embed the possibility of shifting to another realm, by using the analogy of the desert and the ocean, a person living in the Amazon jungle all his life would not easily be able to capture the notion of a desert. Was there another paradigm shift waiting for human beings to transform the way we see the world, I wondered? QM then might not be the ultimate level of science, rather; a new scientific revolution might be possible. All of this to say that engaging with QM concepts transformed my views of NOS, which years later reflected on my physics teaching experience. In *The Meaning of Quantum Theory*, Baggot (1992) highlights the challenges of coming to QM within formal methods rather than its conceptual understanding:

Most graduate courses on quantum theory never touch on the theory's profound conceptual problems. This is because the theory brings us right back to some of the central questions of philosophy and, as we know, there is no room for philosophy in a modern science degree. I find this an absurd situation . . . quantum theory "is" philosophy. Oh, we can dress it up in grand phrases littered with jargon—state vector, Hermitian operator, Hilbert space, projection amplitude, and so on—we can make it all very mechanistic and mathematical and scientific, but this does not hide the truth. Beneath the formalism must be an interpretation, and the interpretation is pure philosophy (Baggot, 1992, p. x).

Between those Hermitian operators, Hilbert space, and eigenvalues, conceptual understanding of QM comes alive, making the QM learning experience meaningful. In teaching physics, it could be that teaching mathematical expressions first, before

providing conceptual understanding, might cause problems in fully comprehending the natural phenomena. Providing conceptual understanding might be relatively easier with classical mechanics, since the concepts already come from everyday life, such as the speed of a car, or a ball thrown in different directions. However, QM concepts are beyond our immediate understanding of the world such as the super-position of a particle or behaviour of a wave function. For instance, gaining conceptual understanding in QM would mean that when we see a particle, it also means that at a sub-atomic level that particle is in fact also a wave. Although QM concepts are counter-intuitive, such as being two different places at the same time, metaphors and examples from everyday life might help in capturing QM concepts, such as the continuous nature of classical mechanics can be represented as liquid water, and discrete energy packages in QM can be represented as ice cubes in a jug. Both are water, but when pouring in the glass the liquid water continuously flows, whereas the ice cubes only move in discrete packages. When I thought of such examples, I realized that it is possible to teach QM through analogies and examples. Especially in QM, the study of micro-scale world, it would be particularly essential to first gain an understanding of the QM concepts and dwell with the concepts before proceeding to the mathematical understanding.

### **My quantum mechanics teaching experience.**

My academic goal right after finishing my Master's degree in education was to continue with a PhD program. However, the Master's program was overwhelmingly theory-laden and although I respectfully recognized the validity of the theories, I also knew from my high school experience that building an ideal education framework on theories was not able to give me the full picture for a completely insightful educational

experience. Internships were helpful, but they were just not enough. I had the feeling that I needed to have teaching experience in high school before continuing to a doctoral program.

QM was not in the physics curriculum, so when I became a physics teacher I wanted to offer this mind-bending experience to my students by introducing the conceptual notions of QM. How could I not teach that fascinating part of physics to my students? It just did not seem fair; there was no justice in providing merely the body of knowledge of classical mechanics, as if it were all there was in the field of physics; physics was not only classical mechanics. I could not, in good conscience, teach physics without including QM as part of a more complete picture of the field of physics.

Since QM did not take place in the curriculum, I taught QM as an extracurricular activity both in my classes and also in philosophy classes as a guest teacher. In my QM teaching experience I tried to utilize constructivist teaching approaches. Constructivism is considered to be an effective pedagogical approach in the field of education (Philips, 2000; Tobin, 1993). Constructivist methodologies can assist teachers to navigate through their teaching process by considering, for example what might be age-appropriate or accessible for students, and gives us pedagogical concepts such as following a pattern in demonstrating concepts from concrete to abstract, or making use of visual aids or introducing role-plays in learning environment.

In high school it appeared that students were divided into two camps, those that liked math and science continued in science, and those who avoided math, and went into social sciences, such as business or education. The philosophy classes, however, were mandatory for all students. After teaching concepts of QM and philosophy of science in

the philosophy classes as a guest teacher, the feedback from the social science students were especially inspiring; some of them mentioned that if they had known that physics was so cool they would have chosen science to study instead of social sciences. After those philosophy classes, some social science students visited me to ask follow-up questions regarding some QM concepts. I noticed that their attitude towards science had changed. Their experience was reciprocal; I was equally inspired by their responses. Apart from my teaching experience, I enjoyed sharing QM ideas with family and friends, something like being a story-teller about the wonderland of QM. The feedback from family and friends, who found these ideas fascinating, reinforced and validated the value of teaching QM concepts, even to people who thought they had no interest in science.

Conceptual understanding of QM notions is essential, since the mathematical applications of QM were beyond high school level. Thus, the content of QM subject matter could be effectively taught within a conceptual, descriptive framework. In my QM teaching experience, I realized that in addition to content knowledge, teaching QM also required pedagogical knowledge. The feedback and questions coming from the students shaped the flow of each class in a unique way; being flexible with the content meant that each class developed its own pace and area of interest.

### **Purpose of the Study**

Given that Grade 8 science teachers in BC are required to learn the topics of QM in the 2016-2017 education year (BC's New Curriculum - Big Ideas, 2016) and that I have been unable to locate any research describing or exploring QM learning and teaching processes for middle school level science teachers, it seems a timely endeavour to understand teachers' experiences as they begin teaching QM. The research question

that guided the study was “How does a Grade 8 science teacher learn and teach QM?” In response to the research question, from the data emerged, it was intended to assist Grade 8 science teachers in making the transition to the Science 8 curriculum that includes the topics of QM. Science educators, principals, colleagues and Grade 8 science teachers will need to understand the impact of this shift, in order to better help not only their colleagues, but also their students. This study will serve to help prepare for this transition by providing insights for the fields of science education practice and science education research.

The outcome of this study may help those who design pre-service teacher education programs at universities, as well as school board personnel such as principals, middle school students, and Grade 8 science teachers themselves, in order to understand the real life experience of a Grade 8 science teacher in learning and teaching QM. Primarily, with this study, it was aimed to provide a platform from which other teachers may be able to compare or anticipate their own QM learning and teaching experience of engaging the concepts of QM. By exploring in depth experience, others may be able to apply learning strategies, recognize outcomes, and lead to strategies for learning concepts of QM as well as teaching strategies and recommendations for teaching Grade 8 students.

### **Significance of the Study**

This study is particularly important at this time because there is a redesigned curriculum by the Ministry of Education in BC, which includes topics of QM for Grade 8 science classes. As of the 2016-2017 education year all Grade 8 science teachers are required to teach concepts of QM as a mandatory subject. The current challenge is that Grade 8 science teachers may not have background in physics and especially content

knowledge of QM. The significance of the study lies in the exploratory nature of the study aiming to illuminate the experience of one Grade 8 science teacher learning to teach QM without having a QM background in order to support other Grade 8 science teachers in BC while going through their own QM learning and teaching experience.

### **Scope of the Study**

The scope of this study is limited to one Grade 8 science teacher's experience in BC in the year of 2016; and thus, the data coming out of this research is specific to this individual and cannot be generalized. The primary focus of the study has been on the teacher's QM learning and teaching experience rather than on the students' experience. However, as the students' experience naturally affected the experience and the teaching practice of the teacher, students' responses were reflected indirectly through teacher's insights regarding her experience.

Given the counter-intuitive concepts of QM, a person learning these concepts would most likely experience and be affected by a paradigm shift on various levels. In this study, the notion of paradigm shift should be understood within Kuhn's (1996) framework. However, apart from the field of science, paradigm shifts can be psychologically experienced as well, by opening up a person's mind to previously unimagined possibilities. In other words, being exposed to paradigm shift on a personal level might refer to engaging with radically new and different ideas that make people to question the underlying assumptions they previously adopted and taken-for-granted reality they have created in their minds. At this point, it is worth mentioning that the psychological impact on my participant facing a paradigm shift is outside of the scope of this study. However on a personal level, the response, whichever way it represents

itself—awe, amazement or even discomfort of engaging with a paradigm shift—will be a part of this study from the participant's and also the researcher's perspective as it pertained to the learning and teaching of QM concepts in her role as a science teacher.

The background of the study was elucidated in this chapter. In the following chapter, I provide an overview of the important concepts for the study, essentially focused on constructivism as the theoretical framework of the study, and the review of literature on the concept of PCK, the topics of QM in school science curriculum, the views of the nature of science, and insights regarding BC's Redesigned curriculum.

## Chapter 2

In this chapter, I provide a review of the literature regarding the key concepts of the study; namely, constructivism as the theoretical framework of the study including its ontological and epistemological underpinnings along with different perspectives of constructivism. Then, I elaborate teacher knowledge including the concept of PCK, QM as a subject in science education, the place of NOS in science education, and the BC Canada's redesigned science curriculum. Shulman (1986, 1987) explains the nature and the domains of knowledge needed for teaching by coining the term PCK. In the following, after providing insights regarding constructivism, I will elaborate the PCK framework along with its re-figurations and unique modifications in science education literature. Then, I will provide the historical reasons why QM was excluded in school curricula despite its profound presence in the field of physics. Additionally, I will elucidate the studies in the field of science education on QM teaching and learning experiences. This section will be followed by a review of literature on the views of NOS in science education. Lastly, I will introduce the BC's redesigned science curriculum with the inclusion of topics of QM as the context and background of the study.

### **Constructivism**

Constructivism as a meta-philosophy investigates the nature of knowledge and how we know what we know by recognizing the individualistic accounts of cognition and the role of an individual within their real life interactions, such as experiences, culture, society, and language (Fosnot, 1996; von Glasersfeld, 1995; Phillips, 2000; Richardson, 2003). The ontological underpinnings of constructivism stem from relativist approaches,

where the nature of knowledge is recognized as locally and specifically co-constructed (Denzin & Lincoln, 2011). The epistemological underpinnings of constructivism draw on subjectivism, in other words the acquisition of knowledge is transactional, which acknowledges the role of the learner as central in their own personal, social, historical context while bringing a unique personal lens in acquiring knowledge, so that reality can “only” be known “in a personal and subjective way” (Tobin & Tippins, 1993, p. 3).

Fosnot (2005) summarizes the origins and the nature of constructivism:

based on work in psychology, philosophy, science, and biology, the theory describes knowledge not as truths to be transmitted or discovered, but as emergent, developmental, non-objective, viable constructed explanations by humans engaged in meaning-making in cultural and social communities of discourse (p. ix).

Constructivist research methodology stems from the philosophical framework of constructivism (Denzin & Lincoln, 2011; Guba, 1990). Constructivist research methodology provides a set of principles offering hermeneutic and dialectic approaches for the inquiry (Creswell, 2007; Guba, 1990). Hermeneutic refers to interpretation of human actions or texts through dialectic and reasoning (Guba, 1990); therefore, in constructivist methodologies, the nature of knowledge is recognized as individual and collective reconstructions (Denzin & Lincoln, 2011).

Constructivism, as a theory of learning, derives from its underlying ontological and epistemological standpoints, where teachers, in the role of facilitator, provide an experience based environments for the learners as a meaning-making venture with the purpose of cementing conceptual understanding of the subject by promoting autonomy,

inter-actions and empowerment (Fosnot, 2005; Mays, 2015). In a constructivist learning environment there is “no one right way to teach and learn, nor one right way to think about knowing in all contexts in which one might know” (Tobin, 1993, p. xvi).

### **Ontological underpinnings of constructivism.**

Ontology is the study of the nature of knowledge encompassing a range of ontological perspectives such as realism and relativism (Crumley, 2009). Realist views stem from Aristotle’s writings, which view the object of perception as material bodies, thus creating material-oriented reality in defining the nature of knowledge (Phillips, 2000). Realism holds the view that the nature of knowledge is an absolute objective truth (Sosa et al., 2008). In this vein, knowledge is viewed as separate from the individual; consequently, independent of mind, time, and other conditions. For instance, the laws of physics, chemistry, and scientific constants are viewed as objective truths that constitute an external reality. According to realism, knowledge is objectively acquired from an external world.

The relativist approach holds the view that the nature of knowledge is relative to individuals. The premise being that y is relative to x, implying that the nature of *a thing* is determined by its relations to other things. In other words, knowledge is relative to a “specific conceptual scheme, theoretical framework, paradigm, form of life, society, or culture . . . there is a non-reducible plurality of such conceptual schemes” (Bernstein, 1983, p. 8). In relativism knowledge is local and specific co-constructed (Guba & Lincoln, 2005). Taking the inter-related nature of knowledge into account, in relativism knowledge is viewed inter-subjectively (Horkheimer, 1972; 2002; Kant, 1781; 1999). Accordingly, from a relativist perspective, knowledge is socially constructed by

individuals and is subject to holding multiple interpretations of reality (Crotty, 1998; Fosnot, 1996). Ontologically, constructivism proposes that there is no one single correct representation of the external world.

### **Epistemological underpinnings of constructivism.**

Epistemology is the study of ways of acquiring knowledge, encompassing a range of perspectives such as objectivism and subjectivism. According to the objectivist perspective, knowledge is discovered in an external world where individuals have direct access to knowledge and perceive an objective reality. A subjectivist approach holds the view that knowledge is internally constructed within each individual; therefore, knowledge is a process of construction as an on-going activity emerging from the relationships of individuals, rather than being an objective end result.

Subjectively constructing knowledge implies that reality is limited to the perception of the researcher and there is no one single truth, since everything is relative due to subjective experiences and perceptions of individuals (Dawson, 2013). This view might hold that constructivism defines the limits of human knowledge, since “we construct our understanding through our experiences, and the character of our experience is influenced profoundly by our cognitive lens” (Confrey, 1990, p. 109). However, constructivism could be also viewed as the enriching factor of human knowledge, since it suggests a myriad ways of constructing knowledge that is unique for each individual (Phillips, 2000; Richardson, 2003; Yilmaz, 2008). In a constructivist research project, the complexity of social environment and the background of the researcher uniquely influence the nature of knowledge constructed in the social context (Guba & Lincoln, 1989). The combination of unique dynamics of the participants, researcher and the

research context creates a unique framework from which to work (Dawson, 2013). From this perspective, findings are viewed as “the creation of the process of interaction” between the inquirer and inquired (Guba, 1990, p. 27).

### **Types of constructivist approaches.**

Different forms of constructivism—social (Vygotsky, 1978), cognitive (or psychological) (Piaget, 1978) and radical constructivism (von Glasersfeld, 1995)—offer a pluralistic arena for various theoretical orientations.

Cognitive or psychological constructivism emerged from the works of Kant, Dewey and Piaget as a developmental learning theory with a focus on the individual as an active learner, suggesting that learning occurs by internal constructions of the individual based on their practices and experiences (Bredo, 2000; Philips, 2000). Drawing on the constructivist framework, Dewey proposed implications of cognitive constructivism in education, suggesting that students’ ability in knowledge acquisition and meaning-making is enhanced through self-organized, experience-based educational approaches (White, 2011). Piaget’s (1978) cognitive development stages describe particular mental patterns that guide behaviour, where the construction of knowledge is based more on the individual’s interpretation of experience, rather than the cultural context in which the individual is situated. In cognitive constructivism, prior cognitive constructions play a crucial role in constructing new knowledge. Therefore, learning is unique to each individual and among individuals “the realities are based on interpretation that are the result of past individual experiences and beliefs that formed different neural networks and pathways” (Fosnot, 2005, p. 280). In this regard, learning can be viewed as cognitive self-organization and is located in the individual (Minick, 1989).

Social constructivism stems from the early writings of Marx (Phillips, 2000). Marx puts an emphasis on individual autonomy within the complex structures of society, such as culture, education, and language consequently rejecting absolute truth or facts in social reality and promoting self-knowledge and self-awareness (Gibson, 1986; McTaggart, 1997). Drawing on Marx's work, Vygotsky (1978) focused on historical, cultural and social dimensions of discourse and knowledge construction including structures of power in a social context (Comstock, 2013; Fosnot & Perry, 2005). Vygotsky expounded the role of representation in learning proposing that language influences construction of knowledge, thus language plays a vital role in learning. In social constructivism, meaning is understood as "the result of humans setting up relationships, reflecting on their actions, and modeling and constructing explanation" (Fosnot, 2005, p. 280). Social constructivists hold the view that learning is constructed jointly and located in the individual-in-social-action (Minick, 1989).

Radical constructivism (von Glasersfeld, 1995) primarily grew out of the 18<sup>th</sup> century works on empiricist philosophy, in particular Berkeley's *Principles of Human Knowledge* and Vico's *On the Most Wisdom of the Italians*, while blended with the notion of Piaget's cognitive constructivism (Matthews, 2014). Radical constructivism refutes the idea of an accessible external world, suggesting instead that the external world is a mere construction by individuals who are not in contact with the external world, but only with individual experience (Matthews, 2000). Von Glasersfeld (1992) describes the ontological understanding of radical constructivism as follows:

The main difficulty of the question arises from the word "exist." In our human usage, it means to have some location in space, or time, or both. But since space

and time are our experiential constructs, “to exist” has no meaning outside the field of our experience, and whatever an independent ontological reality may do, it is not something we can visualize or understand (p. 174).

In radical constructivism, von Glasersfeld advocates an idealistic ontology and subjectivist epistemology (Matthews, 2014). In this vein, the traditional concept of absolute truth is replaced by variability of knowledge, since knowledge is uniquely relative to individuals (von Glasersfeld, 1995). Howe and Berv (2000) suggest that in constructivism, “truth and knowledge are established holistically and tentatively and are not compartmentalized in to language/mind, the world and values. From the constructivist perspective, there is no such thing as knowledge uncontaminated by any particular system of human purposes, beliefs, values and activities” (p. 30). In terms of language, von Glasersfeld (1989) suggests, “language users must individually construct the meaning or words, phrases, sentences, and texts” (p. 132), where he adds that the construction of meaning for words “does not have to start from scratch” (p. 132). In this regard, his claim falls short in order to recognize that individuals learn, relearn, mislearn, or unlearn the words and their meanings from others, unless they create a new language (Matthews, 2014).

Drawing on the constructivist framework, constructivist-based education holds two seemingly contradictory views, where the process of learning is recognized either as an active cognitive reorganization or socio-culturally situated activity (Fosnot, 2005). It could be viewed that cognitive perspectives might undermine the interactive productions of schooling, whereas social constructivist perspectives neglect the individualistic accounts for cognition (Cobb, 2005). In addition, Cobb et al. (1992) provided critical

insights regarding social constructivism by pointing out the “taken-as-shared” nature of knowledge in order to emphasize the lack of self-organizational and adaptive nature of knowledge, particularly within cultural contexts. Despite the differences between cognitive and social constructivism, from a different lens, Krummheuer (1992) suggested that these two constructivist paradigms refer to different aspects of learning. According to him social constructivism in educational framework could advise about the contextual conditions for learning, and cognitive perspectives inform about the individualistic process of knowledge construction (Cobb, 2005).

While Piaget and von Glasersfeld emphasize the individualistic aspect of constructivism, Vygotsky acknowledges cultural and social context in constructing individual’s knowledge. Although both perspectives are of value, this study recognizes the complementarity of both constructivist perspectives. Learning should not be viewed from an either/or perspective, since the individual makes sense of the world within a social, cultural, historical, educational and linguistic context in relation to individualistic accounts of cognition, while bringing a unique set of prior knowledge constructed from personal beliefs and experiences. The individualistic accounts of cognition would not function without being in relation to *a thing*, since the nature of *a thing* is determined by its relations to other things and meaning making cannot take place in isolation (Bernstein, 1983; Fosnot, 2005). Likewise, without the individual’s cognition socio-cultural knowledge would not be developed and find correspondent to make meaning. This complementary approach also aligns with Cobb (2005) where he suggests “learning is both a process of self-organization and a process of enculturation that occurs while participating in cultural practices, frequently while interacting with others” (p. 50-51).

With a QM analogy in particle-wave duality, I acknowledge that cognitive and socio-cultural nature of knowledge construction can co-exist in the process of learning. In this vein, the epistemological and ontological framework of this study draws on the complementary nature of the cognitive and socio-cultural constructivist perspectives.

### **PCK and PCK Development**

Considering the new curriculum implementation in QM, Science 8 teachers are likely facing the challenges of a relatively less familiar journey in terms of developing PCK in QM. To address this challenge, I will explore the development of PCK in QM of a Grade 8 science teacher in relation to the sub-components of PCK as elaborated below. In the writing that follows, I will elucidate teacher knowledge framework and the concept of PCK—its development and sub-components.

#### **Teacher knowledge and PCK.**

According to Shulman (1987), pedagogical content knowledge (PCK) is one of the aspects of teacher knowledge among the other proposed categories such as: curriculum knowledge, knowledge of learners and characteristics, content knowledge, general pedagogical knowledge, knowledge of educational contexts, and knowledge of educational values and their historical and philosophical grounds. However, Shulman (1987) specifically stresses PCK as the most distinctive teacher knowledge aspect, since it is “uniquely province of teachers, their own form of professional understanding” and this category is “most likely to distinguish the understanding of the content specialist from that of the pedagogue” (p. 8). Therefore, PCK can be seen as a crucial notion of what makes a teacher a teacher, consequently teaching expertise should be recognized in terms of teachers’ conceptualization of their PCK (Shulman, 1986; 1987).

As for the emergence of the PCK concept, Shulman (1986) outlines a shift in teaching expertise criteria from 1870 to 1980 from content to pedagogy; he states that in 1870 the method for teaching teachers was highly focused on their knowledge of the subject matter to be taught, with almost no consideration given to how the subject matter is taught. By 1980, the criteria has almost completely reversed, with a strong focus on educating teachers how to teach, without much consideration for ensuring that they knew the content to be taught (Shulman, 1986).

Shulman (1986) argues that the three categories of content knowledge should be distinguished: subject matter, pedagogical, and curricular. Subject matter refers to the direct knowledge of the subject matter being taught. Pedagogical content knowledge, then, refers still to content knowledge (i.e. not teaching methods), but knowledge of the subject matter that is specific to teaching. This includes knowing how to represent the knowledge in a comprehensible way, of which there is no single absolute; therefore, the teacher must know which way is most appropriate for the given field they are teaching. This also includes knowing what kind of misconceptions the students will bring with them, and knowing how best to correct those ideas if they are wrong. Curricular knowledge refers to knowledge of all the possible resources available for teaching, such as textbooks, software programs, videos; therefore, teachers must know what resources to use before they can teach effectively (Shulman, 1986).

Shulman (1987) provides an example of a teacher, who adapts her teaching according to the “difficulty and character of the subject matter, the capacities of the students (which can change even over the span of a single course), and her educational purposes” (p. 3). The pattern of her teaching was not uniform and she was able to be

flexible in responding to changing dynamics of the learning environment. Through this example, Shulman stresses the complex and dynamic nature of educational environment and teaching practices. In a broader perspective, PCK can be viewed as the extent of a teacher's current wisdom in teaching, which is subject to further development and transformation.

Given the importance of PCK in the educational realm, there have been extensive adaptations of PCK over the last three decades. These have included re-figurations such as: Grossman's (1990) highlighting of context, Marks' (1990) emphasis on media, Fernandez-Balboa and Stiehl's (1995) focus on teaching purpose, Park and Oliver's (2008) accentuation on teacher efficacy, Anderson and Clark's (2011) break down of subject matter, and Loughran et al.'s (2012) particularization of content specificity and practice. These contributions elaborate the existing Shulman's (1987) teacher knowledge components, which include: curriculum knowledge, knowledge of learners and characteristics, content knowledge, general pedagogical knowledge, knowledge of educational contexts, and knowledge of educational values and their historical and philosophical grounds. In these re-figurations, the elaborated components of Shulman's (1987) teacher knowledge framework were originally considered to be separate from PCK as a distinctive teacher knowledge domain; however, in the re-figurations they are viewed as an extension of the original PCK concept.

Unique contributions on the impact of constructivist views of time and process are offered by Cochran et al. (1993) by coining the term pedagogical content knowing (PCKg), new perspectives on the exploration of complexity and non-linearity of PCK are presented by Veal et al. (1999), and the individualistic aspect of teachers' values and

beliefs is proposed by Hashweh (2005). These contributions not only expand Shulman's concept of PCKg, but also add on his initial criteria of teacher knowledge. In the writing that follows I will first provide the re-figurations of PCK while connecting each with Shulman's original work to demonstrate that these re-figurations are only the reorganization of the teacher knowledge components. Then I will elaborate on the unique contributions for the nature of PCK proposed by Tamir (1988), Cochran et al (1991, 1993), Veal et al. (1999), Andrews (2001), and Hashweh (2005).

### **Re-figurations of PCK.**

Grossman (1990) along with subject matter knowledge and general pedagogical knowledge, included contextual knowledge in her PCK model and emphasized the reciprocal relationship between these PCK components. While emphasizing the interaction between the teacher knowledge components provides a more realistic approach to educational context, in a broader sense, Grossman's contribution can also be viewed as the elaboration of Shulman's (1986) teacher knowledge component of knowledge of educational contexts. Grossman acknowledged the topic specificity of PCK and viewed PCK as a integrated blend of four components: 1) knowledge of strategies and representations, 2) knowledge of students' understanding, conceptions, and misconceptions about a certain topic, 3) knowledge and beliefs about the purpose for teaching, and 4) knowledge of curriculum materials available for teaching. Accordingly, Grossman rephrased the nature of PCK by including already existing teacher knowledge components, namely, knowledge of students understanding, curricular knowledge, and knowledge of instructional strategies, which have been already identified as distinctive domains of teacher knowledge outside the concept of PCK by Shulman. Relocating the

knowledge components can hardly be viewed as a unique contribution to the existing teacher knowledge framework; however, Grossman contributed to the literature by identifying four sources in order to generate and develop PCK: observation of classes, disciplinary education, teacher education courses, and in-class teaching experience.

Marks (1990) discovered that PCK derives from other types of knowledge, thus making it difficult to determine precisely where one form of knowledge ends and another begins. Marks stated that in many cases the distinction between pedagogical knowledge and pedagogical content knowledge can be arbitrary, but that the concept of PCK remains important for teachers, because it describes the class of knowledge that is best suited for teaching, even though it may not be generally relevant or known among non-teaching subject matter experts. Marks emphasized the integrative nature of PCK development process and includes the elaborated element of knowledge of media for instruction under the concept of PCK, where in the original work media for instruction can be viewed under the category of curriculum knowledge as Shulman (1987) states “particular grasp of materials and programs that serve as tools of the trade for teachers” (p.8).

Fernandez-Balboa and Stiehl (1995) agreed on the integration of knowledge components; however proposed the generic nature of PCK, which essentially undermines the topic specificity of PCK. They added to the concept of PCK through their study of 10 professors from different backgrounds. Each one was selected for being notably good at teaching, and was interviewed at length to determine what elements of PCK they use. By analyzing their responses, five sub-components of PCK were determined: 1) subject matter knowledge, 2) student understanding, 3) instructional strategies, 4) teaching context, and 5) teaching purposes. The first four categories in Fernandez-Balboa and

Stiehl (1995) work very closely align with Cochran et al. (1993) findings; however, they highlighted the domain of teaching purpose, which had been already proposed by Shulman as a distinctive teacher knowledge component, yet neglected in previous works on conceptualization of PCK (Cochran et al., 1993; Marks, 1990; Tamir, 1988).

The participant professors indicated teaching purpose refers to their desire to persuade students of the importance of the subject matter, and enhance the students' lives (Fernandez-Balboa & Stiehl, 1995). In order to persuade students of the importance of the subject matter, the professors tried to convey the subject matter's broad applicability, relevance to students' lives and realism. In order to enhance the students' lives, the professors wanted their students to be good at what they do, be able to solve problems, be able to think critically, participate ethically in society, enjoy life more, and be life-long learners. As their study suggests, teaching purpose can be viewed as utilizing the subject matter knowledge within a pedagogical approach, so that teaching would serve the purpose of improving students' lives in a multi-dimensional way.

Drawing heavily on Tamir's (1988) and Grossman's (1990) work, Magnusson et al. (1999) proposed a conceptualization of PCK for teaching science, which they called orientation to teaching science. According to them, orientation to teaching science is inter-related to the sub-components of, 1) knowledge of science curriculum, 2) knowledge of student understanding of science, 3) knowledge of instructional strategies and 4) knowledge of assessment of scientific literacy. Although Magnusson et al. acknowledged the interconnectedness of PCK sub-components; the model they offer does not reflect the integration of components. Magnusson et al. (1999) intended to propose a science specific conceptualization of PCK; however, studies agree that the very

framework they proposed can be applied to any school subjects, thus making the conceptualization of their PCK generic (Akkoc & Ye, 2010; Hanuscin et al., 2011; Henze et al., 2008).

Loughran et al. (2006) suggest content representation (CoRes) and pedagogical and professional experience repertoires (PaP-eRs) in order to conceptualize the PCK of science teachers. According to them, CoRes and PaP-eRs together could be explored to create a resource folio, which offers teachers insightful and practical representation of PCK. In his book, Loughran (2012) provides examples of CoRes and PaP-eRs for QM, in other words, for particle theory that demonstrates how systematically the development of PCK can be created and measured. With the proposed systemacity and procedural format of PCK, Loughran et al. (2006) aligns with Tamir's perspectives on PCK development and their contribution can be viewed as conceptualizing Shulman's (1987) existing notion of PCK with topic specificity.

Following Magnusson et al. (1999)'s emphasis on the impact of teachers' beliefs as a sub-component of PCK framework, Park & Oliver (2008) highlighted the sixth component of PCK as teacher efficacy. The term teacher efficacy is rooted in the concept of self-efficacy in the social cognitive theory (Bandura, 1986). Soodak & Podell (1996) addresses three components of efficacy as: 1. Personal efficacy: having the skills for implementing change, 2. Outcome efficacy: having the belief that personal efficacy brings desirable outcomes, 3. Teaching efficacy: having the belief for overcoming the problems of the learning environment. In fact, from my perspective, teacher efficacy can be viewed as the ability to effectively perform all of Shulman's (1987) teacher knowledge components as an overarching concept, rather than being a sub-component of

PCK.

Drawing on Schwab's (1978) work, Anderson and Clark (2011) emphasized that in science classes there are two types of subject matter knowledge: 1) knowledge of science, 2) knowledge about science, which implies Schwab's substantive and syntactic knowledge respectively. Knowledge of science refers to the content knowledge in the field of science, whereas knowledge about science refers to epistemological ways of creating an understanding of science including the areas of how it developed, how scientific knowledge is acquired. In this regard, Anderson and Clark's contribution parallels Shulman's (1987) two separate teacher knowledge components of content knowledge and educational purposes in historical and philosophical grounds.

Otto & Everett (2013) presented a Venn diagram, where the intersection of content, context and pedagogy is demonstrated as PCK. In their re-figuration, PCK refers to the special blend of learning objectives, description of class and school environment, and main teaching strategy. The Venn diagram representation allows science teachers to recognize PCK as the integration of content, context and pedagogical knowledge, which has been proposed earlier by Cochran et al. (1991; 1993).

These afore-mentioned authors offer re-figurations of PCK, which aid in understanding Shulman's (1987) original components of teacher knowledge from different angles. However, Tamir (1988), Cochran et al. (1993), Veal et al. (1999), Andrews (2001) and Hashweh (2005) offer unique contributions that extend Shulman's initial framework in terms of constructivist views, non-linearity, complexity and teachers' uniqueness in terms of their beliefs and values.

### **New perspectives of PCK.**

Drawing from Shulman's (1986, 1987) work, Tamir (1988) made a unique contribution and proposed a new component for the PCK framework—teachers' knowledge of evaluation. Tamir's re-conceptualization of PCK include four components, namely, knowledge of: 1) student understanding, 2) knowledge of curriculum, 3) instructional strategies and representations, and 4) knowledge of assessment. Tamir elaborated the concept of PCK within the science education framework by including laboratory activities. He pointed out the structural and procedural development of PCK, emphasizing the specific phases that take place throughout the PCK development for a laboratory class. Although he acknowledged the topic specific nature of PCK, the structural format he offered for the instruction and assessment of science classes seem to yield a more generic way of PCK development.

Andrews (2001) also proposed a new sub-component of PCK—language awareness. According to him, communicative language ability is integral to the subject matter knowledge in language classes. Andrews identified the three elements of language awareness as language competence, strategic competence, and knowledge of subject matter. Despite Andrews' conceptualization of PCK specific for language lessons, language could be viewed, as a way of communicating that is not unique only to language classes, but also critical to all teaching. Considering the meta-cognitive dimension of language (Andrews, 2001), language awareness and communication of scientific concepts would also be crucial in science classes. For example, in a Grade 8 QM class, if a teacher knows that matter has a dual nature—particle and wave—then the use of the plural form of sub-atomic particles, such as photons, would create a misconception, since the word 'photons' refers only to the particle nature of the photon

while disregarding its wave nature. As discussed earlier, the realm of QM is alien to the everyday perception, and thus everyday language; therefore, language awareness, perhaps development of a new vocabulary specific to describe the concepts of QM, can be viewed as an even more essential sub-component of PCK in QM.

Cochran et al. (1993) modified PCK according to a constructivist approach in teaching and learning, coining the term “pedagogical content knowing” (PCKg) to indicate an active, continual and simultaneous PCK construction. According to Cochran et al.’s constructivist PCK modification, knowledge is uniquely created in mind by individuals, rather than discovered. PCKg is thus a constructivist interpretation of PCK; unlike Shulman’s original PCK, PCKg has a greater emphasis on two expanded understanding of teacher knowledge domains: 1) students' abilities, learning strategies, ages, developmental levels, attitudes, motivations, and prior conceptions about the subject matter, 2) social, political, cultural, physical contexts surrounding the teaching environment.

Although PCKg can be broken down into the four categories of pedagogy, subject matter, student understanding, and environmental contexts; constructivists suggest that it is inappropriate to examine these four categories independently; instead, teachers must be taught all four in a simultaneous and integrated manner (Cochran et al., 1993).

Accordingly, Cochran et al. (1993) propose their PCKg development as follows:

- Conceptually integrated instruction (incorporating liberal arts, pedagogy, and subject area courses for these types of knowledge to develop concurrently).
- Developing PCKg appropriate to the program's grade level focus.
- Constructing PCKg from reflections on one's own teaching and that of others in a

content area.

- Early, continued, experiences with real teaching, reflection, and feedback.
- PCKg development requires strong integration and cannot happen in a separate course.
- PCKg development is promoted by case studies, peer coaching, cooperative classroom methods, hypermedia, microteaching, and team teaching.
- Integrated PCKg develops with experience.

Cochran et al. (1993) pointed out that constructivists believe that learning is created by the student, not the teacher; therefore, the more the teacher knows about the students' minds and dynamics of the context as learning environment, the better equipped the teacher is for inciting the students' learning; consequently, teachers would be able to provide students with effective teaching.

The activated conceptualizations of PCK (Cochran et al., 1993; Veal et al., 1999) suggest inter-active (components transform themselves in time), inter-dependent (components cannot be without each other), and inter-connected (components are intrinsically in relation to each other) nature of PCK sub-components. Therefore, the generation and development of PCK take place in a multi-dimensional, simultaneous, and unpredictable context (Doyle, 1990). Since PCK is a domain of teacher knowledge in a dynamic context, PCK can be viewed as emerging from the inter-relationship of a science teacher to the PCK sub-components, such as pedagogical knowledge, scientific knowledge (knowledge of science subject matter knowledge), student characteristics and understanding (Shulman, 1987; Grossman, 1990), teaching and assessment strategies (Grossman, 1990; Magnusson et al., 1999), teaching purpose (Fernandez-Balboa &

Stiehl, 1995), knowledge of science and knowledge about science (Anderson & Clark, 2011), and teachers' values and beliefs (Gudmundsdottir, 1990; Hashweh, 2005).

Given the aforementioned re-configurations of and unique contributions to PCK by a plethora of scholars over the last three decades, what is currently needed in PCK, in relation to this study, is a consideration of the inter-dependence and complexity of multiple components in teaching and learning including those that are less accessible and measurable such as the views in NOS. In this regard, developing PCK in QM is particularly important in science classes for two reasons: 1) the nature of the subject underpinning its ontological and epistemological understanding is fundamentally different than the other school subjects, 2) the concepts of QM do not only deal with concrete and tangible relations of things, but focuses on abstract, counter-intuitive relationships that engage and influence taken-for-granted perspectives that predominantly form through visible, macro-scale everyday life experiences. Recognizing the importance of relatively less solidly accessible components such as NOS in PCK provides a consistent framework for studying a subject area that deals with the micro to macro relations of things in the world. This consideration of the particular importance of understanding the special relationship between NOS, QM, and PCK is essential, and requires that NOS be included as one of the multiple components in the PCK framework.

The Science 8 curriculum revision in BC can be seen as a matter of curriculum change, as well as a matter of change in the inter-dependent context of a science teacher's PCK, which is intrinsically teacher-centered. The PCK development in QM refers to the demand for specificity of pedagogical approaches that will be implemented in order to make abstract and counter-intuitive concepts of QM relevant and accessible. Since QM

reigns in the sub-atomic and invisible realm, unlike classical mechanics, there is no everyday life example that could provide helpful demonstrations to shed light on QM understanding—the micro phenomena at the QM level cannot be understood through the understanding of the macro level phenomena. Without implementing appropriate pedagogies, the content knowledge of QM would not be accessible for students; consequently, it might do more harm than good for students by causing misconceptions. I expect that the use of variation theory, analogies, metaphors, and other approaches will be useful in teaching the topics of QM. Since variation theory promotes learning from discernment, in the writing that follows, I will provide a framework regarding learning from differences.

### **Learning from Differences**

Classical mechanics and QM are fundamentally incommensurable for a number of reasons. Firstly, they emerge from different philosophical understanding of viewing the natural phenomena; classical mechanics underpins deterministic approaches (Baily & Finkelstein, 2010), whereas QM promotes probabilistic perspectives (Bao & Redish, 2001). Classical mechanics is considered to be linear due to its causality-based nature, whereas QM is viewed as nonlinear (Komorek & Duit, 2004; Stavroua & Duit, 2014). Consequently, the predominance of classical mechanics throughout K-12 school curriculum most likely sets the underlying philosophical understanding of the world in physics classes as determinism. Learning non-linear science is viewed as a way of helping students move away from monolithic perspectives that can potentially diminish the richness and diversity of understanding of the world (Johnson, 2005; Komorek & Duit, 2004; Stavroua & Duit, 2014). Stavroua et al. (2008) explains:

From an educational point of view, dealing with core features of nonlinear systems allows the students to develop more adequate physical world views in general. In particular, the fundamental interplay of random and deterministic processes that manifests itself in the limited predictability of deterministic procedures, as well as in the formation of structures, seems to be a most valuable general insight into the nature of science (p. 417).

QM governs a non-linear framework that promotes probabilistic ways of understanding (Johnson, 2005; Martin, 1976), which implies that instead of having one single right answer to a question, the answer inhabits a statistical nature, implying the probability of multiple right answers at the same time. For instance, classically, as macro beings, we can only be at one location at a given time thus on a map our location can be shown by one mark. However, in the quantum world, a sub-atomic particle can be in multiple locations simultaneously and the possible locations of this particle can only be described by its statistical probabilities.

Secondly, in a QM framework the nature of matter can co-exist as both a particle and a wave simultaneously, whereas classical mechanics provides an either/or understanding of the nature of matter; in that, matter can be either a particle or a wave, but never both at the same time. The different perspectives embedded in classical mechanics and QM might most likely yield a cognitive conflict in engaging with these fundamentally different concepts.

### **Cognitive conflict.**

A cognitive conflict that arises from engaging with new ideas is viewed as a desirable condition in learning environments (Kwon et al., 2000; Piaget, 1985; Villani,

1992). Piaget's (1985) cognitive theory suggests that intellectual growth emerges from the cognitive disequilibrium that occurs when encountering new information. From this perspective, intellectual growth is understood as a process of adaptation which emerges from cognitive disequilibrium leading to accommodation and which results in assimilation of the new information.

In fact, Piaget was not the first to highlight the nature of learning emerging from contrasting ideas. Piaget's notion of disequilibrium finds a corresponding concept in Kuhn's (1962; 1996) work. From Kuhn's perspective, Piaget's stage of disequilibrium can be viewed similarly to the stage of anomaly (Kuhn, 1962; 1996) through the proceedings of scientific revolutions. In the structure of scientific revolutions, anomaly refers to a problem which cannot be understood with the existing knowledge level, consequently leading to a crisis (Kuhn, 1962; 1996). According to Kuhn, this crisis is a new paradigm, through which a scientific revolution takes place.

Bateson (1972; 1988; 1991) adds a new angle when he suggests that things can only be understood in relation to other things, stating, "the primary data of experience are differences" (Bateson, 1991, p. 188) and suggests, "we can only know by virtue of differences" (p. 309). Bateson (1991) provides an example:

If we are going to say that the thing has "five fingers," we may be wrong because really it has four gaps between fingers—four relationships between fingers—because growth is governed by relationships, not by the absolutes (p. 181)

Here, he stresses that learning emerges through understanding of differences in phenomena, as in understanding of the relationships between these phenomena. He provides examples of the workings of electrical circuits, steam engines or neural impulse

showing that “a bit of information is definable as a difference that makes a difference” (Bateson, 1972, p. 315). Therefore, learning through differences is viewed as crucial in learning processes.

In this vein, cognitive conflict as in Piaget’s theory, anomaly as in Kuhn’s scientific revolutions, or basically learning as in Bateson’s ecology of mind, all emerge from differences, where a contradictory situation takes the learner into a new space. Therefore, neither intellectual growth nor revolutions can be achieved by staying in only one paradigm or with one single line of thought. Providing the diverse conceptual understandings within a classical mechanics and QM framework, might not only create a platform for effective learning, but also enrich our ways of thinking in multi-dimensional ways. Heisenberg (1999) suggests, “it is probably quite true generally that in the history of human thinking, the most fruitful developments take place at those points where two different lines of thought meet” (p. 187). From this perspective, learning the concepts of QM by contrasting classical physics might generate these two different lines by encouraging “fruitful developments” in science education.

### **Variation theory.**

Variation theory suggests that learning emerges through recognizing differences and focusing on the relationships between concepts, rather than focusing on the concepts in isolation. In variation theory, learning is viewed as seeing the relationship of situations through differences (Cheng, 2016). In this regard, the concept of learning from differences aligns with the variation theory in the PCK framework (Marton & Pang, 2006; Nilsson & Vikström, 2015; Tan & Nashon, 2013), since according to the theory learning occurs through the process of discernment which emerges from variation.

Marton et al. (2004) proposed four types of variation in learning: contrast, generalization, separation and fusion (p. 16-17). Marton and Pang (2006) suggests:

To learn something, the learner must discern what is to be learned (the object of learning). Discerning the object of learning amounts to discerning its critical aspects. To discern an aspect, the learner must experience potential alternatives, that is, variation in a dimension corresponding to that aspect, against the background of invariance in other aspects of the same object of learning (p. 193).

For instance, in the classroom while working with the content knowledge, providing contrasting concepts rather than teaching each concept in isolation would offer more successful learning outcomes (Taylor & Rohrer, 2010). Nilsson and Vikström (2015) provide an example of utilization of the variation theory when they suggest that in science classes, learning about energy would be more effective by contrasting energy with the concept of matter; and thus energy can be learned from the distinction between everyday objects and sunlight as a form of energy. Variation theory can be implemented in classrooms by recognizing the various ways of understanding for students and teachers in relation to the subject matter, and accordingly utilizing pedagogical approaches emerging from student and teacher dynamics.

Variation theory has been used as a way to capture teachers' PCK (Elliot, 2013; Pang & Ling, 2012) especially in the context of pedagogical design, lesson analysis, and student learning (Nilsson, 2014; Vikstrom, 2014). Cheng (2016) suggests that the variation theory “guides the teacher toward proper pedagogical design that can help students discern the object of learning” (p. 290). In this sense, variation theory is an

effective way of improving teachers' practices (Pang & Ling, 2012; Tan & Nashon, 2013) recognizing the dynamic nature of the context of learning (Driel et al., 1998; Magnusson et al., 1999). Nilsson and Vikström (2015) explain the importance of utilizing variation theory in describing teachers' experiences as follows:

Variation theory emphasizes how the content can be handled in powerful ways, a defining quality of the teaching profession. The object of learning has to do with capabilities the students are expected to develop, and what they therefore need to learn . . . Using powerful ways of teaching involves finding out what has to be done in particular cases, for particular learners and for particular objects of learning (p. 2844).

Therefore, teachers would need to create learning opportunities through discernment based on variation of objects of learning. It is my hope that this study will provide a possible bridge between the academy and teacher practice by introducing teachers to the framework provided by variation theory. Variation theory would enable teachers to create lesson plans that offer more authentic and effective learning opportunities for students. Recognizing the relationships between concepts might promote holistic ways of teaching. In the case of QM, the teachers would be comparing and contrasting tangible concepts from classical mechanics with QM, which might be found to be both abstract and counter-intuitive.

### **The Difference Between Classical and Quantum Mechanics**

Newtonian physics, in other words classical mechanics, is necessary to understand the world around us. Classical mechanics provides a successful approximation based on a set of laws about how things work in the macro-scale world, and thus allows us to build

mechanisms, such as engines, cars, and space rockets. However, in the field of physics, classical mechanics is not the ultimate understanding of the inquiry of how the world and the universe work. QM as the science of the micro-scale world, such as sub-atomic particles, is a different branch of physics than classical mechanics.

Both QM and classical mechanics fundamentally investigate matter and energy along with their interactions. However, the difference in scale requires different sets of explanations; and thus QM and classical mechanics operate in different frameworks. The QM framework confronts reality—one that is familiar to human experience; yet also reveals that reality is under no obligation to align with human experience. The discoveries in QM have radically changed our understanding of the field of physics and revealed a new reality, one that is beyond our everyday perception. Despite the counter-intuitive reality that QM offers, the concepts of QM has been utilized by physicists for practical applications; for example, the electronic revolution in terms of computers and cell phones in the late 20<sup>th</sup> century would not be possible without studies in QM.

Etymologically, the name quantum comes from “quanta” (Online Etymology Dictionary, 2015) referring to “quantity” suggesting that in QM energy is quantized in discrete states. In our everyday world, classical mechanics provides laws that show that macro-scale objects move in a continuum such as the revolution of the Earth around the Sun in a continuous motion. However, in QM sub-atomic particles can only be in discrete states. An electron can move from one place to another, not in a continuous motion but rather as a leap, however during this leap the electron cannot be seen in between, it appears in one place and then in another; thus during its motion an electron basically does not exist anywhere between the two places.

The advancements in QM along with other discoveries in modern science, such as the theory of relativity, initiated a paradigm shift (Kuhn, 1996) not just for me, but also in the field of physics. This paradigm shift transformed understanding of natural phenomena, and the views of NOS by radically influencing not only the field of physics, but also the fields of sociology and philosophy of science (Popper, 1959; Feyerabend, 1975; Kuhn, 1996). After the QM paradigm shift, the field of philosophy of science seemed to acknowledge the dynamic, subjective, and complex nature of science, and enabled a more informed understanding of NOS through sociological and epistemological lenses (Lederman, 2000). Consequently, an understanding of NOS has been a significant contributor in the understanding of scientific enterprise and the development of theories in science; and thus, the views of NOS gained significant importance in science education (Alters, 1997; Duschl, 1990; Lederman et al., 2002; Abd-El-Khalick, 2012). However, the paradigm shift in the field of physics and informed understandings of NOS have not effectively been reflected in science education.

### **Historical Reasons for the Exclusion of Quantum Mechanics from School Curricula**

Historically, the study of QM has been intentionally excluded from school curricula for a number of reasons (Barnes et al., 2004; Gaskell, 2002; National Science Foundation, 1962; Petri & Neidderer, 1998). These include, first of all, the limitations of teacher education and the availability of resources in the post-war context, which resulted in curriculum-makers deciding that they could not follow the rapidly changing nature of modern science (National Science Foundation, 1962). Besides, after the launch of Sputnik in 1957, the United States (U.S.) government required curriculum-makers to design curricula that would allow the U.S. to keep up with the space race; consequently

science curricula were developed with a focus on careers in science to improve technological and military developments as well as developments in the health arena (Gaskell, 2002). Therefore, science education was viewed to serve the purpose for innovation through building more science careers, and thus improving the country (Gaskell, 2002; National Science Foundation, 1962).

Secondly, curriculum designers consistently put the practical applications as a priority for the goals of science education, since relevancy of learning outcomes enables meaningful learning experience for students (BC IRP, 2006; Alberta IRP, 2007). QM was mostly theoretical and it was viewed as abstract, highly mathematical and counter-intuitive for high school students (Barnes et al., 2004), and thus QM was not able to provide a large arena of practical applications in the high school context.

On the other hand, there are a number of different perspectives about the reasons for the inclusion of QM in school curricula, which include: 1) demystifying QM; 2) resolving misconceptions about the nature of science; 3) introducing a non-Newtonian worldview where probability is a key concept; 4) making connections to modern technology; 5) inquiring into the quest for interrelated ideas of science, as science is evolving and constantly testing theories, and lastly; 6) understanding current views of reality and the contribution that science has made to them (Barnes et al, 2004; Bohm & Peat, 1987; Johnston et al, 1998; Petri & Neidderer, 1998).

Conceptual understanding of QM is unique as a school science topic, since engaging with the ideas of QM requires an expanded understanding of the natural world beyond a more traditional, classical understanding (Hadzidaki, 2008; Johnson, 2005; Walz-Michaels, 1996). As discussed earlier, QM focuses on the relationships of sub-

atomic particles, in which physicists have discovered remarkable counter-intuitive concepts such as the dual nature of matter, entanglement, quantum tunneling, and probabilistic nature of a quantum system. Since quantum understandings of natural phenomena do not correspond to our everyday understanding of the workings of the world, teachers effectively may need to expand their view of scientific enterprise as part of their preparation for teaching topics related to QM.

The discoveries in QM may also present challenges in philosophical understanding of the scientific enterprise for science educators, since research reveals that most teachers perceive science as an objective study of nature (Abd-El-Khalick & Lederman, 2010). NOS is the understanding of what science is and how science works (Lederman, 2002). Lederman (2002) proposes two perspectives to the NOS: naïve and informed. Naïve views of NOS explain science as primarily an objective study. From this perspective science knowledge is developed through a linear accumulation of information through a straightforward scientific method, whereas informed views of NOS recognizes science as an ongoing human activity that is therefore subjective and often revolutionary (Lederman, 2002; Abd-El-Khalick, 2012). The tendency to perceive science as an objective enterprise likely emerges from the deterministic nature of classical mechanics (Matthews, 1994), whereas studies of QM phenomenon reveal probabilistic perspectives (Barad, 2007). Therefore, the classical understanding of science and quantum mechanical understanding of science may yield different views of NOS. Science teachers engaging with the topics of QM may re-conceptualize their understanding of the scientific endeavour with a new perspective; consequently developing expanded, more informed views of NOS.

In *The Making of Curriculum*, Goodson (1995) suggests that curricular changes involve changing definitions of knowledge; therefore, it can be inferred that curricular changes would follow the changes in the disciplinary fields, since definitions of knowledge have changed and improved radically in the field of physics. Having said that, Osborne (2007) suggests the majority of students need “more than a knowledge of basic concepts of science, but also a vision of how such knowledge relates to other events, why it is important, and how this particular view of the world came to be” (p. 174). In this sense, the exclusion of QM in science education creates a null curriculum (Eisner, 1985) not only in terms of content knowledge of physics, but also in enriched and informed understanding of NOS embedded in the field of physics (Johnson, 2005).

Eisner describes the null curriculum as the information, content and skills that are intentionally or unintentionally left out of the prescribed curriculum. By choosing to teach only one branch of physics and excluding QM in science education, not only the taught curriculum, but also the null curriculum is provided to students. Null curriculum is as crucial as taught curriculum because 1) the subjects that we do not know might also provide evidence just as much as the subjects that we do know, and 2) the fact that there are content and skills that are not taught to students may create significant misconceptions regarding what is being learned. The missing aspects as well as misconceptions affect the intended learning outcomes in science classes (Lijnse, 2010). The exclusion of QM in terms of subject matter knowledge with, its both substantive and syntactic knowledge aspects, builds up the null curriculum and consequently may skew the perception of the field of physics for students.

If curriculum is to represent a broad base of current views of NOS, acknowledging null curriculum makes those views embedded in marginalized subject areas apparent. What is absent from the curriculum canon not only results in misinterpretations of the whole, but also speaks loudly to what is valued (Eisner, 1985). Looking at the current state of QM in schools through the lens of null curriculum makes it apparent that views embedded in QM have been marginalized subjects. The omission of QM might have created the illusion of a mono-reality taught in science education, implying that classical mechanics is the only explanation for the workings of nature. Furthermore, the absence of QM as the null curriculum might also have informed how the views of NOS are developed and presented in science education.

### **Quantum Mechanics in School Curriculum**

An investigation of the provincial Prescribed Learning Outcomes (PLOs) shows that QM is only taught as a minor component in Grade 11 and 12 levels in most of the provinces, and not present at all in New Brunswick, Prince Edward Island (see Appendix A). It is important to note that PLOs are no longer provided by the Ministry of Education in BC due to the redesigned curriculum, which gives the responsibility of what is to be learned through given topics (Big Ideas) to individual teachers. A revision in science curricula in the mentioned provinces to include QM would provide more complete physics knowledge in curriculum (Hurd, 2002), as well as an updated science education by shedding light on the views of NOS (Lederman et al., 2002; Matthews, 1997). As Kalkanis et al. (2003) point out:

The twentieth century is characterized by the prevalence of a radically new scientific viewpoint for the physical phenomena, a new paradigm in physics,

according to Kuhn's epistemological perception. In particular, the viewpoint implied by Quantum Mechanics, not only supports the understanding of modern technological applications, but also forms the cognitive basis for the adequate interpretation of, both, the structure of the matter and the evolution of microscopic phenomena. This forces school curricula to introduce QM topics, such as the atom models, at a very early stage of the instructional process (p. 258).

Studies emphasize the benefits of incorporating QM into school curriculum suggesting that QM would contribute to science education not only as a body of content knowledge, but also as a catalyst to promote informed views of NOS (Mashhadi & Han, 1997; Johnston et al., 1998; Petri & Neidderer, 1998; Sen, 2000; Barnes et al., 2004; Hadzidaki, 2008; Yildiz, 2012). Abd-El-Khalick and Lederman (2000) stress that the understanding of NOS has changed, particularly with the impact of QM, which has also transformed developments in other disciplines:

A case point is the 'leap' from a classical deterministic approach in physics to a quantum indeterministic conceptualization of the discipline. Concomitantly, conceptualizations of NOS have changed with developments in history, philosophy, and sociology of science (p. 666).

While classical mechanics instils deterministic views, QM promotes probabilistic perspectives. The paradigm shift of QM shed light on unexplored perspectives that science could promote. Therefore, the field of QM enhanced not only the field of science, but also the understanding of NOS and the history and philosophy of science (HPS). NOS and HPS seem to be inter-connected, since there is constant inter-play as they inform each other.

Although there is a dearth of literature on Grade 8 science teachers' experiences of learning and teaching the topics of QM, there is literature that provides insights on pre-service teachers' conceptualizations and attitudes about teaching history and philosophy of science and student achievement in QM (Petri & Niedderer, 1998; Galili & Hazan, 2001; Nashon et al., 2008; Höttecke & Silva, 2011; Teixeira et al., 2012). A variety of teaching mediums and materials are proposed in order to provide a more accessible platform for QM learning experience for high school students, such as computer games (Gordon & Gordon, 2012), experiments (Green et al., 2009), animations and simulations in QM (Henriksen et al., 2014), and board games in QM (Chiarello & Castellano, 2016).

In terms of teaching practices, Lemke (1998) emphasizes the multi-modal nature of the language of physics, including: verbal texts, images, diagrams, symbols, and mathematical formulae; however, the majority of the research regarding QM teaching focus on the mathematical and conceptual language of QM, where mathematical understanding of QM does not necessarily lead to conceptual understanding of QM. For instance, Ke et al. (2005) demonstrates that students who are able to do high school level mathematical applications of QM do not necessarily understand the conceptual framework of QM. Ireson (2000) agrees that the challenge of QM is not in the algorithmic problem solving, but rather in the interpretation of the concepts of QM. Papaphotis and Tsaparlis (2008) also highlight that "competence in algorithmic problem solving may be independent of competence in conceptual questions" (p. 323). Johnson et al. (1996) point out that an understanding of abstract models rather than models based on direct observation, would better help to conceptualize QM ideas.

In terms of pedagogical approach, it is suggested that the mathematical structure of QM diminishes the conceptual and philosophical nature of the theory (Pospiech, 2000; Singh, 2001). Yildiz (2012) proposes that promoting writing activities that summarize the conceptual understanding of QM could make scientific knowledge more permanent. Others stress that writing activities could assist students to learn and understand abstract concepts of physics (Hohensell et al., 2004; Rivard & Straw, 2000). Therefore, the pedagogical approaches in teaching QM could be focused on conceptual learning, mathematical thinking, visualization, or problem solving; however, the pedagogical approaches that instil conceptual understanding of QM seem to be more effective (Didis et al., 2008; Singh et al., 2006).

In terms of content knowledge, the literature provides recommendations regarding which topics of QM should be taught to students (Fischler & Lichtfeld, 1992; Hobson, 1996; Hood, 1993). Mutually agreed QM topics can be listed as: QM model of the atom as opposed to the Bohr atom model, energy levels of electrons in atoms, quantization of energy, photons, and the dual nature of matter. For instance, Niedderer et al. (1990) revealed that high school students in Germany were able to successfully explain quantization of energy and energy levels of electrons in the QM atom model. Regarding content knowledge, Arons (1990) points out a potential problem in teaching physics and suggests that heavy jargon should be avoided in the introductory courses in QM at high school level, since complex terminology could hinder the conceptual understanding of QM. However, students' use of jargon in physics is not necessarily an indicator of the level of understanding of the subject matter (Lee et al., 1995). Accordingly, science

teachers who use appropriate topics of QM and avoid heavy jargon seem most likely to effectively teach the topics of QM.

The literature extensively points out the misconceptions of students while engaging with the topics of QM. A fundamental reason for misconceptions has been identified as being caused by using classical mechanical approach in engaging with the concepts of QM. For instance, students were not able to effectively conceptualize the dual nature of matter or quantum atomic model with electron clouds (Bao, 1999; Pospiech, 2000; Mannila et al., 2002; Olsen, 2002). Other reasons that cause misconceptions in learning QM include: 1) conceptual problems (Ozcan, 2013; Didis et al. 2014; Wattanakaswich, 2005) in terms of lacking the conceptual understanding of the topics of QM and interpreting the concepts of QM from intuitive or unscientific perspectives, 2) mathematical problems (Gardner, 2002; Pospiech, 2000; Sadaghiani, 2005) in terms of lacking the necessary calculus background and having difficulty with the notations in mathematical formalism of QM (these studies are in university level QM instruction), 3) visual problems (Cataloglu & Robinett, 2002; Mashhadi & Woolnough, 1999) in terms of lack of appropriate visuals for the learners of QM and visualizing the QM concepts from an malformed ontological perspectives, such visualizing an electron as a hard ball, 4) problems in distinguishing classical and quantum understanding (Mannila et al., 2002; Müller & Wiesner, 2002; Olsen, 2002) in terms of lacking a new ontology that would aid conceptual understanding of QM and not approaching the notions of QM from classical perspectives.

As Grade 8 science teachers face the new mandatory inclusion of QM in BC, it seems crucial to address the gap in the literature regarding how teachers would learn the

topics of QM and develop their PCK in the concepts of QM. Therefore, this study would contribute to the literature as being the first study of its kind. In order to understand the participant's QM learning and teaching process, an understanding of science and NOS seems to be inevitable. In the writing that follows, the misconceptions and tendency for classical ways of understanding of science and naïve approaches of NOS in science education will be elucidated.

### **The Nature of Science**

The 20<sup>th</sup> century QM paradigm shift unveiled the possibility that scientists could discover new scientific theories that can drastically transform not only science, but also our views and understanding of NOS (Abd-El-Khalick & Lederman, 2000). In general, NOS can be understood as “the epistemology and sociology of science, sciences as a way of knowing, or the values and beliefs inherent to scientific knowledge and its development” (Lederman, 2002, p. 498). The naïve or informed views of NOS provide a framework to understand the scientific enterprise. Naïve views of NOS draw on the traditional, objective, linear understanding of science, whereas informed views of NOS recognize science as a creative, tentative, ongoing human activity (Lederman, 2002; Abd-El-Khlaick, 2012).

In the light of new discoveries in modern physics such as the concepts of QM and general relativity, NOS has been revisited by a number of philosophers in terms of revolutionary aspects of science (Kuhn, 1996), falsification as a prerequisite of scientific knowledge (Popper, 1959) and the rejection of a fixed scientific method (Feyerabend, 1975). After the QM paradigm shift, the field of philosophy of science also seemed to acknowledge the dynamic and complex nature of the scientific realm, and allowed a more

informed understanding of NOS through sociological and epistemological lenses (Crumley, 2009; Sosa et al., 2008). Therefore, the QM paradigm shift provided new perspectives contributing to an informed understanding of NOS, that science is not simply a static accumulation of facts that cohere with previous scientific discovery, rather a revolutionary ongoing human activity (Kuhn, 1962; 1996).

Science is of crucial importance in shaping our culture (Matthews, 1994) and an understanding of NOS has been a significant contributor in the understanding of scientific enterprise and the development of theories in science (Alters, 1997; Duschl, 1990; Lederman, 2002). Despite the ongoing debate regarding the lack of a single definition of NOS (Lederman et al., 1998; Alters, 1997), Lederman (2002) suggests the lack of a single definition of NOS should not be viewed as problematic, since science is a dynamic and complex enterprise that is in constant flux, thus a static definition would not be possible.

#### **Aspects of the nature of science.**

A review of literature shows a lack of a mutually agreed and set definition of NOS; however, science educators have created a framework to better understand NOS while proposing different aspects of NOS, for instance the inclusive framework proposed by Lederman (2002):

scientific knowledge is tentative; empirical; theory-laden; partly the product of human inference, imagination, and creativity; and socially and culturally embedded. Three additional important aspects are the distinction between observation and inference, the lack of a universal recipe-like method for

doing science, and the functions of and relationships between scientific theories and laws (p. 499).

Lederman's (2002, 2007) NOS framework has been used in science education research with the attempt to improve the assessment of students' views of NOS (Allchin, 2011; Deng et al., 2011). Abd-El-Khalick (2012) has elaborated and updated Lederman's (2002) framework. Abd-El-Khalick lays out a list of consensus aspects of NOS and associated dimensions as the latest and inclusive NOS framework (see Table 1), which was used as a guiding framework in order to explore the participant teacher's understanding of NOS experience as she learned to teach QM.

Table 1

*The informed aspects of NOS (Abd-El-Khalick, 2012, p. 357-358).*

NOS Aspect	Dimensions
Empirical	<p>Scientific claims are derived from, and/or consistent with, observations of natural phenomena, and eventually adjudicated by reference to these observations. Scientists, however, do not have 'direct' access to most natural phenomena: their observations are almost always filtered through the human perceptual apparatus, mediated by the assumptions underlying the functioning of 'scientific' instruments, and/or interpreted from within elaborate theoretical frameworks</p>
Inferential	<p>There is a crucial distinction between observation and inference. Observations are descriptive statements about natural phenomena that are accessible to the senses (or extensions of the senses) and about which observers can reach consensus with relative ease. Inferences are statements about phenomena that are not directly accessible to the senses. Most scientific constructs are inferential in the sense that they can only be accessed and/or measured through their manifestations or effects</p>
	<p>While necessarily rational and systematic in several respects, scientific</p>

Creative	<p>investigation cannot be reduced to a merely rational and systematic activity. Generating scientific knowledge involves human creativity in the sense of scientists inventing explanations, and theoretical models and entities. Creativity is involved in all stages of scientific investigation, including prior to, during, and following the collection of data, and is particularly relevant to interpreting data and generating conclusions from these data</p>
Theory-laden	<p>Scientists' theoretical and disciplinary commitments, beliefs, prior knowledge, training, and expectations influence their work. These background factors affect scientists' choice of problems to investigate and methods of investigation, observations (both in terms of what is and is not observed), and interpretation of these observations. This (sometimes collective) individuality or mind-set accounts for the role of theory in generating scientific knowledge. Contrary to common belief, science rarely starts with neutral observations. Like investigations, observations are always motivated and guided by, and acquire meaning in light of questions and problems derived from, certain theoretical perspectives</p>
Tentative	<p>Scientific knowledge is reliable and durable, but never absolute or certain. All categories of knowledge ('facts', theories, laws, etc.) are subject to change. Scientific claims change as new evidence, made possible through conceptual and technological advances, is brought to bear; as extant evidence is reinterpreted in light of new or revised theoretical ideas; or due to changes in the cultural and social spheres or shifts in the directions of established research programs</p>
Myth of 'The Scientific Method'	<p>This myth is often manifested in the belief that there is a recipe-like stepwise procedure that typifies all scientific practice. This notion is erroneous: there is no single 'Scientific Method' that would guarantee the development of infallible knowledge. Scientists observe, compare, measure, test, speculate, hypothesize, debate, create ideas and conceptual tools, and construct theories and explanations. However,</p>

there is no single sequence of practical, conceptual, or logical (e.g., inductive, deductive, hypothetico-deductive) activities that will unerringly lead them to valid claims, let alone ‘certain’ knowledge

Scientific theories are well-established, highly substantiated, internally consistent systems of explanation, which (a) account for large sets of seemingly unrelated observations in several fields of investigation, (b) generate research questions and problems, and (c) guide future investigations. Theories often are based on assumptions or axioms and posit the existence of non-observable entities. Thus, direct testing is untenable. Only indirect evidence supports and validates theories: scientists derive specific testable predictions from theories and check them against observations. An agreement between predictions and observations increases confidence in the tested theory

In general, laws are descriptive statements of relationships among observable phenomena. Theories, by contrast, are inferred explanations for observable phenomena or regularities in those phenomena. Contrary to common belief, theories and laws are not hierarchically related (the naive view that theories become laws when ‘enough’ supporting evidence is garnered, or that laws have a higher status than theories). Theories and laws are different kinds of knowledge and one does not become the other. Theories are as legitimate a product of science as laws

Scientific knowledge is socially negotiated. This should not be confused with relativistic notions of science. This dimension specifically refers to the constitutive values associated with established venues for communication and criticism within the scientific enterprise, which serve to enhance the objectivity of collectively scrutinized scientific knowledge through decreasing the impact of individual scientists’ idiosyncrasies and subjectivities. The double-blind peer-review process used by scientific journals is one aspect of the enactment of the NOS dimensions under this aspect

Scientific theories

Scientific laws

Social dimensions of science

Social and cultural embeddedness of science

Science is a human enterprise embedded and practiced in the context of a larger cultural milieu. Thus, science affects and is affected by various cultural elements and spheres, including social fabric, worldview, power structures, philosophy, religion, and political and economic factors. Such effects are manifested, among other things, through public funding for scientific research and, in some cases, in the very nature of ‘acceptable’ explanations of natural phenomena

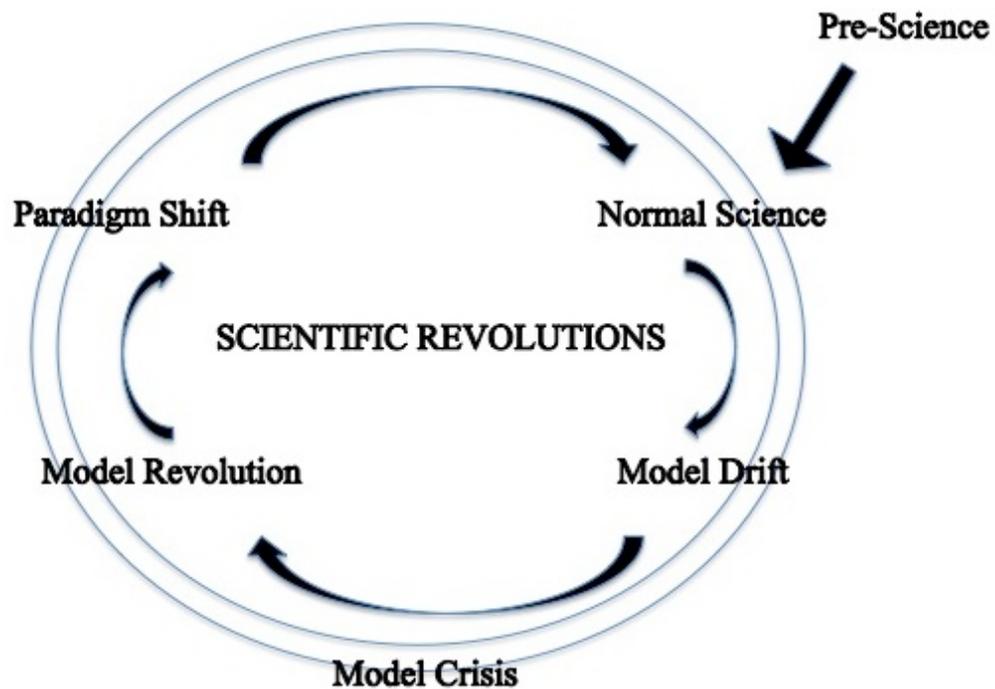
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### **The Concept of Paradigm Shift in Scientific Revolutions**

As noted earlier, learning and teaching the concepts of QM would imply engaging with paradigm shifts. In order to provide a clear understanding for the study, it is important to define the context in which paradigm shifts will be discussed. One of the areas that paradigm shifts can be considered is the field of history and philosophy of science (Kuhn, 1996). In this study, paradigm shifts will be discussed within the framework that Kuhn explains in his book *The Structure of Scientific Revolutions*, where he elaborates the nature and process of scientific discoveries that lead to scientific revolutions.

Kuhn (1996) explains paradigm shift regarding scientific developments in his book *The Structure of Scientific Revolutions*, where he elaborates the nature and progress of scientific discoveries that lead to scientific revolutions. According to Kuhn, there is a particular series of stages in order for scientific revolutions to take place. The pre-science, current scientific knowledge level makes what he calls normal science. At some point scientists may face anomalies in the existing paradigm, that Kuhn calls “normal science” (p. 10), where they fail to find answers to their questions in the existing normal science context. As the anomalies are acknowledged more and more by other scientists, a

drift in scientific model appears (model drift). If the scientific community ends up failing to solve the anomalies and handle the drift in the scientific model, a crisis of the model emerges (model crisis). Kuhn suggests three alternatives for crises to be closed. In that, either normal science prevails or the crises prevails, so that it might be concluded that the issue would be set aside for the next generation scientists to tackle with. As for the third possibility, a new model, in other words a possible for a new paradigm, might emerge and the crisis may end “with the ensuing battle over its acceptance” (p. 84). This new model initiates the model revolution stage. I created a diagram to demonstrate the cycle of scientific revolutions based on Kuhn’s model (see Figure 1).



*Figure 1.* Kuhn’s structure of scientific revolutions.

Throughout the model revolution stage, one or more new model alternatives might emerge. As Kuhn suggests, this new model, in other words the new paradigm, is a

“reconstruction of the field from new fundamentals, a reconstruction that changes some of the field’s most elementary theoretical generalizations as well as many of its paradigm methods and applications” (p. 85). If there are enough supporters for the model revolution, then a paradigm shift takes place. Kuhn explains that:

At times of revolution, when the normal scientific tradition changes, the scientist’s perception of his environment must be re-educated—in some familiar situations he must learn to see a new gestalt. After he has done so the world of his research will seem, here and there, incommensurable with the one he had inhabited before (p. 112).

The important point throughout this process is that the old and the new model can only operate in different frameworks. Scientists discuss the old and the new model from their own perspectives, and thus each model is incommensurate with each other. For instance, QM is a paradigm shift that came after the paradigm of classical mechanics for hundreds of years, changing the nature and understanding of science; however, classical mechanics and QM operate in different frameworks and do not cancel out each other. According to Kuhn, “in the evolution of science new knowledge would replace ignorance rather than replace knowledge of another and incompatible sort” (p. 95), suggesting that the new discoveries in science would illuminate the unknown areas, rather than cancelling out the existing knowledge in science. For instance, QM illuminated the unexplored realm of sub-atomic particles, where classical mechanics was not able to provide explanations. QM and classical mechanics co-exist as two fundamentally different, yet successful and valid paradigms of physics. In this study, the concept of paradigm shift is adopted within the framework of Kuhn’s structure of scientific revolutions.

## **The Nature of Science in Science Education**

Despite the fact that science has gone through a paradigm shift with the field of QM and new perspectives in NOS have emerged, science educators remained unsettled about how to bring the concepts of modern physics within the views of NOS into science classes (Abd-El-Khalick & Lederman, 2000). According to Abd-El-Khalick (2012) science educators and educational institutions hold three different approaches towards NOS. The first approach holds the idea that there is no rigorous consensus about what NOS really is; therefore, due to the uncertainty, NOS should not take place in science education as a separate topic. However, this perspective lacks the essential understanding of NOS, in that; in any science classes a form of NOS is inevitably and indirectly instilled in students, either naïve or informed (Forato et al., 2012; Savall-Alemany, 2016). In order to promote informed views of NOS interventions seem to be effective, since a number of studies demonstrate that with or without NOS interventions neither students (Deng et al., 2011; Osborne et al., 2003; Pedretti & Nazir, 2011) nor teachers (Abd-El-Khalick & Akerson, 2004; Liang et al., 2009; Tsai, 2006; Turgut, et al., 2010; Wong et al., 2008) have an informed view of NOS.

The second approach of utilizing NOS in science education acknowledges and promotes the consensus regarding NOS and is widely adopted by science educators and educational institutions such as the American Association for Advancement of Science (AAAS, 1990) and the Council of Ministers of Education Canada (1997). Lederman (2002) elaborated the understanding of NOS by outlining interconnected aspects of NOS. Abd-El-Khalick (2012) explains the third approach as conditional, since it suggests where to find a consensus for NOS (Wong & Hodson, 2010). The third approach holds the view

that scientists, not philosophers or sociologists, should be in charge of finding consensus about NOS and propose a definition and framework of NOS. While these different approaches regarding what NOS is and how it should be taught have enriched the science education literature, the lack of consensus has undermined the informed views of NOS in science education practice.

### **Historical Underpinnings of the Nature of Science in Science Education**

As noted earlier, the space race between the United States and the Soviet Union had a notable impact on science education (Gaskell, 2002). After the launch of Sputnik in 1957, science communities and science educators received funding in order to promote and improve science through science education, with the express purpose of becoming competitive with the Soviet Union in the space race. In the 1960s science curriculum, developed by scientists, was focused on fact-based teaching of science rather than emphasizing an understanding of how these new scientific theories were developed (Abd-El-Khalick & Lederman, 2000). However, the new curricula failed to attract students to science, and thus AAAS (1990) and the National Research Council Canada (2009) provided reform documents.

In the 1980s there was a shift to an emphasis of NOS; a departure from the content knowledge based science curricula of the 1960s (Duschl, 1990) to a more authentic understanding of science took place including the societal, historical and philosophical aspects of science. Science educators have come to understand that incorporating discussions of NOS allows a better understanding of how science works (Alters, 1997; Abd-El-Khalick, 2012). Alters (1997) suggests that in science education “NOS is *a* major goal, if not *the* major goal of science education” (emphasis in the

original, p. 39). Therefore, promoting the informed views of NOS has become the major thrust of science education literature, yet not in practice (Gaskell, 2001; Cutcliffe, 2000; Nashon et al, 2008).

### **BC's Redesigned Curriculum**

In Canada, responsibility for determining the theory and content of science education curriculum lies entirely with each province (The Council of Ministers of Education Canada, 2015). Most of the provinces in Canada have incorporated topics related to QM as part of their school science and physics curriculum for high school level (see Appendix A). As of 2015, the province of British Columbia has introduced a new K-9 science curriculum, which includes some topics of QM in Grade 8 science classes (BC's New Curriculum, 2015).

While this change encourages the development of science education to include topics in modern physics, teachers presently instructing students in Grade 8 may not have a sufficient background in QM, especially if a teacher was educated for teaching science at the elementary and middle school levels. Elementary and middle school levels include the first 8 years of formal education after the Kindergarten level. Pre-service teachers in order to be qualified to teach these particular levels were mostly required to have only one science course in their teaching education, and that one course was an elective such as biology or chemistry. It is not likely that they have formal education in QM, since these courses at the university level typically require several lower-level physics courses and calculus.

The redesigned science curriculum aims to transform education to match the conditions and needs of the 21<sup>st</sup> century (BC's New Curriculum, 2015). The Ministry of

Education in British Columbia set the key features of the new curriculum as ‘core competencies’, ‘essential learning’ and ‘literacy and numeracy foundations.’ As one of the key features, core competencies are defined as “sets of intellectual, personal, and social and emotional proficiencies that all students need to develop in order to engage in deep learning and life-long learning” (BC’s New Curriculum: Building Student Success, 2015). Throughout Kindergarten to Grade 9 education, three core competencies are recognized by the Ministry: communication, thinking and personal and social competencies for students.

In order to provide the best practice of these concepts, the Ministry of Education adopted the Know-Do-Understand curriculum model for the suggested draft curriculum having the concept-based and competency driven approach in agenda (BC’s New Curriculum: Building Student Success, 2015). In that model the three foundational elements of learning, namely: knowing, doing and understanding, work together to provide a deeper learning experience for students (BC’s New Curriculum: Building Student Success, 2015). In this curriculum model, ‘knowing’ corresponds to the content knowledge; ‘doing’ corresponds to the curricular competencies such as subject-specific the skills, strategies, and processes to be developed within the related grade level, and lastly ‘understanding’ corresponds to the concept of big ideas, which “foster the higher order thinking demanded in today’s world” (BC’s New Curriculum: Building Student Success, 2015).

For instance, one of the big ideas in Grade 8 curriculum is a topic of QM, that “energy can be transferred as both a particle and a wave” (BC’s New Curriculum: Building Student Success, 2015). Firstly, the types of electromagnetic radiation are to be

introduced as radio, microwave, infrared, light, UV, X-ray, and gamma rays. According to the new curriculum, after the introduction the properties of light, behaviours of light will be discussed along with the ways of sensing light. The topic of properties of light will include the concepts of wavelength, amplitude, and frequency of light, in addition to the dual nature of light, which refers to light behaving as both a particle and a wave, which offers a counter-intuitive concept beyond our immediate reality. It could be understood as an ocean made out of both air and earth at the same time—basically it cannot be understood with a common mind-set. It is important to understand that the significance of introducing such a topic promotes a fundamentally different understanding of science—a paradigm shift (Kuhn, 1996). This paradigm shift embedded in the concept of the dual nature of light offers a new understanding of science which conflicts not only with Newtonian physics, but also other concepts and teaching outcomes throughout education, such as acknowledging things that do not make sense can still be scientific. Introduction of the QM paradigm shift in education would be an invitation to see everyday things differently and BC's Redesigned curriculum seems to be innovative by taking this step.

In Chapter 2, I provided a review of the literature starting with the theoretical framework of the study as constructivism, elaborated the concept of PCK in science education, explained the learning and teaching topics of QM in science education framework, elucidated the views of NOS, and lastly introduced BC's Redesigned Curriculum. In the proceeding chapter I provide the research design and methodology for the study.

### Chapter 3

The purpose of this study was for the researcher to gather data on a Grade 8 science teacher in order to explore the teacher's perceptions and experiences of learning and teaching her classes the concepts of QM. In particular, I was interested in how she perceived and engaged with the topics of QM, and how she went through the learning and teaching processes—how and why she made the decisions she made. In order to explore these processes, I needed to choose a methodology that would help me to understand the challenges and benefits of learning and teaching the concepts of QM. In this chapter, I provide insights on the research design and the methodology for the study as exploratory case study elucidating the coding and analysis processes.

#### **Qualitative Research**

A review of the methodological literature identified five main characteristics of qualitative research (Bogdan & Biklen, 1998; Creswell, 2007; Marshall & Rossman, 2011; Rossman & Rallis, 2003). The first characteristic is that a qualitative study is enacted in natural settings. The second is that it focuses and gathers data from the context. Thirdly, data is gathered from a variety of sources such as personal experiences, conversations, personal documents and photographs. The fourth is the emphasis on the process. Lastly, insights are acquired through interpretive, subjective ways of knowing.

In a qualitative study the method of a study should be congruent with the philosophical underpinnings of the methodology (Creswell, 2007). Considering the exploration of the perceptions and experiences of the participant teacher going through a process of learning and teaching QM in this study, it was expected that the participant

would construct her own concepts of QM knowledge on her own, and also through the interactions with the researcher and with her students throughout her teaching practice. The design of the study allowed the teacher to construct her own knowledge rather than the researcher telling her or influencing her in the construction of knowledge. Thus, the underlying philosophical approach was constructivism, which has been outlined in the previous chapter.

### **Selecting the research approach.**

In order to select an approach, the researcher should start with the outcome in mind; in other words, what is aimed to be accomplished with the study (Creswell, 2014). Creswell outlines four factors to consider when selecting a research method: audience, background, scholarly literature, and personal approach. The first factor is to align with the works of the researcher's audience. In academia, case study is a common research method and familiar to both teachers and students. The second consideration is to align the study with the researcher's background. Although I had not previously carried out qualitative research, case study is extensively used in the field of education, and is the one that I was most familiar with throughout my courses in my Masters and doctoral studies. The third is to look for what is missing in the scholarly literature. In this case, I could have selected any research approaches since the literature in the field of education offers a rich variety of research approaches. Given the lack of research regarding learning and teaching the concepts of QM by middle school science teachers, I aligned with Creswell's last criteria in selecting a research approach, which suggests that a researcher must consider what approach they feel most comfortable using. From my perspective, I was looking for an approach that would allow me the flexibility to gather

multiple sources of data and study my participant in the classroom where she would be teaching.

What stood out for me the most in selecting a research approach was the exploration of detailed understanding of the case from a multi-dimensional perspective that would include data collected through interviews, my memos, teacher's learning notes, lesson plans, and teaching materials. In addition, the purpose of the research had to serve a practical purpose for other science teachers as they face the upcoming challenges of teaching a subject for which they are most likely unprepared. Therefore, emerging from constructivist approach, I will elucidate case study as the method of the study followed by the research design.

### **Case Study**

The purpose of case study research is to understand a decision or several decisions—why they were taken, how they were implemented and with what result (Creswell, 2014; Yin, 2014). Case study is defined as a research method that investigates “a contemporary phenomenon (the case) in-depth within its real world context (boundaries), especially when the boundaries between phenomenon and context may not be clearly evident” (Yin, 2014, p. 16). The structure of a case study consists of the problem, the context, the issues, and lessons learned (Lincoln & Guba, 1985). Briefly, through multiple sources, case study research provides detailed, in-depth data, which typically emerge from fieldwork.

In a case study project, the problem is framed by the research question. The research question must identify a specific case, which typically is a how or why question in order to illuminate the underlying dynamics of the decisions taken throughout the

research process (Creswell, 2014; Yin, 1993). The case can be an individual, an event, or an action, which could be viewed as a ‘thing’ that is specific, complex and functioning (Stake, 1995). The case under the study is called the unit of analysis (Yin, 2014), which helps the researcher to avoid data that are not closely related, and to focus only on what is important in order to answer the research question (Baxter & Jack, 2008). In this study, the unit of analysis was defined as the engagement of a Grade 8 science teacher with the topics of QM throughout her learning and PCK development processes.

After defining the unit of analysis, the boundaries around the case were defined, which could be time, space, and context in relation to the case. Bounding the case determines the scope of the data collection by distinguishing the case from the context excluding the data external to the case (Yin, 1993; 2014). In this regard, the boundaries of this particular study are that the case took place in 2016, in a public middle school in Victoria, BC and focused on the teacher’s learning and teaching experience, rather than on student learning process or performance.

Before proceeding to the data analysis stage the researcher sets criteria to interpret their findings (Yin, 2014). As Yin suggested the data analysis provided detailed description of the case under study, the teacher QM learning and teaching processes, along with insights about themes and issues (Yin, 2014). As a result, I drew conclusions in order to present general lessons learned throughout the study (Creswell, 2014; Yin, 2014). I avoided and eliminated the situations in which the data did not address the research questions (Yin, 2014).

Case studies can be distinguished by the size of the bounded case, such as whether the case involves “one individual, several individuals, a group, an entire program

or an activity” (Creswell, 2014, p. 99), where the size of this particular case study was one individual. According to Creswell (2014), case studies can also be categorized in terms of the intent of the research and depending on the intent of the research there are three kinds of case studies: intrinsic, collective, or instrumental. An intrinsic case study is conducted if the case under the study is unique and describes an unusual interest in the case (Stake, 1995). If the researcher uses multiple cases to illustrate an issue, rather than a single case, then it is a collective case study. If the researcher is examining deeper insights regarding a contemporary issue, concern or a problem and selects one bounded case to illustrate this issue, then it would be an instrumental case study (Creswell, 2014). In this regard, this study is an instrumental case study, while providing deeper insights about contemporary concern or a problem regarding the upcoming curriculum issues for Grade 8 science teachers without a QM background in learning and teaching QM for the first time.

#### **Exploratory case study.**

As elaborated above, case study method is conducted in order to understand a contemporary phenomenon within the defined contextual conditions, where the understanding emerges by shedding light on the “how” or “why” part of the incident. The answer to a “how” or “why” question can serve different purposes: explaining, describing or exploring a case or multiple cases (Yin, 2014). As Yin explicates explanatory case studies have an emphasis on correlation where rather complex causal relationships between a treatment and its effect can be explained, whereas descriptive case studies describe and illustrate certain topics in the real world context.

A third type of case study, exploratory case study, aims to enlighten certain cases that do not have single clear end-results. In that, exploratory case studies typically do not lead to conclusions by drawing either/or picture of the experience, rather, given the inquiry of an open-ended research question, exploratory case studies provide different dynamics of a contemporary phenomenon (Yin, 2014). In exploratory case studies the case under the study has no set, predetermined outcome (Baxter & Jack, 2008) and unlike other types of case study design, exploratory case studies do not use hypothesis formulation. As Yin suggests, the purpose and the criteria of exploratory case study are stated in the research design rather than a preliminary theory; and thus, exploratory case study includes a rationale and direction underlying the study. The research question leading this study is an open-ended research question and an exploratory case study framework was adopted with the aim to explore the dynamics engagement of a Grade 8 science teacher with the concepts of QM. I was not able locate any research exploring and examining a middle school science teacher's engagement with the topics of QM, and in this regard, the insight emerging from this study would make unique contributions to the literature.

### **Three principles of case study.**

I have followed Yin's (2014) three principles in proceeding with a case study research. The first principle is to establish the case study on multiple sources of evidence in order to provide triangulation. Triangulation might apply to different aspects of the study including: data, investigators, theory or methodology (Yin, 2014), for instance, in the case of data triangulation, corroboration from different sources of data, such as interviews, documents, and journals would be required. In this study, the data

triangulation emerged through the data; such as the in-person interviews, teacher's QM learning notes, lesson plan documents, teaching materials, the researcher's journals and observation. Consequently, it was hoped that the triangulation of data would offer a holistic approach to the study (Kohlbacher, 2006).

The second principle of case study is to create a study database (Yin, 2014). The database consists of researcher's notes that result from interviews, observations and document analysis (Bryman, 2004; Yin, 2014). In this study, I took hand written notes during the interviews and teaching practice observations, transcribed and transferred them to my computer as soon as possible after the events occur; although, the entire transcriptions were completed over a three-month period. As Yin suggests in case study research annotated bibliography of the documents and possible artifacts and documents created by the participant also contribute to the database. While learning the topics of QM, the participant teacher created handwritten study notes and designed her lesson plans accordingly. Yin suggests that the researcher's narratives at the end of the data collection process constitute the last part of a database, which developed open-ended answers for the case under study. I examined all the pieces of the database, and then through a self-reflexive process, my experiences formed a narrative in response to the research question.

According to Yin, the third principal in conducting a case study is to maintain a chain of evidence. In this study, the chain of evidence begins with the research question "How does a Grade 8 science teacher learn to teach QM?" Then, I linked the research question to the contextual conditions of the study, which were substantiated by the citations to specific evidentiary sources (documents, interviews, journals, observations) in

the database, which occurred through collection of the interview field notes and observation field notes. Through these processes I aimed to maintain the chain of evidence, as it is essential in a case study.

### **Establishing quality in exploratory case study.**

As qualitative studies cannot be viewed objectively, establishing quality requires employment of thorough validity procedures. In order to establish validity throughout a qualitative research process, Creswell and Miller (2000) proposes certain validity procedures depending on the qualitative lens and research paradigm. In terms of qualitative lens they suggest three different viewpoints: 1) the researcher's own lens to determine the time allotted to the field work and saturation of data, 2) the participant's lens in response to the researcher's interpretations, and 3) lens of individuals external to the study. Along with these lenses, Creswell and Miller add that the paradigm or worldview of the researcher shapes the validity procedures in a research process, which can be outlined as postpositivist, constructivist and critical perspective. The combination of lens and paradigm assumptions sets the validity procedures for a qualitative study. For instance, as this study adopts constructivist research paradigm, the validity procedures of the study should be determined by disconfirming evidence revealing the lens of the researcher, prolonged engagement in the field contributing to the lens of participants, and rich description that will enhance the understanding and the experience in reading the study confirming that the account is trustworthy (Creswell & Miller, 2000).

In the earlier writings on establishing quality in exploratory case studies, the terms of credibility, confirmability, and transferability were articulated (Lincoln & Guba, 1985); however, Creswell and Miller (2000) provide a more accessible set of terms, such

as “trustworthiness (i.e. credibility, transferability, dependability, and confirmability), and authenticity (i.e. fairness, enlarges personal constructions, leads to improved understanding of constructions of others, stimulates action, and empowers action)” (p. 126). For instance, credibility of a study parallels internal validity where the participants’ perspectives are represented accurately by the researcher (Zucker, 2009). In this study, I aimed to achieve credibility through prolonged engagement in the field, conducting in-depth interviews and revisiting the data sets multiple times until I felt confident that I had a substantial understanding of the data with a focus on both details and overall comprehension of data shedding light on the research question. I reviewed my research notes and interpretation after the initial interview and a week after the following interview.

Dependability refers to reliability aspect of a study, which I aimed to achieve through consistent data collection, analysis, and recording accuracy. Here, it is important to note that, two of the interviews were lost in the research process due to the technical problems in the recording App on my Ipad. Consequently, I repeated the interviews with the permission of the participant. In order to establish authenticity in the study, I aimed to better understand my participant by allowing her to go beyond the semi-structured interview questions and further explore her emergent thoughts and concepts by providing enough time throughout our interviews. One disadvantage of this approach was that each interview took at least two hours exceeding the scheduled interview period; however, in doing so, I was able to acquire more authentic and pluralistic insights that emerged through a less structured conversation format and learn about what my participant really wanted to say and what she really cared about. This enabled a sense of comfort and trust

between us and helped her to express herself more openly. I believe through these procedures, the lens of the participant became more evident contributing to the validity of the study.

Disconfirming evidence or negative evidence is a validity procedure that allows the researcher's lens become explicit by self-disclosing the researcher's preliminary expectations before the data collection (Creswell & Miller, 2000). In this study, relying on one participant created some form of discomfort for me before meeting the participant; however, after I met Alice, my concerns disappeared. As she was an innovative and progressive science teacher, I expected that she would be enthusiastic about the concepts of QM and would create fun dynamics throughout her PCK development in QM. Her characteristics and former experience in initiating engaging events for her students did not relive in her QM teaching experience; particularly the first lesson in all three classes was different than what I anticipated in terms of pedagogical approach. However, in terms of the QM content she covered, she surprised me with her passion to teach as many QM topics as she could, and exceeded my expectations. Prior to the study, I also assumed that a science teacher would understand the essence of the topics of QM by merely engaging with a couple of online QM resources. Nonetheless, I then realized that our discussions about the QM topics and a variety of resources that she digested in a longer period of time provided a more effective learning process for Alice. These aspects of my expectations prior to the study can be viewed as disconfirming evidence; however, one major positive evidence I expected before the study was that my participant would be fascinated by the concepts of QM, which happened to be consistent with the findings.

In order to establish validity through the lens of readers or reviewers, the researcher provides a rich and detailed description of the setting and events (Creswell & Miller, 2000). In order to achieve validity through the lens of the readers, I aimed to describe the class setting, my participant and her interaction with her students in detail while still respecting the confidentiality issues. Providing thick and rich descriptions would enable readers to understand the intrinsic dynamics of a science class setting in Victoria, BC and help to anticipate the potential applications in similar or different settings (Creswell & Miller, 2000). Therefore, by adopting constructivist research perspective revealing disconfirming evidence, spending prolonging time in the field, and providing rich descriptions, I aimed to determine validity for the study.

### **Research Design**

The study was focused on one Grade 8 science teacher presently employed with the greater Victoria School District 61. In order to provide an authentic picture of the existing Grade 8 science teacher profile, volunteer teacher without QM background was selected. The research setting was the teacher's classroom. The teacher learned the topics of QM on her own, in relative isolation. This was part of the research design as I intended to explore her learning process without external influence, given that the current Grade 8 science teachers are faced with learning these concepts of QM on their own and not necessarily through a professional development program provided by the government. The learning and teaching materials, resources that were found independently by the participant and the lesson plans she created have been included as a part of the data collection.

In terms of developing understanding on Alice's views of NOS, Abd-El-Khalick's (2012) NOS questionnaire was utilized (Appendix B). In fact, Lederman's (2002) NOS framework has been extensively used in science education literature (Allchin, 2011; Deng et al., 2011; Liang et al., 2011); however, Abd-El-Khalick elaborated and updated the Lederman's NOS aspects and he outlines the ten aspects of NOS as the latest and more inclusive version of NOS understanding, which was used as a guiding framework in order to explore the participant's views of NOS as she learned and taught the concepts of QM.

Alice had three Grade 8 science classes. She taught two lessons of QM in each of them, following the same lesson plan in each class. Her first lesson was dedicated to the introduction of QM providing its terminology, history, key experiments and fundamental sub-atomic particles. The second QM lesson was focused on the dual nature of light along with elaboration of key concepts of QM. The allotted time for each lesson was one hour.

These two lessons of QM were followed by another session where she asked for students' responses regarding their QM learning process in the classroom. In this third session, Alice asked for students' feedback of the content and order of topics that were taught in QM classes, age-appropriateness of the teaching material, and the challenges and motivational aspects of learning QM. I was able to observe these classes. The development of her PCK in QM through these classes was investigated through observation, learning and teaching documents where she created a worksheet and used it as both a teaching material and a lesson plan.

Unfolding from a constructivist philosophical framework, case study method was utilized for this study. Case study typically starts with a preliminary theory and inquires

into the how and why questions of underlying contextual conditions of a contemporary real life event with a focus on a defined case such as an individual, a decision, an organization, or a process (Yin, 2014). In a case study methodology, after defining the case as a unit of analysis the boundaries need to be defined (Yin, 2014). In this particular study the unit of analysis was set as the engagement of the teacher with the concepts of QM. After setting the unit of analysis as the case, the case needs to be bounded, meaning that the boundaries need to be defined in order to set the context and the scope of the research (Yin, 2014). According to Yin, the case, in other words the unit of analysis, is typically bounded in relation to different contextual conditions. For instance, the participant is a Grade 8 science teacher who was bounded with the particular elements of location and time period, namely, in the Victoria, BC School District 61, and participated in this research over a three month time period. The focus of the study has been on the engagement of the teacher with the topics of QM throughout her learning and PCK development process, leading to identify Alice's views of NOS. In this study, the exploratory case study research method along with a thematic analysis technique was utilized in order to analyze the findings.

### **Going Through the Three Stages of Case Study**

A case study research design consists of three main stages: pre-field work, fieldwork and analysis (Yin, 2014). The preliminary steps of the pre-field work in a case study research are firstly setting boundaries, defining the unit of analysis, selecting a site, establishing initial contact, developing data collection systems and defining fieldwork procedures. Setting boundaries refers to defining the context of the study. The boundaries of my study were set to be the perceptions of a Grade 8 science teacher in a

public middle school in Victoria BC, Canada. The case, in other words the unit of analysis of this study is the engagement of teacher with the topics of QM by exploring how she perceived the challenges of learning and teaching QM, how she perceived the benefits of learning and teaching QM, and why she made the decisions she made throughout the research process.

### **Pre-field work.**

For studies involving human subjects it is necessary to go through an ethics approval process from both the university and school districts. In both ethics application I described the research design and potential harms and benefits for the participant. After receiving the ethics approval from the university, I applied to the ethics board in School Districts 61 and 63. When the school board gave me their approval, I then created a research information letter for potential teacher participants. My goal was to reach all the Grade 8 science teachers in these two districts and the school boards co-operated by sending my letter to all the Grade 8 science teachers via email. I received four responses of interest; however, when elaborating the time commitment for the research only one teacher was able to devote the time required. Therefore, one volunteer Grade 8 science teacher named Alice (pseudonym) was selected from middle schools located in the School District 61 in Victoria, BC.

As one of the preliminary steps of pre-field work, I prepared semi-structured interview questions prior to the interviews. Semi-structured questions include open-ended questions and encourage the participant to express her views freely. The questions were aimed to elicit the participant's process; the insights from the participant's perceptions and experience while learning and teaching QM, in particular the challenges

she faced, the motivations she found throughout the research process, the impact of the research process on her perception in understanding the scientific enterprise, and recommendations for her colleagues who will be going through experiences of learning and teaching QM in their careers.

***Initial contact with the participant.***

The initial contact with the participant was made by the School District 61. The School District 61 sent out an invitation and information email to all the Grade 8 science teachers in the district. Teachers who were interested in gaining more information contacted me via email and I provided more information regarding the research process to the interested teachers via emails or telephone contact. One out of four interested science teachers was able to commit to the research. This teacher, whom I will refer to as Alice, was contacted by email to establish an in-person interview date. The first meeting was set up just to meet each other and talk briefly about the research process. In the second meeting the consent forms (see Appendix C) were signed and returned to the researcher.

***The research setting.***

The setting was a Grade 8 science classroom in a public middle school in Victoria, BC, located in the center of town. Alice's classroom was made up of 24 students of mixed gender, all 13-14 years of age, from various socio-economic backgrounds. Alice took care to provide a stimulating atmosphere in the classroom, complete with a large colourful picture of hands that formed an arch over the doorway. In addition, three full size replicas of animals hung from the ceiling, each showing internal body systems such as intestines and organs. Interspersed between the models

were handcrafted art pieces made by students hanging on the wall, as well as inspirational posters and quotes. There were two white boards and an overhead projector located in front of the boards on the table. The teacher had set up two desks in one corner of the room where she clearly had her own space, complete with pictures of her family.

### ***The participant.***

Case study is an in-depth inquiry of one or more person (Yin, 2014); in this particular study Alice was the sole participant. Alice is an experienced science and physical education teacher. She has taught science for almost thirty years. Alice has a genuine interest in science and is eager to learn a variety of subjects in science and technology. She answered a request from the School District 61 to participate in the study, because she saw participation as an opportunity to learn more about QM. Her friendly nature and dedication to her work became apparent as the first impression. She has a broad interest area, likes science fiction, is an animal advocate, loves farming, is active in sports, and spends time in nature as an avid camper.

### **Fieldwork.**

Creswell (2014) outlines four main forms of data: “observations, interviews, documents, and audiovisual documents” (p. 121). I focused on gathering data through multiple sources in the fieldwork stage of the research in order to cultivate triangulation.

Verbal data were gathered through in-person interviews. I visited the participant’s classroom, her office-work space, for a total of eight meetings, and asked the semi-structured interview questions (see Appendix D) recording all the conversations. For the audio recording an iPad application was utilized. In case of an unfortunate technological failure I used two cameras for the purpose of audio recording; however the

cameras were directed to the ceiling of the room in order to follow the consent form regulations. All recorded conversations were transcribed and all parts of the conversation remain intact in the typed transcript. In addition to this record, I made handwritten field notes during the interviews and also reflecting my observation.

### **Researcher's journal.**

Self-reflection is crucial in a case study in order to provide insight regarding the research process at a deeper level from the researcher's perspective (Yin, 2014). After Alice signed the informed consent form at our first meeting, I started creating a research process journal reflecting my thoughts as the research unfolded. I kept detailed notes that described our interactions and my thoughts and feelings, in retrospect of the subject that we covered. For instance, before our first meeting I wrote, "I wonder about if having only one participant will be enough to provide enough research." Despite the plethora of researchers suggesting that one participant was enough to conduct a qualitative study (Creswell, 2009; 2014; Marshall & Rossman, 2011; Miles et al., 2014; Yin, 2014), I needed to find out for myself. After having the first meeting with Alice and engaging in conversation, I realized that one participant can provide a great deal of data, since with Alice there was so much ease to delve into topics and going deeper with them. I wrote, "Alice is so enthusiastic! She is excited and so eager to contribute and cooperate for this research. I know that I am going to enjoy the data collection." I was further reassured when we had a few interviews which went almost two hours. Alice seemed to know that it was important for her to answer all my questions, and we continued until we covered everything that needed to be shared for that day.

Yin (2014) suggests that journal writing is a deep and exploratory process. I continued to write in my journal, not only after meetings with Alice, but as I did my reading and writing. For instance, I found that my journal was a place where I could ask and revise my interview questions, and keep track of my unfolding understanding. Rereading it generated further questions and development of my answers. I used it to go over my research questions and I found subtle differences in how I asked questions as I wondered how to deepen our conversations. For instance, I wrote out different ways of asking the same question. I realized in my reviews that her answers were sometimes ambiguous or conflicting. My journal was the place where I rehearsed different ways of asking questions in order to get clearer answers. I was also making sure that I talk about different things in between before going to the same question again, but with a different spin. For instance, at one point Alice had said “science is objective and fact-based” and then later she said, “science is time-dependent” and recognized the importance of a paradigm shift in the development of science, where she gave an example of building a house and then making renovations in the house. In order to clarify I toyed with various wording: “so is science fixed?” then I tried wording it like this: “are renovations allowed in science?” In the end I used the question “Do you think different scientists can come up with different results based on the same data?” giving the example of the universe, some scientists say it is shrinking, some say it is expanding based on the same data set. Then she remembered the movie she saw about Stephen Hawking’s life, and consolidated her answer to mean that she thought science until the university level is objective and set. Then she added that there was room for paradigm shifts and subjectivity in the teaching and research at the university level.

**Interviews.**

Interviews are one of the methods by which the research can obtain rich, personalized information (Mason, 2002). Semi-structured interviews are particularly useful for a case study research (Hancock & Algozine, 2006). The goal of semi-structured interviews is to create a “rich dialogue” with the participants using open-ended questions (Yin, 2009, p. 69). I carefully constructed my semi-structured interview questions using my journal to record my thinking (see Appendix D). The questions were designed to achieve three main goals: how the participant perceived the challenges of learning and teaching concepts of QM, how she perceived the benefits of learning and teaching concepts of QM, how she perceived the nature of QM and NOS, and what lessons can be learned from her experience in order to provide recommendations for other science teachers.

**Observations.**

Direct observations provide insightful data in gathering information (Yin, 1993; 2009). In this stage, as Hancock and Algozine (2006) point out, I was trying to be aware of my biases and the judgments that I could potentially make. Interviewing the participant seemed fairly comfortable, almost like two friends or two colleagues chatting after a teaching day. However, while observing Alice while she was teaching, I realized that it was my first time watching anyone teaching QM to middle school students. I have been in her shoes before, and having my own experience was inevitably following and shadowing my observation. In my journal I wrote, “Do I have a posture like this? Would I have said that?” I was reflecting on my own teaching and making comparisons with hers. However, I have never watched my teaching experience on a video, so I am not

sure that my perception of myself was accurate. Teaching is like acting, you go on the stage and act your role. Sometimes we get lost in our roles and it becomes hard to know what we do and do not do. Alice was enthusiastic and active in teaching throughout the whole class. She paid attention to student interaction as it would be expected in constructivist modes of teaching. She went over the worksheet with her students.

Although, she predominantly made her teaching interactive, I noted in my field notes that there were times when she was going over a worksheet that her teaching style seemed traditional. The data from the journal entry coheres with the recordings throughout her teaching practice. However, overall she primarily used a student-centered approach.

In the writing that follows, I will elaborate the analysis stage of the findings. I will then outline the categories that emerged from the data corpus gathered from multiple sources, such as interviews, observations, and documents: namely, Alice's QM learning notes, QM lesson plans, teaching materials, and my field notes and journal entries.

### **Analysis: Thematic Coding**

The purpose of qualitative data analysis is to “organize and reduce the data gathered into themes and essences, which in turn, can be fed into descriptions, models or theories” (Walker & Myrick, 2006, p. 549). For an instrumental exploratory case study, pattern-matching technique is considered to be the most appropriate analysis technique (Creswell, 2014) as it is used to compare a predicted pattern with the observed pattern during the research process, which contributes to internal validity of the study (Yin, 2014). Bernard (2011) suggests “the search for patterns in the data and for ideas that help explain why these patterns are there in the first place” (p. 338). Looking for patterns, then identifying and interpreting them is viewed as the goal of the data analysis, so that

the researcher can draw and form conclusions (Neuman, 1997).

Coding allows the researcher to “organize and group similarly added data into categories or families because they share some characteristics—the beginning of a pattern” (Saldana, 2013, p. 9). In my thematic coding stage, I followed Saldana’s (2013) coding steps: coding, finding patterns, codifying to categorize, recoding and finding themes and concepts. Saldana (2013) defines a code as “a word or short phrase that symbolically assigns a summative, salient, essence-capturing, and/or evocative attribute for a portion of language based or visual data” (p. 3). The function of coding is to bridge data collection with their explanations for the research. Saldana (2013) recommends first-time or small-scale researchers to execute the coding process on paper by writing and manipulating codes in pencil, so as to have “more control over and ownership of the work” (p. 26). Admittedly, at first I tried to execute my manual coding process on computer going through the data line by line by creating notable numbers of word documents, but it quickly became overwhelming, so I went back to the instructions and created three large posters using the back of gift wrapping papers and wrote all the themes in pencil. This allowed me to see all the codes at once and enabled me to better create a temporal and organized way of dealing with codes.

After completing all the transcriptions, I started the coding process by going over each sentence and trying to identify the essence of the sentence with a word or a phrase. For example, some of the first codes were: self-confidence, motivation, challenge, and evolving NOS. At times these codes seemed too general; and thus, in my second round of going over the data I added a parenthesis for most of the codes emphasizing a more detailed and insightful description of the sentence. For example, under the code of self-

confidence, I indicated whether Alice was or was not feeling self-confident.

Lichtman (2006) suggests that in a qualitative study the appropriate amount of codes would be 80 to 100 codes. Then codes might be organized into 15 to 20 categories and sub-categories, and these categories might create five to seven major concepts. For the same process, Creswell (2007) proposes five to six provisional codes that would lead to 25 to 30 categories and eventually would be combined to five to six major themes. In terms of general guidelines for qualitative analysis, Saldana (2013) suggests “the final number of major themes or concepts should be held to a minimum to keep the analysis coherent, but there is no standardized and magic number to achieve” (p. 21). While providing insight to different approaches for analysis, this statement also indicates that in qualitative inquiry not only the set of numbers vary, but also the terminology is identified differently; since, what Lichtman (2006) calls ‘concept’ is called ‘theme’ by other qualitative researchers, such as Creswell (2007) and Saldana (2013). In this study, I will use the term ‘theme’ in order to identify “any principle recurrent in a number of domains, tacit or explicit,” which can be understood in a number of ways in terms of their ways of emergence in the data and their function (Spradley, 1980, p. 141).

After deliberating on the codes with parenthesis, I ended up with 93 codes. Most of them were repetitive not only in the same data set, such as interviews, but also emerging in different data sets, such as journals and field notes throughout the class observation. For instance, Alice elaborated her attitude to learning QM from different perspectives throughout our interviews, and also shared her QM learning experience with her students in the beginning of the QM classes. In addition, I had written my perception about her learning in my journal entries. Approaching a code from different data sets

enhanced my understanding of this particular theme.

Repetitions of codes create a categorical structure that is useful in grasping and comprehending the big picture (Saldana, 2013). As Saldana suggests, repetitions are natural and deliberate, natural because “there are mostly repetitive patterns of action and consistencies in human affairs, and deliberate because the goal is to find these repetitive patterns as documented in the data” (p. 5). For instance, Alice’s current views of NOS were predominantly informed by her prior knowledge in history of science and a synthesis of this knowledge. The accumulation of historical knowledge in and about science enabled a synthesis of prior knowledge in history and philosophy of science (HPS); consequently shaped Alice’s views of NOS. These concepts emerged as a repetitive pattern and created a category in my analysis.

In terms of her teaching practice Alice emphasized the importance of building trust with the students for effective teaching before embarking on the subjects to teach, and this particular “building trusting relationship with students” pattern emerged in different data sources referring at times to pedagogy and creating a positive learning environment, and other times it referred to determining the order of topics to teach throughout the year. Alice believed that counter-intuitive topics require trust between students and teachers and since QM is counter-intuitive, it would be more effective to teach QM after building trust, which puts the order of teaching topics of QM in the middle of the year or later. The dual perspective for one code made me look at the data again from a different standpoint helping me to have a fuller understanding. This aligns with Saldana’s recoding process, where he explains “codes, categories, and themes as the researcher defines them can be developed and subdivided differently during the data

analysis.” As in this case, the recoding process either re-shaped the existing patterns or created new ones creating new categories.

Spradley (1980) proposes different perspectives in understanding of a theme, such as themes can be examples of participant’s words and recurrent expressions; relationship among different domains; or interpretations, assertions, and assumptions that have a high level of generalizability (Spradley, 1980). It is important to note that the theme building trust was recurrent both as Alice’s words, where she explicitly articulated this expression repeatedly, and also this theme emerged from my interpretations in my journal. The emergence of this theme was straightforward. However, contemplating the relationship among other themes from a critical and creative perspective, I noticed an overarching theme that would combine multiple themes as an overarching theme. For instance, building sincere and trusting relationship with students is a complex notion in an educational environment, so is developing self-confidence in classroom for the teacher, which was also explicitly articulated throughout our interviews. Another complex notion that contributed to the development of her PCK in QM was Alice’s changing roles, oscillating between traditional approaches and student-centered approaches. Stepping back from data and trying to see the bigger picture, I realized that the notion of complexity emerged as an overarching theme combining other domains contributing to the development of PCK in a complex way. Therefore, I identified the first major theme as “the development of PCK is complex” and listed eight sub-themes that contribute to this major theme. This aligns with Spradley’s (1980) definition of a theme in the sense that themes connect different sub-systems—I call these sub-systems sub-themes in this study in order to maintain a coherent terminology. I applied these principles to the other

emergent themes and found five major overarching themes. The major and sub-themes will be elaborated in chapter five.

In this study, I was expecting that the patterns taken from the data—in-person interviews, journals, learning and teaching notes of Alice, field notes—would provide insight that may fall into different categories, such as insights regarding learning and teaching processes, views of NOS, emotional states while engaging with the concepts of QM. However, conflicting patterns emerged in some particular categories, for instance, regarding the concepts of QM, at times Alice expressed motivational positive attitude such as excitement, inspiration, acceptance, humility and at times she expressed that she found the QM concepts intimidating, difficult to grasp, or reconcile. These conflicting patterns were elaborated as sub-categories, such as motivations in learning process and challenges in learning process.

After finding the patterns, I moved to a “codifying” stage, which is “to arrange things around in a systematic order to make something part of a system or classification, to categorize” (Saldana, 2013, p. 9). The patterns were organized into broader categories. I determined the categories in alignment with Shulman’s components of teacher knowledge. Shulman’s teacher knowledge framework does not include a teacher’s learning process of a new subject, therefore, I created a category titled *Learning Process* in addition to the components of teacher knowledge. Some of these categories were subcategorized such as the learning process was broken down into challenges and motivations. The analysis of these sections will be provided in the next chapter.

It is important to note that the thematic analysis process is a subjective process. The researchers contribute to the process with their “own subjectivities, personalities,

predispositions, and quirks;” and thus “all coding is a judgment call” (Sipe & Ghiso, 2004, p. 482-483). In order to establish validity throughout this intrinsically subjective process, Creswell and Miller (2000) outlines three different viewpoints, namely three lenses: 1) the researcher’s own lens in terms of determining the time allotted to the field work and saturation of data, 2) the participant’s lens in response to the researcher’s interpretations, and 3) reviewers’ lens who are external to the study. This also implies that data analysis is related to reasonable social accord between the domains of the researcher, participant and external factors contributing to the research such as readers or the informed literature.

Saldana suggests there is an inevitable filter in each coding process and continues, “the act of coding requires that you wear your researcher’s analytic lens. But how you perceive and interpret what is happening in the data depends on what type of filter covers that lens” (p. 7). The type of filter relates to the reflexivity and the personal attributes of the researcher. For instance, in this case my personal attributes in relation to this study as having a background in physics, education and physics teaching inevitably contributed to the analysis of my qualitative inquiry.

In order to execute an effective coding process Saldana points out a number of personal attributes, such as being organized, exercising perseverance, dealing with ambiguity, exercising flexibility, being creative, being ethical, and having an extensive vocabulary. I noticed that all of these attributes came into play as I was doing the coding. For instance, I am a naturally organized person so that I found that it was easy for me to sort through the data and find which categories were linked. However, I found that my vocabulary was affected when I was trying to find the most accurate words to describe

different data given that English is a second language for me.

Coding was one of the most fun and engaging parts of the research. Firstly, I like the way that it was hands-on, in that the data corpus became solid and tangible, which helped with clarity. Secondly, by going through the transcription word by word, I noticed that certain words might go by unnoticed during an interview; however managing sentences word by word on paper enabled deeper understanding and access to the bigger picture. Thirdly, I appreciated the flexibility that was encouraged in the coding stage, allowing me to think about, not just where data might fit, but where it would best fit. It helped me to keep moving, because I knew that if later, the data needed to be moved, that would be okay. As Saldana recommends, I utilized my journal where I could think critically and reflect upon my own process—of what I was doing and why—in order to recognize preconceptions that might be shaping my actions, the decisions that I made, and how I was limited in what I could see.

The journal documents, field notes, the participant's QM learning notes, lesson plans and teaching notes formed the data from which these themes emerged. The coding process led to the categories. I categorized results according to the Shulman's teacher knowledge components in addition to the challenges and motivations Alice experienced in her QM learning process. Revisiting the categories, making associations, constant-comparisons enabled emergence of the themes. I utilized Hancock and Algozzine's (p. 63) following questions in order to find patterns:

- “What information from different sources goes together?”
- “How do various sources of information affect findings?”
- “What previous work provides a basis for analysis?”

- “What questions are being answered?”
- “What generalization can be made?”

By utilizing these questions, some certain patterns emerged which described the research process while providing insights to the research question. The compiled themes were organized and collapsed into final themes. This procedure is consistent the pattern-matching technique as suggested by Yin (2014), whereby I was able to draw conclusions by grouping of data from different sources and comparing them to the data available in a review of literature. In this chapter, I explicated the method of the study along with the coding and analysis stages. In the following chapter I will provide the findings of the study.

## Chapter 4

In Chapter 4, I will provide the findings in terms of categories in alignment with the Shulman's teacher knowledge components. Shulman's teacher knowledge framework does not include a teacher's learning process of a new subject; therefore Learning Process is elucidated as the first category with two sub-categories: challenges and motivations of Alice's learning process. Following this section, I elaborated each component of teacher knowledge as a category such as, general pedagogy, content knowledge, PCK in QM, teaching materials, characteristics of learners, knowledge of educational values, curriculum knowledge, and the views of the nature of QM and science. The data I had obtained throughout the research process enabled for the emergence of an additional category focusing on professional learning opportunities, which will be elucidated as the final category. In the writing that follows each level two heading represents the main category followed by its sub-categories.

### **Learning Process**

Alice's learning process will be examined under two sub-categories, challenges she faced throughout her QM learning process and the motivations she had that helped her to fulfill her task of learning about the topics of QM.

#### **Learning process: Challenges.**

Alice has thirty years of teaching experience and appears to be a successful and inspiring science teacher. Throughout her career, Alice initiated and organized several exciting, stimulating events. For instance, she organized a science fair for students, and organized and coached a replica of a famous show with her middle school students entailing almost professional levels of choreography. She is full of innovative ideas and

shows a high level of energy in executing them. In my journal I wrote, “I feel so fortunate to have Alice as my research participant. Alice and I seem to be kindred spirits, we both love to embark on innovative projects and neither of us mind the challenges that come with those projects. We also both seem to have a high sense of responsibility for our students.” This sense of kinship made it easy to relate to Alice and may have made it safer to talk about some of the challenges.

One of these challenges for Alice was to participate in this study, because her pre-conception about QM was that it was different from learning other science subjects. She said that she had thought QM was a topic beyond her, because of its futuristic elements that she only knew of from science fiction movies. A number of times she articulated, “learning QM requires being imaginative and stepping out of your comfort zone.” Alice admits that she was scared when she began this project. “At first I thought, ‘What did I embark into?’ But then I thought, it is good, I like to challenge myself.” Despite being out of her comfort zone, Alice was not afraid to ask questions about QM throughout our interviews while focusing on her learning process. She was okay with the notion of not being able to know everything, once she understood that it is the nature of QM not to be able to provide all the answers. Even after reading QM materials and watching some informative videos, she was still not sure if she completely understood the concepts. During our interviews I interpreted her hesitation as the first sign of understanding QM. Even though I enjoyed our conversations and wanted to talk more about QM, I struggled to find a balance between trying to support her, while at the same time tracking her authentic QM exploration process.

I was curious about her level of fear. In my journal I wrote, I wondered if her fear

might be related to her feeling of responsibility. Since she is a successful teacher and a successful mother of three, and with her personal characteristics she gives the impression of a responsible and trustworthy person. Taking the challenge of participating in this project perhaps requires letting go of fear, a healthy dose of self-confidence and risk taking. Alice articulated that she was scared, but she was still demonstrating elements of self-confidence in her learning process, by saying “everything is learnable if you go one step at a time.” According to her, there is nothing that cannot be learned if a step-by-step approach is taken.

Alice expressed that she felt overwhelmed at times, as she came to realize how much there was to learn. She mentioned that she was surprised at how many different concepts were involved in learning QM. Apart from the number of different concepts, for instance, each concept had its own challenges; the terminology, definitions that come up for each concept, the understanding of the experiment or the idea where those concepts emerge from, just to name a few.

Alice came to realize the extent of the challenge she took more and more throughout her QM learning process. However, once she found out the breadth of the content, she made a decision to spend more time in learning the variety of QM topics, rather than choosing to narrow the number of topics, which was a testament to her dedication to learning and her willingness to apply her mind to the challenge of learning these concepts. In doing so, she revealed her own growth mindset, which she earlier expressed that promoting growth mindset was important to her.

Alice is a teacher who aims to encourage critical thinking and higher order thinking skills in her students. She mentioned that previously, a few months ago, she taught her

students the concept of growth mindset as opposed to fixed mindset and talked about how to develop growth mindset. Her philosophy of teaching came up a number of times in our interviews. In one of the interviews, she had been talking about the importance of students being able to apply critical thinking. According to her, the students' future "...is not about just getting a job and buying a car, but being able to function in society—being able to be flexible." She refers to this trait as having a "growth mindset," by which she identifies in her own words "keeping the brain ready and adaptable for changes by being open to new ideas and new strategies." In a growth mindset (Dweck, 2000; 2006; Esparza et al., 2014; Shumow & Schmidt, 2013) she said that a person must be "open to new possibilities, keeping the brain open to radically different ideas." Alice was struck with how her own philosophy of having a growth mindset was so aligned with the concepts of QM. Alice seemed to appreciate the value of the conceptual and philosophical underpinnings of QM, when she mentioned that learning QM could actually help with development of a growth mindset.

**Learning process: Motivations.**

***The content.***

Alice was well aware that she took up a fairly big challenge by attempting to learn and teach the concepts of QM. Learning about the concepts of QM was a commitment for her not only to the research, but also to her students as well. Considering that she already maintained a busy schedule, the amount of work required to participate was notable. For instance, she explored eight different topics of QM in her learning process, namely: electromagnetic spectrum, black body radiation, dark matter, entanglement, the dual nature of light, quantum tunneling, superposition, and quantum teleportation. She

learned each topic through her handwritten notes in her learning process, starting with the historical emergence of these concepts, then a diagram or an illustration that she drew herself, then some facts and key words around the figure, and a list of the key features about the concept. In terms of the breadth of the content, in fact she went beyond my expectations, demonstrating that she enjoyed learning about the concepts of QM, and was willing to do the best for her students. I wrote in my journal “Alice is the best imaginable participant that I could have had. Her dedication to learning and to her students makes me proud to be a teacher.”

*Alice’s learning strategies.*

Alice believes that “learning is about feeling comfortable with the topic.” In our conversation Alice mentioned that starting from A and going to Z, one step at a time, has been the way in which she engages with a new topic. When engaging with a new topic, she likes to create a context for that specific topic, by studying for instance, the historical context of the topic—when it emerged, who studied it, and what doors it opened. She says with this strategy any topic would be easy to learn, because it contributes to the meaning-making of the concepts. She emphasizes the importance of establishing basic knowledge as a way of developing self-confidence and motivation to move forward.

Alice makes an analogy of learning a new topic with a journey by telling, “when I go on a journey, sometimes I like to explore on my own and sometimes I like to explore with other people.” In retrospect, she says she found it useful that in our first two meetings I made an introduction to the field of QM, so that she had a place to begin to her independent exploration. Later, when she had completed a section, she found it helpful to crosscheck her notes and findings with me.

Alice said that one of the things that helped her learning was sharing her process with another person to confirm the process and the level she has come, and receive guidance. She says, “learning futuristic topics require conversation and community.” According to her, conversation is crucial in the learning process, since “conversation leads to ownership of the ideas, and ownership leads to understanding the concept better.” I wrote in my journal that I had a similar experience as Alice, when I was learning QM by engaging in conversations with my classmates and professors, which created a form of grounding, enhancing my learning and providing a safe place to explore.

***Growth Mindset Attitude.***

Alice was struck with how her own philosophy of having a growth mindset was so aligned with the concepts of QM. In a growth mindset, she said that a person must be “open to new possibilities, keeping the brain open to radically different ideas.” In learning QM she said that learning QM could actually help with development of a growth mindset, revealing that she had seen the value of the conceptual and philosophical underpinnings of QM.

In introducing new topics to her students, Alice underlined that she always starts with the purpose of learning that topic. In her own learning experience, she realized that she also needed to keep her purpose in mind, which was to learn the concepts of QM for her teaching. By participating in this research she was not only preparing herself for the upcoming curriculum change, but also helping other teachers who will be facing similar challenges. Having this dual purpose created motivation in her learning process.

From my understanding, Alice likes to make connections between her experiences

gained in different fields. For instance, she pointed out resemblances between learning physical education with learning QM. Once she said that in introducing a new topic or a skill in her physical education class, it becomes more powerful when students use that skill in a game they learn.

According to her, this sense of familiarity is helpful in her learning process, and thus she started to pay more attention and interest to the QM concepts that come up in these contexts. She says that she is now “hooked on QM.” For her there is “no turning back,” and she says that she will follow up the on developments in QM even after she retires. I could see that the QM concepts were perceived as noticeably captivating, that they most likely have intrinsic value to her.

Alice is a naturally curious person, keen on learning different kind of subjects within or outside of her area, which motivated her to learn about the concepts of QM. When I asked her how does it feel knowing about QM, she says:

Oh, it feels good! But I like learning about a whole bunch of different things. It is not different in that way, because if I happen to learn more about a historical event or about . . . music, I am always appreciative of what I have learned. QM is definitely something in that realm. It is fun to have been exposed to it.

If a science teacher has already a personal interest in science, it seems that the motivations for learning the concepts of QM boiled down to three premises: having a purpose, getting familiar with the concepts through different mediums, and having the mindset that learning is fun.

### **The Domains of Teacher Knowledge**

In the proceeding section by following Shulman’s teacher knowledge framework, I

elaborate the domains of teacher knowledge that Alice demonstrated in her QM teaching practice including general pedagogy, content knowledge, teaching materials, and PCK.

**General pedagogy.**

General pedagogy refers to “what is known from how to teach” Shulman (1986, p. 6). In this regard, general pedagogy does not include the knowledge of content or teaching materials, but refers to actions and decisions that teachers take in relation to their students.

***Promoting conversation.***

According to Alice, cultivating a conversation throughout classes, asking questions and bouncing ideas off the class creates an effective teaching environment. Learning scientific concepts can be challenging at times, but that is part of the fun she explains. She adds that in teaching science, it is crucial for the teacher not to overwhelm students with facts or overloading knowledge in short time.

Alice is a teacher who promotes critical thinking and higher order thinking skills into her teaching. Her philosophy of teaching came up a number of times in our interviews. In one of them she had been talking about the importance of students being able to apply critical thinking. According to her, their future “...is not about just getting a job and buying a car, but being able to function in society—being able to be flexible.” She refers to this trait as having a “growth mindset,” by which she means in her own words “keeping the brain ready and adaptable for changes by being open to new ideas and new strategies.”

Alice is an innovative teacher, in that she has initiated science events adopting constructivist approaches, where students actively participated to the science activities

and enhanced their skills and knowledge in science. In her classes, Alice does not merely transmit facts and knowledge to students in a linear fashion, but rather adopts the role of a guide. For instance, she might introduce a new topic and then encourage her students to independently explore the topic, following their own interests for further discovery. For her, it is important to “send students home not only with answers, but also questions.” Alice explains this by acknowledging that in today’s technological world accessing factual information is easy for students, and no longer the responsibility of a teacher. Rather, in stimulating them to question and encouraging for further inquiry, she sees her role as a facilitator to foster students’ passion for learning.

***Building trust.***

Alice emphasized the importance of building trust with students in teaching from the beginning of new semester. She said that in order to be an effective science teacher, building relationships with student is essential, that “teachers need to know their students.” Alice pointed out that there might be a risk doing the QM teaching at the very beginning of the semester. According to Alice, the teachings of QM should wait until you know a bit about students’ characteristics and about the class dynamic. She continued, “Once you get to know your class dynamic, they will be able to focus on things more effectively.” Alice explained the value of teaching an unfamiliar topic at the end of the school year when the teacher is already caught up in the momentum of the school year, and confidence is high. Likewise, students have gelled as a class by this point and they have developed trust with their teacher. Alice stresses out the importance of this strategy especially when embarking on a new topic. This timing is also the added benefit of preparing the students with other topics, such as molecular structure in

chemistry, in order to provide some groundwork for QM.

This aspect of her teaching aligns with one of the key domains of teacher knowledge, namely student characteristics, that was initially proposed by Shulman (1986, 1987). While building trust might be viewed as one quality of this domain, it includes teacher's knowledge of and about students. From her experience, even if a student does not understand a concept, if they have faith in the teacher they will still do the work, at the very least they would memorize the content. She gives her students the message "if you follow me, you take a chance of knowing something and having fun along the way. Maybe the journey can be challenging, but it could be interesting." She said, learning requires so much effort on the students' end, but with trust "they will make an effort to learn, lean forward, and try to be absorbing new information—if they trust that the person in front is a good a person and a good shepherd." Alice pays attention to her students from the beginning of the semester and she says that building trust with students is the main hook for effective teaching. Alice stressed that by building trusting sincere relationship with students teachers can create an equal and transparent dialogue in the classroom, which will help students to open up to unimagined possibilities, and teachers would be able to make their vulnerability explicit without loosing respect.

Alice also emphasizes teachers' self-confidence in teaching as an essential aspect, particularly teaching abstract and counter-intuitive notions. She says,

Most of the things we teach—they sort of make sense for the teacher—but for some of the students maybe not. We try and explain as well as we can. For some subjects this is easier because as teachers we feel comfortable with the subject.

Alice adds that students need to have faith in their teachers because as teachers "we

look like we know what we are doing.” The teacher’s confidence and the trust between students and teacher become even more important especially when learning counter-intuitive subjects. She continues “as a teacher, I have had experience many times about certain topics and I am hoping that this will happen again with QM.”

Even though teaching QM can be challenging due to its unfamiliar framework, Alice believes that maintaining a positive trust relationship between students and teachers contributes to an effective teaching experience for both teacher and students.

### ***Taking notes.***

In the classroom, Alice encourages her students to take notes. The worksheets she created provide a place for students to verbalize their own understanding of the subjects. Alice says, “When they write and take notes they will have time to process the information a bit more, coloured pencils and crayons can help too.” Alice is encouraging the students to engage with the material, so that by taking notes students have to decide what is important enough to write down. Taking notes according to her creates personal learning opportunities for students.

### ***Executing teaching materials.***

In terms of using media and teaching materials Alice makes the materials accessible, age-appropriate and fun. She prefers visually dominant videos both in her own learning and in teaching. As she planned in her lesson plans, explanations of some theoretical knowledge was enhanced with visuals in all the classes. Her use of video materials appeared to be effective in helping students to understand the concepts and as she explains, “It is important to mention every part of the video right away, otherwise the students would be lost. According to her, a teacher can always pause the video and have

a discussion saying, “Hey, does everybody see this? How interesting that is!” This strategy seems to help the students to follow the video and understand the subjects presented.

***General pedagogical approach in introducing a new subject.***

In terms of a general pedagogical approach in introducing a new topic, Alice aims to talk about the concepts in general, beginning with teaching general concepts and moving towards specific concepts. She said that a bottom up approach works better for effective classes at the middle school level, unlike universities where the class sizes are much bigger and a top down approach is followed. She added, “I would like to provide some keywords and resources, so that when looking at the additional video resources, the students will be able to say, “Okay, I have heard this word.” For her, the idea was to be sure that the students will later be able to identify the concept by remembering the video. This approach provided a platform for the students to get familiar with the concepts of QM on their own, and then Alice elaborated the concepts of QM in the classroom.

As discussed earlier in the review of the literature, the variation theory is an effective approach in learning. In her teaching, Alice did not explicitly utilize the variation theory as in making two columns and listing the differences between classical physics and QM either in her worksheet or throughout her in-class practice. However, she did make contrasts and comparisons in class. For instance, she emphasized that QM involves the micro-scale world, whereas classical mechanics involves the macro-scale world, which sets an example of the variation theory. She also stressed the word *counter-intuitive* for the concepts of QM, which is inherently a practice of the variation theory,

since a contrast is embedded in the word itself. Therefore, the variation theory was implicitly used by Alice in the development of her PCK in QM.

As introducing a new topic could be a challenge for any school topic, it may require more care and consideration. At times teaching a new topic could be both exciting and anxiety-provoking for both teachers and students. She said:

before the class I was quite nervous, more nervous, let's say, than normal because it was a new topic, but at the same time it was a good time of the year (June), because I had had the whole year to build relationships with the students.

Alice mentioned that teaching a new subject is “humbling” in that it “breaks down the big familiarity gap” between the teacher and students in terms of knowledge, and makes the teacher “equal with students.” This impact is more evident when teaching QM because Alice was no different than any student in her class a month ago. She clearly demonstrated a sense of humility giving the message that “this topic is also new for me” or “I started learning about QM just recently,” mentioning it a few times in her classes.

Alice emphasized the perspective that helped her throughout her teaching practice, commenting that, “there is no need for embarrassment for the teacher if the teacher cannot come up with an answer.” This is because, she had not previously been required to learn QM earlier in her pre-service science teacher education, and she recognized that there are many unanswered questions in the field of QM. At times there is no certain explanation to why a QM phenomenon is happening, such as entanglement, as the field is still evolving. She said this evolving nature of QM meant that she did not have to have all the answers for everything, which created “relief” for her as a teacher. She also added that the nature of QM “leaves room for discovery” which makes her teaching “cool” for

her and her students. She expressed and demonstrated in her teaching experience that she enjoys the dynamic nature of exploring QM through discussion with her students rather than having to be an authority on the subject. She says:

A teacher like me who is just been exposed to this, I am just trying to figure out. You need to be a little bit trusting in what is around us, and what other people think. It is a leap of faith into something new. But it is not damaging, it is out there and it is available. The big thing is making sure that students are not turned off and they are excited about this, they keep their minds open.

Alice mentioned that for a teacher learning and effectively teaching a new subject depends on the teacher's determination and willingness. She said, "Some teachers may say I cannot invest the time and energy in new subjects. I do not quite believe them. They put hurdles in front of themselves." Alice proved that if a teacher truly wants to learn and teach a new subject, despite the challenges the teacher would invest time and effort in it.

According to Alice there must be a balance between providing content knowledge and having fun in learning by using appropriate pedagogies. She said, "It is always a balance of presenting enough to make it is "like, wow this is part of science that is worth respect and there is a lot of learning that can be done and it is revolutionary!" Alice thinks that the revolutionary aspect of QM would be the fun part for her students. According to her making learning fun promotes effective learning helping students to internalize the information, so that they retain the concepts. Although Alice emphasized the importance of fun in her science classes, this element was neither the focus, nor fully present in her actual practice.

Throughout the interviews Alice was transparent and willing to share all aspects of engaging in a new subject, even when asked about her emotions. She expressed frankly that at some point she was scared about teaching QM:

For us —with students or myself or the general public— it is nice to say, "Here, the curtain is open. You can have a peek behind the scene and see these people working on cutting edge science." Then you get a bit scared, and wait for the show to happen. Or you could watch surgeons who work with fancy tools. If you are not in the field it could be frightening, but at the same time everybody is happy that some people are working on that sort of cutting edge science and going beyond what we already know. It is the same with the quantum model and the advancements in QM.

Alice explained her feelings of fear by referring to standing behind the stage curtain and having to present a cutting edge science. Listening to her, I wondered if it was the nature of unknown territory and the notion of unfamiliarity that was frightening. I also wondered why she said that we enjoy the outcome of science, but do not want to engage with it behind the stage curtain. Is it because anything unknown can happen behind the curtain, and it is safer to stay on this side of the curtain? Does the challenge of science come from willing to stay in the comfort zone?

Alice said science is perceived to be difficult, challenging and requiring relatively more time in order to feel confident about it. These might also be the common perceptions of science engrained in society, that science might be intimidating and viewed as being out of the comfort zone; and thus, it would be better to stay on the front side of the curtain and just watch the scientific performances taking place on the stage from safe, comfortable chairs. I noticed the alienation of science and scientists in her

analogy, which I also witnessed as an articulated perception of science in general public.

Then I asked Alice why she took this scary challenge and what made her to overcome this challenge, was that her age and thirty years of experience in teaching? She said:

No, it is not age. Sometimes it is about trusting yourself, trusting your students that they will appreciate it. The trust in you as a teacher is needed when you are going to be teaching something that is not, like you say, as straightforward as other subjects.

I am known to be a kind of a risk-taker.

Alice is definitely a risk-taker. She had a history of embarking on, initiating, and accomplishing innovative projects for students in different fields, such as science fairs and a particularly innovative project that involved dancing and acrobatics. In discussion with Alice, I acknowledged that she had bravely jumped into a totally new subject with the courage to teach it. She replied “I would not do it without a parachute” referring to her conversations with me. We laughed and I concluded that hopefully the insights coming from her experience would serve as a parachute for other teachers as they learn and teach the concepts of QM. Since I cannot be available as a parachute for all the other Grade 8 science teachers, Alice’s comment might point to the need for other types of parachutes, such as professional development programs, updated textbooks, and access to web-based support.

#### **Teacher’s role as a facilitator.**

Alice acknowledged that her responsibility as a teacher is to use contemporary constructivist approaches to guide her students as mandated in the redesigned curriculum. She said that she did not have to know everything about a topic in order to teach it. She said:

You as a teacher do a bit of bushwhacking. You go and explore the unknown, as well as making the students believe that the subject is important and relevant. As a teacher I do not need to know all the details, but the students need to know that it is there.

Other teachers approach Alice and want to talk about teaching either of her fields—science and physical education—in order to understand how she has become so good in teaching. For instance, when asked how to teach volleyball the way Alice does, she tells them that they do not have to teach it the way she does; however, she recommended them to introduce the general idea of a new topics briefly and let students play a bit. Alice used the words fun and play often, revealing her attitude towards science, which conveys to the students igniting their curiosity and interest. Having an adequate content knowledge is also important for her, but if a teacher does not master the content knowledge for a topic, this should not stop the teacher to completely abandon that subject matter. She told the teachers that even if they do not know the subject well, they can teach some other aspects of the subject they know—a skill, a game—and the students will follow, because according to Alice, students will know that whether the teacher likes the subject or not, and when a teacher likes the subject students will trust that the teacher will teach it correctly. Alice said the same thing goes for science. She continued as a suggestion to other teachers:

If a teacher says, “I cannot teach electromagnetism because I know that I do not know it,” I would suggest to understand and master some of the topics, just go for it. You do not have to call it science, but just let the students have fun, so that the students may associate the word science with something fun. But do not ignore

science because you think you are not good enough in it. Just make sure you are going step by step. Plan a few lessons that are really good and fun.

The findings show that the general pedagogical approach that Alice follows contributes to an effective learning environment. The main aspects of her pedagogical approach can be summarized as: building trusting relationships with the students, developing self-confidence as a teacher, promoting engaging conversation for exchanging ideas, following a bottom up approach by introducing the key terminology for the topic, promoting critical thinking, and sparking interest for further learning. While there are certainly other general pedagogical approaches that can be effective, Alice's pedagogical framework offers a platform for her on which to build strategic approaches specific to the content knowledge of the subject. In the writing that follows, I provide the content knowledge she developed in QM, and consequently how she developed PCK in QM in her teaching practice. Alice likes to use analogies and metaphors in describing her experience, according to her, teaching "should be like serving delicious food" and she said, "You do not want to leave your students with a bad taste."

### **Content Knowledge**

In terms of content knowledge Alice did not have any prior knowledge in QM. After exploring the concepts of QM, Alice said that she was surprised at how incomplete that her views of science had been. Alice believes that the challenge in teaching QM is that in the past, the science curriculum has not offered a complete representation of the field of science. She says that the whole content of the past science curriculum was fact-based and rational, while QM is counter-intuitive and requires imagination to grasp the concepts. Alice explains that teaching students fact-based science throughout elementary

and middle school and then all of a sudden trying to inspire them to open their minds for conceptual understanding of QM seems “contradictory.” She says gradually introducing the general ideas of QM starting at younger ages would prepare students for a more accessible QM lessons in Grade 8 classes.

*Choice of topics.*

When preparing her lesson plan Alice developed a general framework of the main concepts of QM. The choice of what topics would be covered in her classes was her own. She said “I am still at that stage where I am still feeling my way in here;” however, the choice of topics seemed significant in terms of representing the field of QM and potentially engaging for students, and I supported her with her choice of topics. Her lesson plan covered the following QM topics, introducing some of the key concepts of QM: the fundamental particles, electron microscopy, scaling, electromagnetic light spectrum, dark matter, dark energy, black body radiation, photoelectric effect, entanglement, quantum tunneling, quantum computing, superposition, quantum leap and implications of QM.

Alice taught her classes following the worksheet she prepared introducing the concept of QM by explaining the words quantum and mechanics separately. The details of this worksheet will be elaborated in the teaching material section. Interestingly, even though quantum atom model is a fundamental and introductory concept of QM, Alice did not teach the quantum atom model in her QM teaching. When I asked the reason, she said she already taught her students the Bohr atom model and did not want to confuse them. She said:

The Bohr atom model is the most common atom model and the one I am familiar with. Of course students come up with questions “If these protons are all positively charged, how do they hold together? So now after learning about the strong force in QM, I can answer them.”

As she was showing me her learning notes, she pointed out the sub-atomic particles table saying that “Higgs boson is missing on this table, this must be an old image.” As the Higgs boson was discovered just a few years ago, she demonstrated her content knowledge by recognizing the fact that the table she found online was relatively an old one.

***Order of topics.***

When introducing the content knowledge of a new topic, Alice stressed the importance of going step by step and pacing the class. Alice started her QM teaching with the key words of the concepts and the terminology. She explained that having language for the new topic makes it easier for students to engage. After introducing the key words, she said key concepts could be introduced such as fundamental particles and fundamental forces. She was able to successfully create a gradual progression of concepts that lead to understanding of specific topics of QM. For instance, when students wanted to know about neutrino, she replied that it would be better to teach the fundamental concepts first. She explained “before you go and run a marathon you need to make sure you can run the 10k first.”

Alice thinks that students should first know about atoms. Then they should learn about electrons, neutrons, and protons and how the change in the number of these particles would create different atoms. After the students have this basic knowledge,

Alice mentioned that it would be fun to say to her students “Hey you know what? We thought that the smallest part of an atom was these particles, now we know that there are smaller particles that make up protons and neutrons, and also even smaller particles that create the force to hold the nucleus together.” Therefore, her way of introducing content knowledge can be viewed as starting from bigger particles such as atoms and then proceeding to the smaller sub-atomic particles, first electrons, protons, and neutrons and then quarks and force carrier particles such as gluons.

### **PCK in QM**

As Shulman proposed, PCK is a special blend of teacher knowledge including the domains of pedagogical and content knowledge. All subject content is related to the ways that specific content can be taught. As QM is a new topic, not only for Grade 8 students, but also for their teachers, the generation and development of PCK has not taken place yet. In the following section I elaborate on the action and dialogue that Alice created in the development of PCK in QM.

Alice had already announced that she would be starting to teach QM classes three weeks in advance, and kept reminding the students of this, so in the first QM class the students were prepared to learn something new. In the first lessons in all three classes, Alice introduced me to the students and talked briefly about my research. In the beginning, as a class they talked about QM and Alice asked them if they had heard of it before. For most of the students QM was a new subject, with only a few students in each class having heard of the words quantum and mechanics together.

Alice says that exposing students to basic concepts may create a perception that students would feel that they know more than they actually do, which has a positive

effect. She adds that students now have not only a sense of familiarity, but also eagerness and confidence that they can learn more about these concepts when they encounter QM concepts in different contexts.

### **Introducing QM as an event.**

Alice lays a foundation first when she begins to teach a new topic. For instance, she wrote on the board in the classroom announcing that they would do QM a month in advance, and she made it sound like an event for students. Then she updated the message every week until the QM classes in order to build a growing sense of excitement and mental preparation. Alice recommended other teachers this technique of presenting the QM classes as if it were an anticipated event.

Alice emphasized the importance of explaining the purpose of learning the concepts of QM. According to her the benefit of this approach is to create motivation for learning. She told her students that the purpose of the QM event was to explore a new branch of science, which provides the underlying technology in our lives, such as smart phones, computers, MRI machines, and telescopes. She said after learning the concepts of QM, the students will have a much broader understanding in technological conversations and what they encounter in science fiction movies.

Two days before the first QM class she advised her students to look at the video resources in the teaching material she prepared. In an interview before her teaching practice she explained:

The students need a base. I have got a couple of videos in mind. I plan to tell the students that “I will explain the video later, just have a look at it and try to see

how much you get out of it. Then later on we will come back and see it in more detail. This gives them time to reflect a bit.”

Encouraging students to explore on their own and then letting them to share their experience in the class promoted student-centered pedagogies and most likely enhanced the student understanding in the concepts of QM.

***Critical thinking.***

Alice emphasized the significance and value of encouraging students to expand their imagination and open their minds. After her learning experience, Alice believes that QM would help students to see things differently and open their minds to the concepts beyond their perception. Alice said, “One of the goals that teachers need to accomplish is thinking outside the box and QM is a suitable topic to do that.” She continued, “What I really liked about QM is the fact that the students will try to explain things that would not be explained without thinking outside the box.” Alice believes that learning and wrestling with the concepts of QM would enable students to be the critical thinkers that Alice and the Ministry of Education want them to be, and what society will need them to be.

According to Alice, in learning QM students need to engage with “imaginative ways of thinking”, “be open to counter-intuitive ideas” and “recognize that at times QM offers more questions than answers.” When I asked Alice how she found her QM teaching experience, she said, “introducing QM was like opening a window” for her students. In continuing the conversation, she elucidated what she meant; according to her, opening a window refers to critical thinking and developing a growth mindset. She taught the concept of ‘growth mindset’ in her science classes earlier, and she expressed

that one of the requirements to learn about QM is having an open mind to embrace a different reality, and this relates to the concept of growth mindset.

***Self-evaluation.***

I asked Alice what would she like to do differently in her next QM teaching practice. She brought up three points: first, she would like to devote more time to learning and teaching QM. Secondly, she is eager to incorporate some hands-on activities and have students work in groups, starting with the double slit experiment in order to demonstrate the dual nature of light. Although Alice thought that perhaps her school had the materials necessary for the experiment, even if they did not have, it would be relatively easy and inexpensive to acquire (a laser pointer, a marker, a razor, and a small glass plate). Thirdly, she would like her students to do their own research about QM before the classes and share their own QM learning experience in the class, because she saw from her own experience how valuable it is to do some independent research and then share what is found with other students in the class.

Alice prepared two lesson plans in QM, in the first day covering the key concepts of QM, in the second day focusing on the dual nature of light. She has three science classes for this semester; consequently, she practiced six QM lessons in total. With the very first class, Alice realized that she did not have enough time to cover all the content she has prepared. We had a brief conversation in the recess, and she decided to eliminate the topics of dark matter and photoelectric effect from her lesson plan for the next two classes of the day.

Alice also explained that longer classroom time for QM would have allowed her to stop the videos and deliberate on the topic, cover more content, promote more and deeper

conversations, and make the class more interactive. She said that four hours would be an appropriate time to cover the topics she prepared for her classes. She said as a recommendation for future practices that it would be helpful to have prioritized topics beforehand in case time becomes short.

In summarizing her experience of teaching QM she seems to feel satisfied with her teaching. While recognizing that QM does require calculus, her teachings demonstrated that a conceptual form of QM can be taught much earlier in education than she had thought. She said that the feeling of having done a good job teaching these concepts motivated her to try again and she has already begun to think about how she can improve her teaching.

***Terminology.***

Alice is very careful in choosing the right words to introduce the concepts of QM in her teaching practice and feels responsible with every word she uses.

I have to be careful about explaining QM and electromagnetic waves, because I do not want to mislead them into something that is not quite right. I have to make sure I am providing the right info, because those sharp kids will memorize what I say.

Alice believes that before introducing a new subject, it is important to provide the key terms that will be used. In this case she started the student's worksheet with definitions of the following: quantum, mechanics, sub-atomic particle, force. The students later said that they had found starting with the terminology helpful.

One particularly motivating strategy that Alice had used in one of her previous science classes was where she had shown a video of a three-year-old girl who could name

all the elements in the periodic table and where those elements were used. This girl was invited to talk shows. Her goal in showing this video had been to make students realize that they even small children can learn about science. When choosing the QM teaching materials, she chose a video that used the voice of a young girl talking explaining QM. Later in our interview, it came up that this was Alice's way of trying to break down the stereotype that science is for older people and particularly for boys and men. Since gender issues are outside of the scope of this study, and it was only mentioned once, I did not further explore this topic with Alice, but suffice it to say that she seemed to take gender issues a given.

*Historical aspects of the content knowledge.*

Throughout her QM learning process and in her teaching, Alice expressed consistent interest in history of science and engaging with scientific concepts starting from their origins. For instance, Alice shows that she researched the emergence of the field of QM. She shows that she has a good grasp of QM history as she says "starting in the late 1900s and there are a few main physicists like Planck. It seems that we keep coming back to Planck." Planck really is viewed as the father of QM, and as we were talking about Planck, I noted that she also recognizes Planck's contributions to the field of QM.

In her science teaching in general, Alice advocates gradual step-by-step learning of science, particularly beginning with providing the historical development of the topic. Alice says:

It is always nice to provide a little bit of background. You can see how things have evolved over time. That tells if it has evolved once, then it means it will

evolve again. The history of science is showing the development of science over time and this timeline is interesting for me.

She explains the emergence of QM as “the idea why QM came out was because they tried to explain some phenomenon that cannot be explained with classical physics”. She continues, “the way we think is black or white, yes or no, zero or one, but there is more to it. More solutions can be added onto one another like in superposition” by demonstrating an appropriate understanding of the foundations of QM.

Alice made a comparison between teaching school subjects such as geometry, literature, art and QM. She said that the nature and teaching of QM is like art and literature, in the way that they all may evolve, change over time unlike math and geometry. She also made a comparison between teaching strategies for the subjects: literature, art and QM. She said that all literature, art and QM offer some foundational technique and then leave the rest for imagination and creativity.

In order to emphasize the importance and relevance of QM, Alice pointed out that we have technology today that people could not even have imagined only a few decades ago. She said “you know that a few years ago iPads, Skype, smartphones did not exist, QM is the upcoming new science, so why not learn more about QM?” Then she explained, in doing so the students would be able to fantasize that strange phenomena such as teleportation is just science fiction, but could potentially occur in real life, which is very stimulating for their imaginations. She says to her students “QM concepts are not trivial, they are important in everyday life.”

Alice explained her learning experience, humbly mentioning that she had no prior knowledge about these QM concepts and she shared her vulnerability in learning a new

subject as a teacher. From my observation in the class, she demonstrated for her students that it was good to take on the challenge of learning something new. In my journal I noted two examples of how her tone and attitude with her students was very friendly and down to earth. The first example was the way she presented herself as a co-learner with her students in exploring the topics of QM, which positively contributed to two domains of teacher knowledge: general pedagogy and student knowledge. In that, as she stated she came to understand what would work out the best for her students to enhance their learning, and cultivating a sincere, friendly and humble tone has been effective in improving the learning environment. The second example was that she kindly gave me credit for the support I had provided throughout her QM learning and lesson plan development process. In doing so, she modeled her own enthusiasm for engaging in a new topic, and set an appropriate example as a role-model for her students.

***Using analogies and metaphors.***

In terms of introducing the concepts of QM to middle school students, Alice stressed the importance of using metaphors, as she said, “until we find models or metaphors to explain it or see the effect of it, it is going to be hard for someone to grasp it.” She recommended that “scaling is a good way to teach the concepts of QM: the length of a building, grain of sugar, bacteria, molecule, atom, nucleus, and quarks.” Alice also added “it is important to create awareness that QM is everywhere, such as photosynthesis, and most of the electronic devices. She suggested to other teachers to “make QM obvious that it is all around us.” Alice believed that this approach would create interest and curiosity in the classroom. She continued, “I told students that microwaves, infrared rays, UV rays, radio waves are all around us and are made of

quantum particles. For instance, cellphones use one area of the EM spectrum, so, when we talk on a cellphone we are using EM waves and cellphone EM spectrum does not have nearly as much energy as a X-ray EM waves.” Alice thinks making the invisible parts of QM explicit by emphasizing its effects would enable effective teaching.

We can see the visible light, which is a very small part of the EM spectrum, but we cannot see other waves, but we feel or see the effect of the other rays. For instance, microwaves can cook meals, thermal waves make us warm, radio waves make radios work. I do not think it is hard to teach that there are EM waves and quantum particles around us, because if we can see the effect, although it is invisible it is not hard to believe.

In preparing lesson plans Alice found an image online that shows the importance of perspective in terms of defining the truth. For example, in an example of a cylinder, depending on where the light source is directed, the shadow will be either a rectangle or a circle. Alice says that the point in introducing this example is to refer to the dual nature of light and say “before you judge or assume something make sure you take the time to look at it from different angles.” She used this cylinder example on her worksheet as a way of introducing the idea to the students that the same thing can be perceived in two different ways, just like the dual nature of light as both particle and wave.

While Alice was showing the video clip on the dual nature of light, she was able to stop the video and check in with the class by asking questions. For instance, at one point she asked, “How does the electron behave?” She pointed out to the students and said, “The electron splits into two and then after going through the double slit it appears

to combine with itself.” She created wonder when she said, “Look, it appears to have a mind of its own when it was observed”.

When talking about quantum tunneling, which implies that a subatomic particle can go through a barrier, Alice asked the question to the class “How can we picture a ball going through the walls? From my understanding, when the students showed disbelief that this cannot be possible, they were starting to understand the QM concepts. This form of disbelief served also to further engage their interest. Alice emphasized that the reality of sub-atomic particles is different than the reality we perceive, and thus she highlighted the counter-intuitiveness of QM concepts to the class. In her teaching, the way Alice presented the concepts of QM as if they were part of an exciting, gradually unfolding story. From my observation Alice was able to kindle interest in her students in all three classes.

***Creating interest and making QM relevant.***

As a science teacher, Alice’s general pedagogical approach is to relate science topics to everyday life, so that the topics would be more appealing for the students. She said, “creating familiarity with the subjects is important, so that the students will not feel remote from it and they will be able to follow the philosophy behind it.” Alice believes that learning is not about being smart, it is about being interested, and thus it is the teacher’s responsibility to awaken students’ interest in science. If a topic is of interest for a student, then the topic would most likely not be perceived as difficult. When creating lesson plans she said:

In my notes, I went back to see if they could relate QM to some of the things in their everyday life. The minute they cannot connect with their personal life, it is

not going to work. There always needs to be a balance between practice and theory. They should be wowed about the topic and not sick of the theoretical part of it.

Alice believes in the power of providing her students with the purpose of learning a subject. She said that the “why should I learn QM?” question is an important question, and answers herself as saying because it is relevant and opens up new perspectives in understanding the world. She continued “also we need the understanding of QM, since QM is going to be in our everyday conversation not far from now, making those connections and preparing them for the future is important.” Before introducing a new topic, providing the purpose for the new topic will make it relevant and might create a motivation to engage with the new topic.

Alice felt some relief to know that QM concepts appear in social media so that students might be exposed to these ideas outside the school, and that teaching these concepts would not be solely her responsibility, in that she could teach the concepts at an introductory level to make students familiar with the concepts knowing that over time students can easily access more information through the internet or popular media. For instance, she pointed out the QM concepts that appear in media and science fiction movies, so that her students, after learning QM concepts would have a more informed position from which to think about and discuss these movies.

As mentioned above, Alice puts the time and effort into getting to know her students throughout the year; therefore she has a good idea about what her students would enjoy learning. She said “Most of the students will really enjoy this part about the quarks

in the protons and neutrons. I will try to keep it quite simple.” Alice created her PCK in QM by focusing on students’ interest areas and keeping it age-appropriate.

Alice has found that students are more engaged when the material is not intuitive. She says that “students become passionate when things are counter-intuitive” as that leads to disruption of their pre-conception of science making sense. It is mind-opening for students when, for the first time, reality no longer makes sense—a natural consequence of learning the concepts of QM. Alice mentioned that engaging with counter-intuitive concepts creates a playful perception of science.

One way that Alice made the QM topics interesting and relevant was scaling. She told the students:

Now with the new science (QM), we will be able to go into what we call subatomic. Now we are going to go into the atom. The atom was indivisible and was the smallest part we could think of. Now we are going inside it. It is kind of interesting for people like us who like big things. . . . Prepare yourself guys, in my generation, we only knew about protons and neutrons, in your generation you are going to learn what is inside them.

In my journal entry I wrote, “By making a comment like this, she not only makes an introduction to the topic, but also sparks curiosity and anticipation for what they are about to learn.”

Alice thinks that in order to convey the content knowledge of the dual nature of light, the pedagogical approach should be complementary, which means making abstract notions concrete by providing some hands-on materials. She said:

it is always nice to have something physical in your hands, showing that the light particles can be at several places at the same time. A wave is everywhere, but it is not a single object. I told the students that later on, we would see this weird thing in an important experiment, called the double slit experiment.

Although she believes in the importance of using hands-on activities in her science classes, she did not create any hands-on activities in her QM teaching. One of the key points for developing effective PCK in science topics is making the concepts accessible and age-appropriate. When looking into QM materials in her learning process, Alice was also looking for the right materials to include in her lesson plan. Alice said, “I was also looking at the content from a 13 year old perspective. Where will it be catchy? Where was it short enough but with enough information to create interest?”

Alice added that as a teacher it is important to introduce a variety of key scientific concepts at an early age in order to create “familiarity and comfort” with particular science topics; and thus, for instance, electives such as physics, chemistry and biology would be considered “natural” and “not difficult or complicated” for students any longer. She believes that her teaching practice will make a difference in students’ perception of QM; and consequently would create a sense of familiarity and comfort for students in engaging with these topics later in their schooling or everyday life.

### ***Misconceptions through developing PCK in QM.***

Whenever a new subject of study is undertaken, there is potential that the teacher will have misconceptions, and QM can be particularly tricky. For instance, the dual nature of light in QM refers to light being both a particle and a wave at the same time. Alice, despite her understanding of the topic throughout her learning process, explained

to her students in her second class that the dual nature of light was a particle “or” wave, as if light behaves like a particle and then like a wave depending on the circumstances. At that point, one of the students, who already had a personal interest and prior knowledge in QM, cleverly corrected her misconception saying that the particles can be both particle “and” wave, not particle “or” wave. A thing inhabiting two contrasting natures at the same time may be a difficult concept to grasp; it is like saying fire is fire and water at the same time. One of the challenges in teaching QM is that there is no real life analogy or examples available to promote QM understanding, thus comprehending the concepts of QM requires creative imagination.

Alice was proud and amused that the student provided an accurate answer, and afterwards she was able to laugh about it in our interview. She referred to the boy’s comment saying, “I am sure inside he was pretty happy about it. He was right, the light is both particle and wave.” This incident perhaps also points to Alice’s underlying pedagogy that nurtures relationship, valuing trust and mutual learning between teacher and student. In terms of teacher knowledge components this might refer to the knowledge of student characteristics and general pedagogy demonstrating that the teacher can be, not only non-defensive, but rather excited when a student points out her mistake. Another instance of effective pedagogy occurred after the second session of teaching when a student brought a book about Schrodinger’s cat and told Alice that she should take a look at it. The book was about an inter-galactic trip. Alice responded by having a look at the book online since her student suggested it, reinforcing the students independent learning and enthusiasm about the subject.

*Alice’s favourite QM topics to teach.*

Alice found the electromagnetic spectrum of light as the most interesting and engaging topic. She expressed her enthusiasm by saying that “the visible and invisible light part was big for me, after I read this I think I understand this better now than 30 years ago. The impact of the invisible electromagnetic spectrum matters as much as what is visible. I thought that was quite the revelation. This is one of the things, that hopefully the students will remember.” She also mentioned that she enjoyed learning about the Schrodinger’s cat thought experiment.

***Students’ input through conversation.***

Alice taught two QM lessons to three different Grade 8 classes. After the two QM lessons, Alice did another session with her students to talk about students’ perception in QM. She asked questions, such as “What parts of the QM classes were most memorable and interesting?” “When would be a good time to start learning about the concepts of QM?” The students in all her three classes remembered the dual nature of light part very well, perhaps indicating that the PCK she developed for the dual nature of light was effective. That was also the sense I have gotten during her teaching. Students’ feedback demonstrated that they liked the topics of QM, such as teleportation, the dual nature of light, superposition, and entanglement. This might refer that by the number of QM topics mentioned, in general QM was well received by the students, finding it fun, interesting and exciting.

There were some eager students in all three of Alice’s classes who had prior knowledge of QM. When Alice asked for feedback, some students mentioned that the table of the subatomic particles was the most important part of QM classes. One of the students who had prior knowledge in QM said that they should have learned more about

neutrino, others disagreed saying that it had been good to learn the basic concepts as taught by Alice.

In one of the QM classes, a student who apparently up to this point had minimal interest in science became actively involved in the class, raising a question and also staying after the class to ask Alice another question. Alice commented that this had never happened before. She speculated the reason might be that the student was failing to keep up with her peers in her science and math classes, but when it came to learning QM, for the first time everybody had the same background and started from the same level of knowledge, since it was new to everyone. Alice wondered if being in the same position as the other students might have given her some confidence and motivation to participate in the class. The sense of participation and success carried on for this particular student after the QM class, and the next week, she prepared for the biology class for the first time by memorizing the dissection parts. After the first QM teaching class, another student brought a book about QM to show Alice. As well as these individual conversations there were about five to ten students who stayed after the class to engage in further conversation with Alice and I, asking questions and also listening to other students. This might suggest that students were captivated by the topics of QM and that their interest had been sparked enough to stay and forego their recess time.

In the feedback session Alice also asked students if they thought that they should be pushed to learn more in science classes. The students were in agreement that they enjoyed engaging new topics and the concepts of QM could start being taught as early as Grade 3. The students' argument was that if they were introduced to the QM concepts earlier, they would be more familiar to the terminology and counter-intuitive aspect of

QM and be more prepared to go into depth by Grade 8.

It seems to me that sharing the teacher's own excitement for the subject has a potential to create further interest from students, leading to engaging discussions. In my journal, I wrote "I am very impressed by the excitement of the students who came by and asked their burning questions after the class." Alice comments about the students during her teaching practice:

The students were open to it. They were open to learning more about it, and I did not see anybody's face like, "When is this over, do we have to suffer through this?" They were playing along with it, taking a chance that it could be fun. They are learning something that their parents do not know about and the older generation does not know much about. They were cooperative and calm, but enthusiastic at the same time, behaving well. Some of them were asking more questions, and volunteering to answer the questions. You could tell that for those students, it was like . . . I do not know, a step toward their future studies. I know that is really what they are passionate about, something that is not intuitive like other science topics.

After the feedback session, Alice said, "the feedback I have heard today was pretty close to what I was expecting. I know them well enough now." After I asked about the highlight of her teaching experience, she said, "just to see that some of those students who have a spark in their eyes. You know that they could make a difference to our future because of that." She added that she is enthusiastic and committed to teaching QM for the rest of her career.

At the end of the school year, Alice included six QM questions in the final multiple-choice exam. The choice of topics for the questions in the QM exam were

determined by Alice. Her criteria for the QM exam questions were expressed by her as “Topics that the students could follow. They took their notes during the QM classes and studied.” She predicted that the students would do quite well, as the questions were based on fundamental understanding of QM. This prediction may also have come from the quality of class discussions and the enthusiasm shown by the students.

### **Teaching Materials**

In her teaching practice Alice used multiple sources of teaching materials, most of which she found in her own learning process. She evaluated each source to see if it was age appropriate for her students based on her teaching experience and eventually utilized teaching materials such as Wikipedia images and figures, YouTube videos, along with her own drawings on the blackboard.

Alice created QM worksheets entitled Introduction to Quantum Mechanics (see Appendix E) for students to follow throughout the course, along with the recommended age appropriate educational video sources at the bottom. The worksheet includes four sections, where she taught the sections A, B, and C in her first class, then the section D in the subsequent class. Section A covers the key terminology to proceed to the teachings of QM including three examples of quantum phenomenon such as dark matter, photoelectric effect and electromagnetic spectrum. Section B is devoted to the history of physics, history of QM and also the implications of QM in everyday world. Section C focuses on the atomic and sub-atomic particle and fundamental forces. Section D is devoted to the dual nature of light along with seven resources of video material.

Alice’s execution of the worksheet differed in terms of her pedagogy from the first session to the second. In the first lesson (once with each of three classes) Alice followed

her worksheet line by line, copying her notes almost word by word to the projector. The pedagogy she used almost resembled a traditional approach, where the teacher conveys knowledge following a one-size fits all method. However, when she included some visual materials and promoted a conversation with her questions, it seemed that she was departing from traditional pedagogies. In the second sessions of QM, in all three of her classes she seemed more relaxed and confident with the topics, moving around the room, engaging in intriguing conversations with the students, demonstrating a more inter-active classroom management. I speculated in my journal about this change, wondering if her increased comfort and confidence was related to her success in her first class. It appeared to me that using traditional methods built a foundation in the first sessions of QM that created the confidence for her to use a more flexible and interactive pedagogy. By the time the second classes took place, I had been in her first three classes and I wondered if that might also have contributed to her sense of ease in teaching. Additionally, I speculated that since I was not a stranger for the students any longer, it may have allowed them to act more authentic and less self-conscious.

The worksheet in the Appendix E includes Alice's own notes to follow during the class. She filled all the blank parts left for students with her answers. Alice commented that the worksheet was to prevent students from having to take long notes, given the amount of new terminology and definitions of the topics; still she left blank places on the sheet for students to briefly take personal notes after each section, since she believed in the power of taking notes in learning new subjects.

Alice tried to use the worksheet in an interactive, collaborative way by going over it with her students as they brainstormed and filled in the blanks together. For instance, the

first part of the worksheet was about the key terminology of QM where students worked together to generate words that fit under the key concepts of QM. In this particular section students offered relevant words such as, sub-atomic particles, fundamental forces, quantity, and electrons, so that the first part of the worksheet was filled out differently in each class. This section serves as an assessment, showing Alice the students' prior knowledge of the concepts of QM.

In section A, Alice also asked the class to define the words quantum and mechanics (see Figure 2). After the student attempts to define the words, she provided a definition as follows: quantum is a “small quantity of energy proportional to the frequency of radiation” and mechanics is a “minimum amount of any physical entity involved in an interaction, a discrete value and it leaps.” Following the definitions she provided an explanation of the emergence of QM follows, where she emphasized QM as a field of physics that studies small particles such as atoms and sub-atomic particles. She related the history of QM telling the students that it started around the year 1910 by approximately ten prominent European and American physicists; she identifies Max Planck to be the father of QM.

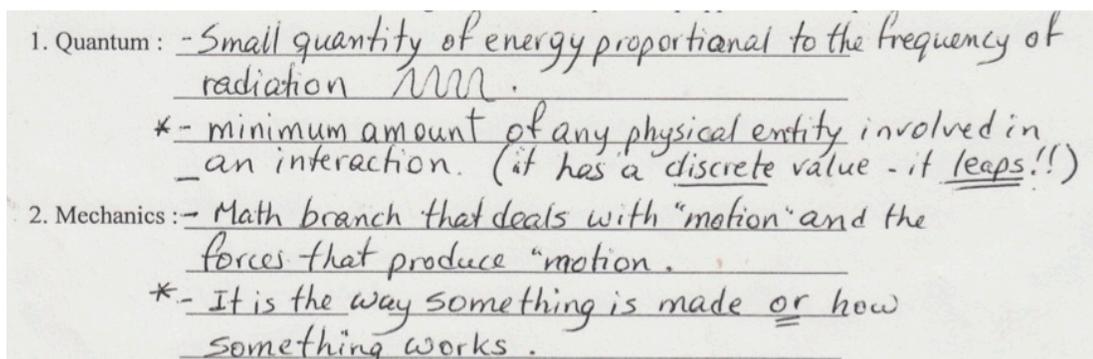


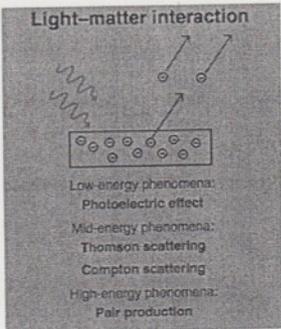
Figure 2. Definitions of the words quantum and mechanics in worksheet section A.

Alice told students an engaging story that outlined how physicists encountered

problems with some natural phenomenon that could not be explained with classical mechanics. She uses three examples: dark matter, photoelectric effect, and spectrum rays, allowing for students to take notes. Since she had an understanding of her students characteristics, she selected topics that were most likely, in her opinion, to captivate the students' interest, such as that dark matter has no interaction with light and cannot be seen, adding that the matter we know makes up the stars and galaxies and only accounts for about 5 percent of the content of the universe, the rest being made up of 27 percent dark matter and 78 percent dark energy. In the photoelectric section, she explained the date and setting of Einstein's 1905 experiment, explaining that electrons are produced when light shines upon a material requiring a certain amount of energy of light to produce photo-electricity (see Figure 3). As the third example of phenomenon that cannot be explained by classical mechanics, Alice provided the concept of spectrum rays, explaining that each atom has some kind of genetic code (see Figure 3). Using a biology terminology created a metaphor that students could visualize. She then further explained that the genetic code of atoms is a series of dark or light lines, depending on the nature of the atoms. She added some history of this spectrum experiment, providing some dates for the discovery of certain atom's spectrum rays.

Ex b. Photoelectric effect (or photoemission)

This was observed in 1839.



Light-matter interaction

Low-energy phenomena:  
Photoelectric effect

Mid-energy phenomena:  
Thomson scattering  
Compton scattering

High-energy phenomena:  
Pair production

- electrons are produced when a light shines upon a material

- It requires a certain amount of light (energy) to produce these 'photo electrons'

Einstein (1905) called it 'Photon'

\*particle that has no mass!!

Ex c. Spectrum Rays :

- Each element (atom) has some kind of genetic code.

- It is a serie of dark or light lines (coloured).

- It depends on the interaction of the atoms.

The sodium spectrum was discovered in 1752

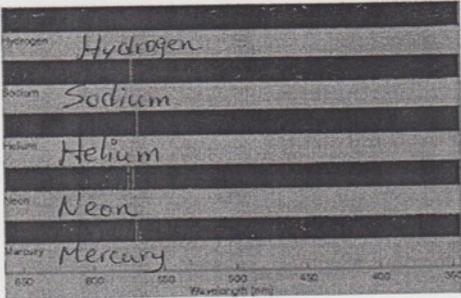


Figure 3. Photoelectric effect and spectrum rays explained in worksheet section A.

After the three examples of dark matter, photoelectric effect, and spectrum rays, she introduced the electromagnetic spectrum, highlighting that the electromagnetic (EM) waves are made of photons, which are particles without mass. She provided the wavelength and frequency values for radio waves, infrared, ultraviolet, X-rays and visible light spectrum, emphasizing that in the EM spectrum the visible light constitutes only a very small part of the whole spectrum highlighting that there was so much more beyond what we actually see (see Figure 4). Alice stressed that “we cannot see the waves other than the visible light spectrum, but we feel or see the effect of the other rays, as in when microwaves cook our meals, and when radio-waves help to work our radios and cell phones.” With this explanation Alice provided a basis to make the topic of EM waves relevant for student as they potentially engage with radios, cell phones in their everyday life.

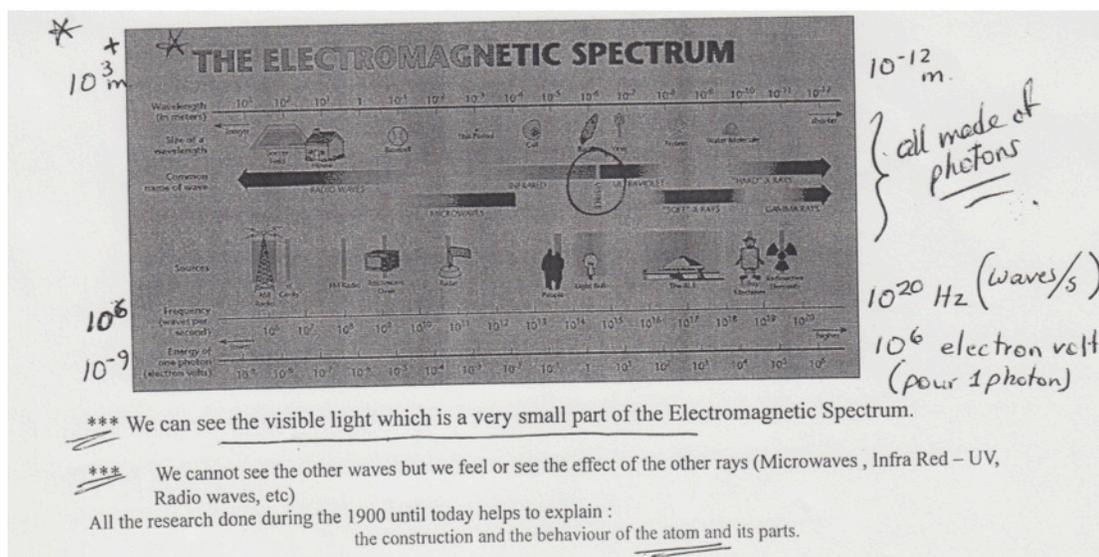


Figure 4. Electromagnetic (EM) spectrum in worksheet section A.

In Section B, Alice devoted the whole class time to the history of physics in general, elaborating the development various concepts of QM (see Figure 5). She outlined that the early physics can be identified the developments that took place before 1900. Before 1900 in physics, she tells, there were three branches of physics: classical mechanics, thermodynamics, and electrodynamics. After explaining each of the branches, she continued with the physics from 1900s until now as QM. She outlined the topics of QM as quantum tunneling, teleportation, the dual nature of light, superposition, and entanglement. The brief explanations of each concept can be seen in Appendix E; however, she elaborated each concept verbally. In section B, she emphasized the implications of QM, listing: superconducting magnets, light emitting diodes and laser as everyday electronics, transistor and semi-conductors seen in microprocessors, magnetic resonance imaging, and electron microscopy, and lastly, implications of QM in natural phenomena that we see in photosynthesis and bioluminescence. All these examples were aimed to help make the abstract concepts of QM relevant for students by connecting them

to everyday life.

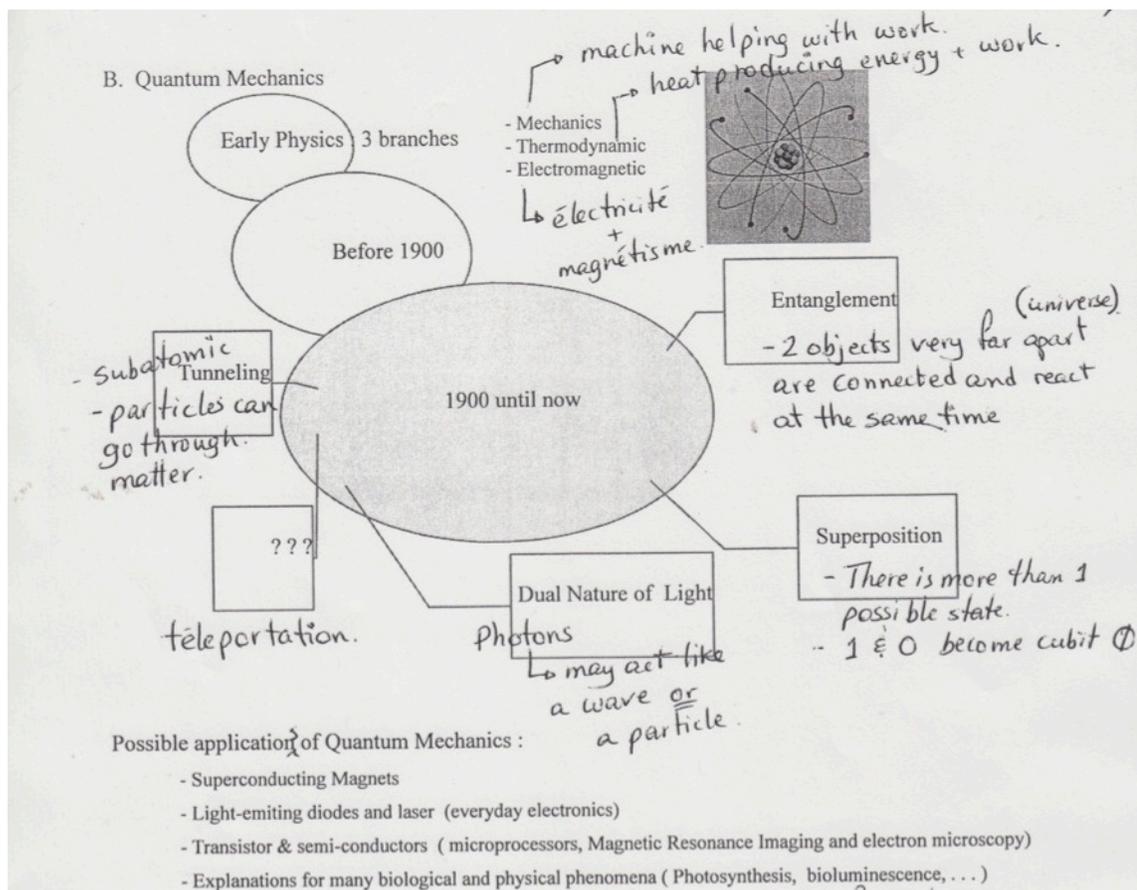


Figure 5. The historical development of QM in worksheet section B.

Alice devotes section C to the atomic and sub-atomic particles providing the sub-atomic particles table including leptons, bosons, and quarks (see Figure 6). She identifies these fundamental particles with their characteristic properties and then she explains that there are four fundamental forces in nature: strong force, weak force, electromagnetic force and gravitational force and that all these forces are made of particles called gauge bosons. As an example she explains that the electromagnetic force is made of photons, strong force is made of gluons, weak force is made of w and z bosons, and gravity is made of particles called gravitons. She concludes by putting these discoveries into context within an historical timeline that mark the discovery of particles.

C. Atomic and Subatomic particles :

Protons : 2 up Quarks  
1 down Quark.

Neutrons : 1 up Quark  
2 down Quark.

- electrons, neutrinos  
muons  
tau.

light particles

3 Generations of Fermions until 2008

u up	c charm	t top	g gluon	H Higgs boson
d down	s strange	b bottom	γ photon	
e electron	μ muon	τ tau	Z Z boson	
ν <sub>e</sub> electron neutrino	ν <sub>μ</sub> muon neutrino	ν <sub>τ</sub> tau neutrino	W W boson	

4 Forces : ① Strong atomic Force  
g = gluon.

② Electro-magnetic  
γ

③ Weak Force  
Z & W

④ G - Graviton

\*\* 2012 Higgs Boson → makes the Higgs Field → gives a mass to matter

made of particles ...

Figure 6. Subatomic particles in worksheet section C

Section D is devoted entirely to the dual nature of light along with some other counter-intuitive concepts of QM, such as Schrodinger's cat, Higgs boson and entanglement. As mentioned before, while Alice followed the worksheet line by line in her first lessons, in the second lessons she predominantly used visuals and animated videos referred to on the worksheet. In the first video, she let students take notes about the Schrodinger's cat, explaining, "The physics we observe everyday is different than the physics at the atomic and sub-atomic level. For instance here, the cat can be both alive and dead at the same time and it is called a superposition state." Then she connected this thought experiment to the atomic level saying "in order to learn where the electron is in hydrogen, we need to observe it like we observe the cat, and once the electron is observed, we change the system ultimately." The second and third videos are about Higgs Boson, where she explains that a Higgs field would give mass to the sub-atomic particles, and less mass to smaller sub-atomic particles (see Figure 7). She gives an analogy of a fish and a person swimming in the water, elaborating that the bigger the

object is in the water, the bigger the interaction, meaning more mass in the Higgs field.

The fourth video mentioned on the worksheet is about the quantum atom model and was assigned for homework.

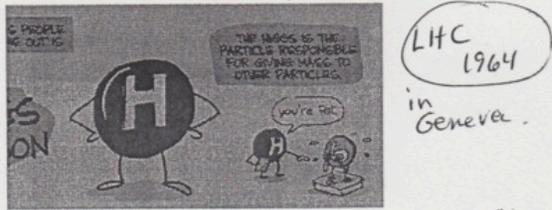
Entanglement

2) What is a Higgs Boson? (4 min) in 2011 before it was discovered or proven !!

<https://www.youtube.com/watch?v=R1g1Vh7uPyw>

3) The Higgs Boson Simplified Through Animation (4 min)

<https://www.youtube.com/watch?v=L6AN6UwTTjU>



Hypothesis:  
A field (Higgs) would give a mass to some subatomic particles (large) and less to others (the smaller one)

Comparison with a fish in water vs a human,  
 smaller particles  $\rightarrow$  field  $\rightarrow$  less interaction.  
 bigger particles  $\rightarrow$  more interaction  $\rightarrow$  more mass

Figure 7. Higgs boson in worksheet section D.

The fifth video is about the dual nature of matter including some aspects of the origin of QM. The sixth animated video is again the dual nature of light, where Alice emphasized the setting of the double slit experiment and the interference pattern. The seventh video is about the quantum atom model told by an animated female character, which highlights the sub-atomic particles in an atom. These videos were carefully chosen from YouTube by her to be engaging and age appropriate.

At the end of the worksheet there are personal notes written by Alice (see Figure 8). For instance, one note refers to the cylinder analogy, holding two different natures simultaneously. Here Alice wrote, “electrons are smart, they change their behaviour,” referring to the double slit experiment, or after writing the word philosophy in capital letters, she wrote, “anything that can happen, does happen” referring to the many world theory. Many-world theory, as opposed to the Copenhagen interpretation of QM, refutes the wave function collapse in a quantum system. For instance, when a wave function is

observed, the Copenhagen interpretation posits that the infinite possibilities of the wave function collapses into one single quantum state and the rest of the wave disappears in the universe, whereas many world theory holds the perspective that when a wave function is observed, although it gives one observable quantum state, the other possibilities that the wave function inhabits still exist somewhere even if it is not available to us, concluding that there must be many different universes for the other possibilities to take place.

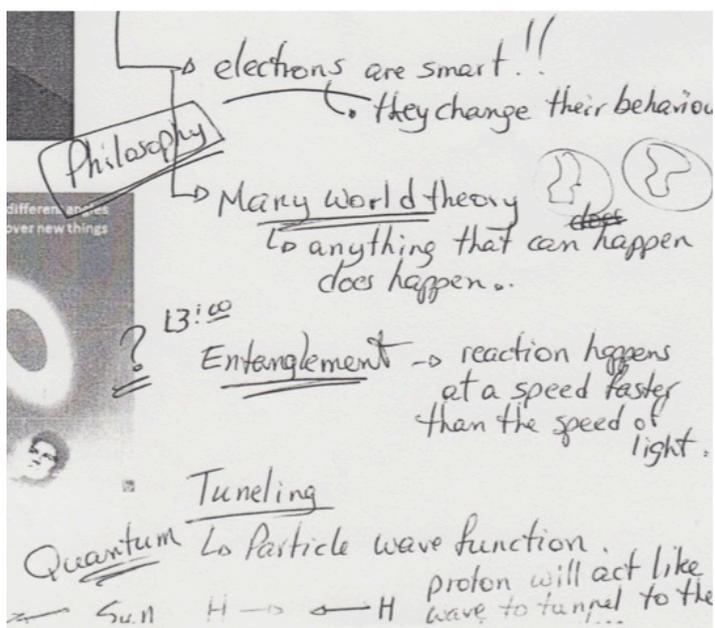


Figure 8: Personal learning notes of Alice

When considering how to improve her teaching of QM, Alice acknowledges that hands-on activities or group discussions would have been complementary to her lesson plans and materials. Her school already has double slit experiment sets, but in addition to that she is considering making models for sub-atomic particles, fundamental forces, and the quantum atom model for next year. She had not realized that there was more current information regarding the quantum atom model and regrets that she has not taught the quantum atom model that she found online. She wished that the quantum atom model had been included in a textbook, which she would have found helpful as a teacher

preparing lessons. “Outdated textbooks are not convenient for teachers,” she says, adding that if students see the concepts of QM in textbooks they would “take the QM topic more seriously.”

Alice said that in terms of finding images and teaching materials, search engines such as Google and YouTube were a big help for teachers in preparing for their classes. Her criteria for choosing videos was to select videos that are short with engaging storylines and animated figures, and that explain QM concepts in simple terms. She avoided university level QM videos, which she explained, were too long and dry. A list of videos she used in her teaching practice is provided on her worksheet (see Appendix E).

For instance, when a student missed a class and tried to catch up with the class through the worksheet, Alice emphasized that the student would need to watch the videos as well; otherwise the notes would not make sense. She also believed that the video material was fun and was designed to make the information accessible to younger students. Alice’s approach might be a demonstration of how content, pedagogy and teaching material are inter-related referring to the holistic and complementary nature of PCK.

### **Characteristics of Learners**

Alice emphasized the importance of a teacher knowing their students. She said “You have to know the students you teach, as far as how much they can handle and what kind of things they will find funny and entertaining.” This might inform, for instance, the appropriate pacing in teaching the content and choosing the most appropriate material for specific students. She said one way to know the students is to give them a big challenge

and observe how they deal with it. Additionally, she likes to play the devil's advocate in order to find genuine responses from the students and to further understand their thinking. Alice expressed that this strategy is a way to eliminate hierarchical gap between teacher and students by encouraging authentic conversation where disagreement is allowed. Therefore, Alice demonstrated knowledge in characteristics of students as one of the Shulman's teacher's knowledge domains.

### **Knowledge of Educational Values**

The BC Education Ministry's stated goal in creating the new curriculum is to cultivate "sets of intellectual, personal, social and emotional proficiencies that all students need to develop in order to engage in deep learning and life-long learning" (BC's New Curriculum: Building Student Success, 2015). The Ministry is putting an emphasis on understanding "big ideas" such as the concepts of QM, which they say will "foster the higher order thinking demanded in today's world" (BC's New Curriculum: Building Student Success, 2015).

Alice explained that the Ministry of Education in BC expects their teachers to teach any subject regardless of whether or not they have a background in that subject. In regards to QM, although it is mandatory in BC as of 2016, there is no systematic procedures in place that audits or monitors teachers. Alice pointed out that most teachers would most likely skip this topic. However, if there is a curriculum change or addition for a subject, it is technically the teachers' responsibility to learn about the subject. In the case of QM inclusion, she does not know what kind of resources and support will be available for teachers the next year when the new curriculum becomes mandatory. She said that lack of specific resources might be one of the biggest challenges for this

particular change in the curriculum. She speculated that there might be a professional development day to introduce the concepts of QM to Grade 8 science teachers, in which she would be willingly take part in order to help other teachers to make the transition to teaching QM.

Alice embodies the knowledge and understanding of educational purposes, values that Shulman identified as a domain of teacher knowledge, along with providing their historical and philosophical aspects of science subjects that she is teaching. She believes in the value of teaching QM and wants to encourage her colleagues “I wish all Grade 8 teachers know a bit of QM. That would be fun. I will bring this up in the staff meeting tomorrow.” She emphasized that in the initial stages of incorporating the topics of QM teachers have to be easy, not only with students, but also with themselves in order to prevent higher expectations. Although the topics of QM are mandatory in Science 8 curriculum, Alice has a firm belief that most teachers will not teach the topics of QM. When talking about the place of QM in the curriculum, she shares her thought as follows:

I am confident that everybody else will have some respect for it, a little bit like when we talk about anti-bullying. People, they have knowledge that it is not right, or right, or fun, they will be educated about it a bit. They will be able to, when time comes, be able to support them. If they themselves do not get directly involved, but at least they will be able to have a bit of a, "Mm-hmm, OK, yeah" show appreciation and support.

The Redesigned Curriculum in BC emphasizes creating interest and passion in students. Alice’s teaching strategy demonstrated this goal. She believes that a difficult subject can be taught by making the lessons fun and engaging. According to her “success

is not related to being smart, it is about cultivating student interest.” She says “once the interest is created, students will see it as easy, and teaching it will be easy too.”

### **Curriculum Knowledge**

Alice has an extensive body of curriculum knowledge due to her three decades as a science teacher. Prior to the QM classes, she taught molecular theory, atomic structure and phases of matter. Since the textbook provided the old Bohr atom model, she taught the outdated model of atom in her classes, not being aware of the quantum atom model with electron clouds (The quantum atom model was discovered by Schrodinger and accepted in the scientific community in 1926). Alice was able to relate her understanding in QM with the prior topics she taught in her science classes; however, she emphasized that if the topics of QM were on the textbook, she would have taught the quantum atom model. This points to the need for teachers to stay current with the scientific concepts as practiced in the field using appropriate resources and updated textbooks.

### **The Views of the Nature of QM**

From a historical perspective, physicists had more opportunities to explore the theoretical understanding of QM with mathematical formalism, rather than experimental understanding of QM due to the limitations of technology to investigate sub-atomic particles. The study of QM has been improved by the special form of mathematics that is designed and invented for further advances of the mathematical understanding of QM. Alice is aware that QM is fundamentally being researched with those specific mathematical formulations. When I asked her about the nature of QM, she was only able to provide insights about the conceptual understanding as expected. From the very first meeting, it was made clear that as she has no background in advanced mathematics, she

would therefore be focusing on the conceptual aspects of QM and not the mathematical equations. In the writing that follows I provide Alice's perception of QM and her views of the nature of QM.

### **The tenets of QM.**

Alice identified four tenets of QM throughout our conversations: futuristic, counter-intuitive, open-ended, and ever-evolving. The first is that QM is "futuristic," in that it is a new branch of physics which is still being explored and not fully understood. She may have gotten that impression because of the concepts of QM she viewed in science fiction movies. The second tenet is the counter-intuitive nature of QM, where Alice uses the word counter-intuitive as the opposite of straightforward. She had a witty way of describing QM, when she said that the fascinating thing about the counter-intuitive nature of QM is that, as a study of science "QM sounds unreal, but it is real."

Thirdly, Alice described QM as open-ended, where she acknowledges that this field of science is still under research. She says, "not knowing everything about a topic leaves room for mystery, curiosity, different possibilities, and thus makes it interesting." She also finds it fun when she encounters QM concepts in movies now, because she has a more educated perspective, which enriches her viewing. Finally, Alice depicts a fourth tenet as ever-evolving. She enjoys the fact that "the concepts of QM are still being explored—what it is and how it works." She says that the dynamic nature of QM offers a rich venue for further exploration.

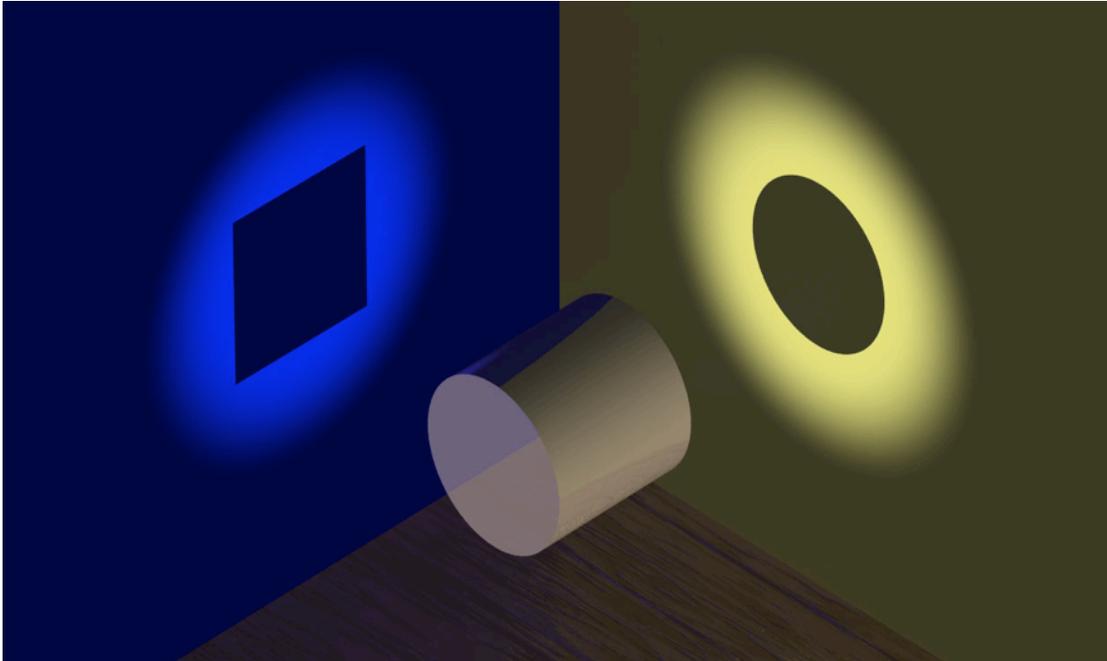
### **The nature of QM.**

The counter-intuitive nature of QM has been discussed in our interviews in different frameworks, in one of which Alice linked the counter-intuitive nature of QM

with subjectivity. According to Alice, the counter-intuitive nature of QM aligns QM with the field of humanities such as sociology and psychology; areas that she would not classify as objective, but like human focused studies, more subjective. In the social sciences, two seemingly different or even opposite attributes can be true at the same time. For instance, from a psychological perspective, a person can both love and hate another person, or they can be attracted and repulsed at the same time. In this sense, she says, QM is more akin to the social sciences. Since the outcome of a QM system depends on the perspective taken when looking at the data, according to Alice, QM is subjective and intrinsically counter-intuitive. Here, Alice undermined the potential for the tentativeness of other fields of science, since they align with common sense, thus intuitive. Therefore, Alice seemed to hold a more traditional understanding of the other fields of science such as biology and chemistry; however, according to her, two things can only be right at the same time in social sciences and QM.

### **Philosophical dimensions of QM.**

Alice recognizes that QM offers a medium to promote philosophical perspectives. In order to represent the notion of the dual nature of light, Alice shows a picture of a cylinder that is in the corner of a room, and when light shines on it, it has two shadows, one square, and the other circular, demonstrating that two things are true at the same time (see Figure 9). She said she found this image on Google and thought it would be a good analogy for the dual nature of light.



*Figure 9.* Cylinder demonstrates that one thing can be perceived differently based on perspective

The cylinder demonstration seemed to be accessible and effective in helping students to comprehend the core idea underlying the dual nature of light. Alice says the ostensibly impossible and counter-intuitive concepts promoted by QM are thought-provoking, offering the wonder of the philosophical understanding to the nature of science.

According to Alice many-world theory in QM also has the potential to initiate philosophical thoughts in science classes. She says, the philosophical approach “allows for students to bounce ideas off each other, and to think creatively. Students are encouraged to think in a creative way that inspires them to ask ‘what if?’ questions and brainstorm possibilities.

In her teaching practice, when talking about teleportation, Alice brought up the necessity of thinking about ethical aspects of QM topics. For instance, she encouraged

the students to delve deeper into the topic of teleportation by pointing out the potential ethical questions regarding teleportation. She said “teleportation is interesting, because we see it in movies.” She initiated a conversation regarding the consequences of teleportation saying if we were able to replicate ourselves by teleportation, would it be still us who was teleported? She pointed out the girl in the teleportation video saying “is the person teleported real or is she a copy? She wouldn’t be there anymore to argue whether it is her or not.” While this interchange was done in fun, it also required students to contemplate the consequences of technology and to engage with potential ethical issues using critical thinking skills. After observing this class, I wrote in my journal “These kids are at the center of accelerating technological advancements, and it is good that they do not engage with technology not only to have fun, but also to think critically of the consequences of the implications from an ethical and social perspective.” Even for a short time, emphasizing the ethical dimensions of QM and advancements in science created an engaging approach to the topic.

### **The Views of the Nature of Science**

Alice defines science as a way of understanding the world. In one of our first conversations, while talking about the nature of science, Alice initially says that science is objective and there is one ultimate truth thereby displaying traditional views of NOS. However, after studying the history of QM, she started to think that science is not objective and factual. Later on, I found out that she had actually held two different conceptions of science: first, the one that is taught in schools until university, second, science that is being researched at the universities. She said, “in science there is an effort to be objective and factual . . . to make it like there is a frame around it.” She explained

that this approach is probably successful until middle or high school, “but after that science becomes something different.” She elaborated by describing the almost schizophrenic situation of science education in today’s schools, in that, science is taught differently in middle and high school science education, which is currently based more on the traditional views of NOS, whereas informed views of NOS are promoted at the university level in teaching and research. As mentioned in the literature review, the views of NOS are indirectly taught, an explicit NOS teaching is not necessary to provide an understanding of science. For instance, teaching science as an accumulation of fixed facts yields traditional views of NOS. The way science topics are presented by the teacher seems to promote certain views of NOS, rather than the content knowledge in science.

Alice also emphasized the ever-evolving nature of science. When I asked her how she came up with the idea that science is continually evolving, she explained with an easy logic “the content of science evolved since Aristotle times. If it has evolved since then, then it must keep evolving from now on.” She continued:

now I do not think that too many scientists believe that everything is set in stone.

Things are evolving. Things change. You already mentioned paradigm shifts, but I believed in the ever-evolving nature of science before I was exposed to QM. QM proves that those ideas are real.

In her teaching, Alice also mentioned the ever-evolving aspect of science by pointing out the scientific studies at the universities. She told her students; “Now this is cutting edge science, we are still discovering things and people are working at this while we are talking” highlighting further discoveries will be taking place in the field.

Apart from emphasizing the transformative and ever-evolving nature of scientific knowledge, Alice further considers that science as time-dependent. Her example was species of viruses that change over time; therefore like astronomy and physics, biology is also an ever-evolving branch of science. She says there is a “timeline” behind science. However, I wondered whether her use of the word ‘evolving’ refers to the concept of collected of facts and not the paradigm shift nature of science. Then she continued, and helped me to see that I misunderstood, by saying:

in some ways science for me is like trying to learn as much as you can, some for fun and some because it is useful for your trade or professions, but it also serves to help us to keep sharp, keep investigating, and keep our eyes open. Science could be very, very overwhelming for the majority of people and because it seems to be so much out there that you... like music in some ways or more... where it seems like you can never learn it all. You can never be perfect. Some people don't like that.

With her last statement, she says that the notions of ‘perfect’ and ‘complete’ do not apply to scientific knowledge, since it embeds paradigm shifts in its nature. The dynamic nature of scientific developments aligns with the nature of PCK since it is continually evolving.

Alice explained the development of science with an analogy. According to her, science is like building a house. She said, “twenty years after building a house, people might want to change the bathroom. They will add to the house or they will renovate another part. Science is a bit like that.” Although, paradigm shifts in science are not intentionally planned, after this analogy I asked whether renovations were allowed in science and she said, “I think so.” Then she pointed out “what is that movie with Stephen

Hawking, that came out a few years ago, he himself is counted as a genius, but I think over the course of his life he has changed his mind about his scientific discoveries quite a few times.”

I asked Alice what else she remembers about Hawking changing his mind in the movie. She said, “somebody questioned his initial proposition, then he went home, thought about it differently and came up with a different proposition. Both were breakthroughs in the field of science.” She continued with another name that she encountered in her QM learning process when she said, “I remember another name, Planck, that was already sort of an older scientist who decided to deviate from what they had done before him.” With the house analogy, lessons learned from a movie and QM learning process, Alice demonstrated that she adopts the informed views of NOS.

Then I asked her how does she feel about this aspect of science, referring to the tentative, ever-evolving NOS. She replied with laughter:

I was still using pi today in my class. I said, "3.14, whatever it is." Some of these days somebody is going to come up and say that were wrong. [laughter] Even though we have been using it for 2000 years. I am suspicious of everything now.

The value of pi is not a scientific concept, only the mathematical constant as the ratio of a circle's circumference to its diameter. Making a reference to pi was perhaps pushed the limits of tentative nature of scientific concepts. Alice's suspicion was not about rejecting the current scientific developments, but of an acknowledgement that she cannot be one hundred percent sure about the current content of science. Her perspective revealed openness to the upcoming scientific developments that no matter how shocking

and ground-breaking they would be, she would be ready to move on and adapt to what the most current scientific knowledge offers.

In our conversations regarding NOS, Alice brought up another aspect of NOS connected to the nature of knowledge. Alice recognizes that some scientific knowledge cannot be ever knowable. She said, “people talk about science for a long time trying to answer questions explaining the world. Some of the questions of science could not be answered and some people started to form a new religion bringing a new approach to things to answer these questions.” The data set reveals that in the beginning of the research Alice might have been lacking knowledge in topics of QM; however, she had encountered and pondered some concepts of NOS in her engagement with science, and thus by drawing conclusions from what she has learned, she already has developed certain views of NOS, which align with the aspects of the informed views of NOS.

Alice’s ideas about science can be summarized with her own words as follows:

Science is continuously advancing and as human beings we might be proud of the level of science we have come so far. At the same time I look at this here (her QM notes) and I say “okay, we think we are pretty smart knowing this stuff but we know that somebody will come up and is going to break this down again and maybe find something else that we do not see today. . . I know that it is never finished. There is always somebody who is going to dig deeper and find something new.

At that point I asked her “do you think it is always digging the same hole or opening a new hole as well?” and she answered “yes, digging new holes, opening new doors.” From Alice’s perspective, science will find new forms of knowledge that can

expose us to new ideas that would go beyond both quantum and classical mechanics. She said:

Science is an act of faith and you have to trust that we are still at a dawn of this form of science, there is still more to discover. What I am saying today might not be valid tomorrow or next week, so let's not panic about it. Let's share what we know and have a good time with it.

### **Professional Learning Opportunities**

Alice enthusiastically wants to offer help to her peers who will be learning about QM. She gives a hint that even though it is mandatory to teach QM for all the Grade 8 teachers, they might not be teaching it, explaining that if teachers are left alone with a new topic and are not provided with learning materials they might take only a little time for preparation, and therefore their teaching would not be as detailed or deep as what Alice has demonstrated, yet Alice mentioned even her teaching practice could be improved drastically if there were more time for her learning and teaching. Alice is confident that she can give the kind of support that will help teachers to more fully engage with learning the concepts of QM. She is adamant that providing the basics, the fundamentals of QM teaching notes and materials to the teachers who are new to the topic is a must. She mentioned that viewing accessible and reliable online QM resources, such as videos and simulations, would be essential for both teachers and students. From her perspective, apart from providing external support, creating interest in QM would hopefully inspire other teachers to have the motivation to explore QM fully, on their own.

Alice is willing to share her QM experiences in a Professional Development session. She suggests that this would encourage other teachers interested in teaching QM

as well, particularly when she offers her notes and lesson plans as a service to other teachers. She is willing to present a lesson plan for three or four classes, which would be revised based on her experience, so that there is sufficient time for students to interactively participate in the class. She explained that teachers would prefer teaching notes which are based on experience, which has already been proven to work successfully in the classroom environment. She added if teachers watch a Grade 8 science teacher teaching a completely new topic, they would feel more comfortable teaching that topic. She said that if she were to teach QM to other teachers she would use the same materials and resources, exactly how she taught the subject to her students.

Alice explained that once teachers embrace the challenge of initiating a new expedition of learning QM, the rest would follow. She continued “it is all about taking the first step, and then not panicking; just go slowly and take it one step at a time.” Alice explained that teachers need to learn the basics of QM quickly and have the confidence to teach the subject “making sure that they will be able to take the plunge and feel that they have the basic knowledge.” In doing so, teachers need to feel confident that they can explore the subject on their own. Teachers need to personalize their learning experiences and then customize them according to their students’ needs and interests. This customization was referred as “spicing it up,” making the topics interesting, engaging, age appropriate and aligning with the profile of the students.

Alice said, “Futuristic topics require conversation and community in learning.” She suggests a workshop model to help teachers to learn to teach QM, where they can share their thoughts extensively and also approach QM from a philosophical perspective. Having a conversation and sharing ideas is crucial in the learning process of teachers,

who are being introduced to a new topic. She explained that sharing and confirming the new concepts with an expert person is also important as they go through the learning process.

Alice worries that some science teachers are conservative and might not want to teach the concepts of QM. Although QM is mandatory, here is presently no way of confirming whether an individual teacher is actually teaching the curriculum or not. Alice thinks that offering prepared learning and teaching materials to teachers may encourage these conservative teachers. She explains how positive feedback and lived experience are important in encouraging other teachers to teach a new topic. She suggests that if teachers are directed to the right videos and learning materials they will feel more confident and comfortable in learning and teaching QM.

From my observations, Alice's strategies were helpful throughout her learning process and in terms of developing PCK in QM, despite the challenges and misconceptions she was able to create an effective teaching environment. In the next chapter I link the findings to the concepts found in the literature, and discuss the themes emerged from the data.

## Chapter 5

### Discussion

The purpose of this exploratory case study was to understand how a Grade 8 science teacher learned and taught the concepts of QM. In other words, how she made sense of the counter-intuitive nature of QM, how she developed her PCK for the topics of QM, and how she developed her views of NOS through her learning and PCK development processes. The findings chapter provided the main and sub-categories, where I grouped the coded segments. The patterns between these categories led to the emergence of the themes while providing higher-level and critical insights into the research question, “How does a Grade 8 science teacher learn to teach QM?”

The overall emergent themes were identified as: 1) The development of PCK in QM is complex, 2) The student-centered approach mandated in the redesigned curriculum may be limiting, 3) The nature of learning QM is not different than learning other subjects, 4) Middle school science education is inconsistent with the current level of scientific knowledge, and 5) The development of informed views of NOS requires an accumulation and synthesis of prior knowledge in history and philosophy of science on that subject. The themes and their sub-components are outlined below (see Table 2) to provide a general and accessible understanding for this particular chapter.

Table 2

*Themes of the study*

Theme 1: The development of PCK in QM is complex	
1	Changing roles of the teacher
2	Developing self-confidence

- 3 Building sincere and trusting relationship with students
- 4 The time allotted to learning and teaching changes the nature of PCK
- 5 The need for a new vocabulary that reflects the ontology of QM  
New ways of teaching science is required: utilizing metaphors, analogies
- 6 and story telling in relation to history and philosophy of science and ethics
- 7 Introducing a new subject requires pre-PCK
- 8 A model for introducing a new subject

Theme 2: The student-centered approach mandated in the redesigned curriculum may be limiting

- 1 A specifically mandated pedagogical approach by the Ministry may be limiting for science teachers who will be exploring effective ways of developing PCK in QM.

Theme 3: The nature of learning QM is not different than learning other subjects

- 1 Growth mindset is a prerequisite
- 2 Conversation is vital in learning
- 3 Gradual, step by step learning including the history of the subject
- 4 Making QM relevant

Theme 4: Middle school science education is inconsistent with the current level of scientific knowledge

- 1 Content knowledge in middle school science curriculum is outdated, so is the underlying views of NOS
- 2 Teaching QM can instil informed views of NOS through critical thinking

Theme 5: The development of informed views of NOS requires an accumulation and synthesis of prior knowledge in history and philosophy of science (HPS)

### **Theme 1: Development of PCK in QM is complex.**

PCK is a special blend of pedagogical knowledge and content knowledge and is essentially context dependent (Cochran et al., 1993; Grossman, 2010; Shulman, 1987). As elaborated in the review of literature, the nature of PCK sub-components are inter-

active (components transform themselves in time), inter-dependent (components cannot be without each other), and inter-connected (components are intrinsically in relation to each other), which offers a dynamic platform (Cochran et al., 1993; Doyle, 1990). The findings of this study aligns with the dynamic nature of PCK as well as suggests that the development of PCK in QM becomes complex for several reasons: 1) changing roles of the teacher, 2) developing self-confidence, 3) building sincere and trusting relationships with students, 4) time allotted to learning and teaching the subject, 5) the lack of a vocabulary that reflects the ontology of QM, 6) the need for pre-PCK, 7) the need for new ways of teaching in science based on analogies and story telling, and 8) introducing a new subject requires particular elements. All these aspects cultivate a complex nature for the PCK development in QM.

### *Changing roles of the teacher.*

In developing her PCK in QM Alice used both traditional and constructivist approaches, shifting between teacher-centered and student-centered pedagogies. Teaching materials were predominantly based on worksheets where she mainly followed teacher-centered pedagogies; however, in terms of incorporating thought provoking video materials and promoting conversation student-centered pedagogies became present and her role as a teacher changed to more of a co-learner position and it could be viewed that she followed constructivist approaches. Alice's role was changing throughout her PCK development.

The worksheet Alice prepared acted as a lesson plan and created a structure that she could follow. As being newly exposed to the topics of QM, the worksheet material seemed to be an effective teaching strategy; in that, the worksheet enabled her to follow

the topics within the previously planned timeline in an orderly fashion and appeared to enhance her confidence in her teaching by instilling a sense of order. In introducing new topics, when there are time limitations to cover a certain number of topics, it seems wise to create a practical tool that will provide the teacher with structure. From this perspective, Alice's worksheet provided not only the content knowledge, but also a pedagogical approach to follow in her PCK development. The teaching material sets the tone for the teaching practice for both content and pedagogy, thus teaching material could be viewed as a sub-component of PCK. This aligns with Marks (1990) re-figuration of PCK, where he includes the knowledge of media or teaching materials as an integrated aspect of PCK.

Alice supplemented the worksheet material with age appropriate video clips and images. The questions she asked provided interaction with students contributing to engaging conversations. Merely utilizing the worksheet material in a teacher-centered way may have offered traditional and linear pedagogies; however, enhancing the worksheet with visuals and promoting conversation expanded the usefulness of the worksheet and improved her PCK while offering an effective learning environment for students.

In trying to understand Alice's choice to use the worksheet and her tendency to remain more on the traditional approach, I realized that a teacher would be unlikely to feel confident after only a month of studying such an unfamiliar subject like QM. One way to overcome this challenge for her was to create and follow a worksheet that contained the main points that she wanted to make in her teaching. It was satisfying to see that in her second session of QM teaching in her all three classes, it was clear that she

significantly gained confidence even after teaching only one class. From my observation, following a structured approach also contributed to students' understanding by providing a bigger picture of the whole content through the worksheet and helping them to make sense of the subject, to be engaged and fully present in following the topics. Other teachers might find this strategy encouraging as a way to build confidence in introducing a new subject.

*Developing self-confidence.*

Alice emphasized that it is essential for teachers to develop self-confidence in teaching, particularly teaching abstract and counter-intuitive notions. Since micro scale concepts of QM are not readily available for students in the classroom, students are dependent on what teachers' verbal and visual presentations. According to her, the trust between students and teacher positively contributes to the teacher's self-confidence. Even though teaching QM can be challenging in terms of feeling confident about the topic due to the unfamiliar framework of QM, Alice believes that maintaining a positive trusting relationship between students and teachers not only boosts teachers' self-confidence in teaching, but also contributes to an effective PCK development.

Given the complex nature of educational environments, when introducing a new subject, there might be value in drawing on both traditional and contemporary pedagogical approaches in response to the challenges that educators face. The recent science education literature predominantly recommends that teachers should abandon traditional approaches and follow student centered pedagogies; however, when learning and teaching a new subject, it is essential for teachers to assess their own needs for building confidence. Portraying confidence and building a positive self-image is viewed

as crucial in teaching a new subject effectively (Appleton, 1995). Therefore, at least in the beginning stages of incorporating new topics or new subjects in the classroom, relying more on traditional approaches might be effective.

***Building sincere and trusting relationship with students.***

Alice's commitment to building trustworthy relationship with her students appeared to be helpful not only to the students, but also to her, because the students showed respect and trust towards Alice, which in turn appeared to help her to remain focused and enabled her to stay within her timeline. According to Alice knowing the characteristics of students is a key to effective teaching practices, as she elaborated this might inform, for instance, the appropriate pacing in teaching the content and choosing the most appropriate material for specific students. Cochran et al. (1993) also pointed out that the more the teacher knows about the students' minds and dynamics of the context as learning environment, the better equipped the teacher is for inciting the students' learning; consequently, teachers would be able to provide students with effective teaching. This indicates the complex nature of PCK and shows how PCK can be transformed by the nature of students individually and collectively in relation to the teacher.

As introducing a new topic could be a challenge for any school topic, QM may require more care and consideration because of the reasons discussed extensively and at times teaching a new topic could be both exciting and anxiety-provoking for both teachers and students. Alice admitted that she was more nervous than normal before her first class in QM, but as she openly expressed her comfort point was that she has built trusting sincere relationship with students throughout the school year. Here, as she was

making a distinction between the PCK developments for a new subject and experienced one, she pointed out the importance of building trusting relationship in the development of PCK. From her experience, even if students have challenges with the new topic, if they have faith in the teacher they will still respect the teacher and try their best to learn the topics.

In this regard, building trusting and sincere relationship seems to be a positive contributor to an effective PCK development. Knowing students' characteristics, their interest areas, getting to know them was mentioned by Shulman (1986; 1987) as one of the key domains of teacher knowledge. While building trust might be viewed as one aspect of this domain, it essentially includes teacher's knowledge of and about students.

***Time allotted to learning and teaching changes the nature of PCK.***

Alice devoted four to five hours per week for learning the concepts of QM over a one-month period. Throughout this time she was not only learning QM, but also doing her lesson preparations, in particular finding accessible resources for her students. She was persistent in searching for supplementary teaching materials to her teaching practice, such as locating engaging video materials that would provide the concepts of QM for her students by capturing their attention and imagination, which has been a challenge and required notable amount of time and effort on her side. The challenges that she faced were not specific to her, but most likely would apply to other science and physics teachers, as there is a marked lack of existing quantum models to use in teaching the concepts of QM (Savall-Aleman et al., 2016). Alice mentioned if she had more time for the lesson plan preparation, she might have come up with a different lesson plan. She added that having more time for both learning and preparation would have created a

different teaching experience for her; in that, the flow, content and pedagogy for the same topics would have been different. Similarly, she noted that had she had more time to teach the concepts of QM the content knowledge she covered, the pedagogical approach she followed would have been different, as she was eager to do the double slit experiment as a hands-on activity in her classes, but could not do it due to the time constraints. From her experience, introducing the general framework of QM and teaching the mandatory topics in the curriculum require more than two classes. This points the importance of the notion of time in PCK development as a transformative and integrative aspect of PCK, as the time allotted for learning a subject, preparation and teaching contributes to the complex nature of PCK.

***The need for a new vocabulary that reflects the ontology of QM.***

It is important to note that throughout our interviews, I did not articulate the words ontology or epistemology to Alice, the conversations regarding the ontological and epistemological understanding of QM and science took place through non-academic terminology and explanations that generally included analogies and metaphors as elaborated in the previous chapter. The challenge to grasp the QM standpoint is essentially ontological as QM has no correspondence in everyday life, as Heraud et al. (2017) suggest:

The quantum object is problematic because its structure is radically different from the objects in classical physics: both the photon and the electron, for example, present wave and particle properties, while in classical physics the notions of wave and particle are mutually exclusive. . . this problem requires a change of ontological register: the ontology of classical physics (the exact determination of

trajectory by determination of the variables of position and velocity) must be abandoned in order to enter the “undetermined” ontology of the quantum object (e.g., the problematic wave-particle duality, by definition impossible due to an incompatibility in classical physics) (p. 4).

Whenever a new subject of study is undertaken, there is a potential that the teacher will have misconceptions, and QM can be particularly tricky in terms of its ontological basis, since it offers ontologically counter-intuitive concepts. Since there is no real life examples available to develop QM understanding, comprehending the ontological nature of QM concepts requires creative imagination. In developing PCK in QM science teachers might need to think creatively to devise real life analogies and examples to promote a correct ontological understanding of QM.

When introducing new topics, Alice said she places importance on providing terminology, which contributes to the scientific literacy regarding that subject. She started her QM lessons with the definition of the terms starting with the words quantum and mechanics. On reflection, it is clear that making the terminology clear would make the concepts more accessible for her students before presenting more complex dynamics regarding the scientific understanding of the concepts. Scientific literacy promotes informed-decision making skills, not only on a personal level, but also on a national level by encouraging students to participate in scientific discussion that might impact the future of the country, and is viewed as one of the major goals of science education (Alters et al., 1999; Hodson, 2003; Mitcham, 1999).

While a few students in each class expressed their prior knowledge in QM, the majority of the students found most of the terminology alien, as well as the concepts. As

earlier reviewed in the literature, there is a plethora of studies regarding student understanding of QM concepts stressing the misconceptions; however, unlike Alice's practice, none of these studies included the definition of QM terms in their QM teaching practice. I was not able to locate any mention of introducing terminology in the introductory stage of QM in related studies; rather, the studies on teaching of QM dwelled on the instruction of the key concepts and experiments of QM based on the choice of the instructors or the nature of the study. Perhaps, the researchers and teachers were making the assumption that the students would have been already familiar with the terminology of QM, since these studies focus on Grade 11, 12 and university students. However, it might be plausible that numerous reports that show students' misunderstandings and misconceptions about QM topics might be caused because of skipping this fundamental stage of clarifying the prominent terms of QM.

Alice mentioned that in learning and teaching QM, the terminology has been challenging for her at times. In my opinion, the challenges in engaging with terminology would arise for any teacher who is aspiring to learn about QM and it should be noted that the wrong use of terminology might cause misconceptions for the key concepts of QM. For instance, despite this scientific break-through in understanding the dual nature of light, in the scientific community the misuse of language regarding sub-atomic phenomena persists, as Olsen (2002) suggests:

The fact that electrons are objects that can be talked about in plural gives the connotation that these are separable objects, a distinct particle property. Light on the other hand, could not in this context be put in the plural. This carries the implicit meaning that light is something that cannot be divided into several objects.

If we want to comment on the particle nature of light, we have to use phrases like light-particles or introduce the concept of the photon (p. 567).

By the same token, the phrase “particle-wave duality” inherently embeds the misconception because of the word duality, since duality refers to having two parts. In trying to understand the nature of light, some experiments, such as photoelectric effect, resulted in demonstrating that light was conceived of as particles, and other experiments, such as Young double-slit experiment, put forth the wave nature of light. Basically light responds to the settings of the experiments differently and our perception of light is determined in relation to the measurement instruments. Therefore, light is neither particle nor wave; it is one thing, the unison of particle and wave, and the concept of light could be better understood with the term “particle-wave unity.”

The term “particle-wave unity” provides a more accurate understanding of the nature of light. The particle-wave part in the phrase already refers to two different states of being; however, the word unity implies the unison of these two states as one being. The phrase particle-wave duality intrinsically conveys a misconception—an either/or reality—for the nature of light, as if light is either particle or wave, which Alice practiced in the class by articulating particle or wave. The term particle-wave unity promotes the understanding of ‘particle and wave’ nature of light. Therefore, an update in the term as “particle-wave unity” would eliminate the misconception by emphasizing the inherent unison.

This points to the need for a new vocabulary that would reflect a deeper understanding of terms and ontological nature of the QM concepts. As discussed earlier in the theoretical framework of constructivism, language plays a crucial role in

constructing knowledge and directly influences what is learned (von Glasersfeld, 1989; Vygotsky, 1978). It is suggested that learning environments should be supported with words, rather than merely drawing on activity or experience (Howe, 1993). Furthermore, in order to fully comprehend a concept, it needs to be represented in words (Cakir, 2008); consequently the construction of knowledge is shaped by and through words. The role of language has also been elaborated in the PCK framework, where Andrews (2001) proposed language as a sub-component of PCK in language classes; however, considering language as a way of communication, the role of language in PCK development applies to all school subjects. Particularly in teaching sub-atomic phenomena, language can be viewed as one of the crucial mediums bridging these out worldly concepts to student understanding. Developing awareness in language as in new vocabulary and accessible definition of terms would create a more effective platform to communicate the concepts of QM.

A science curriculum that is about to incorporate QM should pay close attention to the language that is used in communicating the new scientific knowledge in science classrooms. As Wieman (2007) suggests in science education “informed scientific understanding” is required (p. 9). The significance of scientific literacy has been argued in the literature extensively and is viewed as a part of the goal of education in order to eliminate misconceptions and provide a more realistic understanding of science (Bybee & McCrae, 2011; Kruckeberg, 2006; Oulton et al., 2004; Papanastasiou, 2003). The literature also suggests that providing informed views of NOS in science classes would enhance the scientific literacy (Deng et al., 2011; McComas, 1998; Pedretti & Nazir, 2011). Therefore, as the use of language shapes the nature of PCK, the accurate

utilization of language, terminology would improve the informed views of NOS, and consequently enhance scientific literacy.

Although the literature does not provide insight regarding middle school or high school teachers learning about QM, it does provide examples of challenges that high school students face in learning QM, which was extensively elaborated in chapter two. One of the challenges was stated as pre-conceptions in classical mechanics, which was found to be the most common and fundamental challenge in engaging with the concepts of QM. In fact, the same challenges apply to pre-service science teachers who are learning QM for the first time (Savall-Aleman et al., 2016). Merely teaching classical mechanics lays a foundation that promotes monolithic and linear perspectives, consequently hinders an adequate understanding of QM ideas (Johnson, 2005).

Introducing the topics of QM at earlier ages would provide a platform for students to engage with a non-classical understanding of the world and prepare them to effectively learn about QM. This would not only improve students' engagement with terminology, but also would eliminate misconceptions. In the QM discussion session with students, the students expressed that they would like to be familiar with the concepts of QM starting earlier ages, where two of the classes refer to Grade 3.

***New ways of science teaching is required: utilizing analogies, metaphors, and story telling in relation to history and philosophy of science.***

QM is the physics of subatomic phenomenon. It is not typically possible to create hands-on experiments for all the concepts of QM in a regular middle school classroom environment. Alice likes to use analogies and metaphors in her conversations and in her

teaching, for instance according to her, teaching “should be like serving delicious food” and she says, “You do not want to leave your students with a bad taste.”

One of the fundamental PCK strategies that Alice used in her three classrooms was analogy. Analogies are essential in teaching not immediately accessible and intrinsically counter-intuitive subjects such as QM. Her use of analogies served to build up examples from familiar to unfamiliar, or from concrete to abstract, creating profound visualization opportunities in conceptualizing and capturing sub-atomic phenomena. Analogies play a crucial role in QM teaching, since “with the increasing complexity, abstractness, counter-intuitiveness, and mathematical nature of quantum theory, providing appropriate analogies to make understanding the theory easier might allow students to make better sense of the concepts.” (Didis, 2015, p. 359). The literature emphasizes how difficult, if not impossible, to teach QM concepts without using analogies and metaphors to introduce different philosophical perspectives than the ones classical physics offers (Didis, 2015; Wattanakasiwich, 2005).

Although a dearth of analogies and metaphors exist in textbooks or online resources, Alice was persistent and was able to find accessible and helpful videos and visuals that provided some analogies and metaphors. For instance, she located the cylinder analogy where there were two different shapes of shades at the same time. This was a pedagogically effective metaphor that promoted the counter-intuitive notion of the dual nature of light. However, the origin of these materials was not from academic sources, but rather from YouTube and Google. This represents a gap in the literature and in the textbooks that need to be addressed as BC science teachers approach the mandated curriculum.

Another effective PCK strategy that Alice used was storytelling. Science is beyond scientific facts, and storytelling can enrich the instruction of science, since “science deserves to be taught as an intellectual achievement and not as a set of principles” (Dagenais, 2010, p. 335). Consequently, storytelling in science classes can help to create science courses that are “a cohesive unit modified by ideas and concepts from the history and philosophy of science” (p. 336). In telling the history of science, and the struggles that scientists had in developing the concepts of QM in their experiments, Alice brought to life the marginalized and human aspects of science, so that students could relate to the people associated with the discoveries, such as spectrum rays or photoelectric effect. Alice’s way of presenting the scientific developments as an unfolding story seemed to help students to have a more complete picture of the emergence of the field of QM. This resonated with my own experience where I once told a story that illustrated the micro-scale aspect of QM, asking students to look at their own fingers and then imagine that by some magic they could no longer recognize their finger, but rather could only see the tissues in the finger. I then suggested that their vision changed, so that they could see it gradually reducing to smaller and smaller particles where they could only see the cells, then the molecules, then the atoms, and then the quarks. From my experience, this kind of improvised storytelling also could help to make the QM concepts more accessible.

Alice initiated a discussion regarding ethical implications of scientific developments and technology when talking about the topic of teleportation. This was particularly important because despite the disconnect between science and ethics being practiced in science education, there have been notable attempts to include ethical perspectives in science curriculum. Ethics, from a simplistic perspective, refers to the

“questions of good and evil, right or wrong, virtue and vice, and justice and injustice” (Herreid et al., 2012, p. 268). In fact, considering the complex nature of ethics, these are bigger questions than they may seem and essentially require informed decision-making and reasoning skills (Reiss, 2010). Ethics and scientific research have been separate until the implications of scientific research created new technologies and started to make an impact on society; therefore, the recent advancements in the field of physics in the 20th century, such as making atom bombs, begged the requirement of having conversations about the concepts of technology and social responsibility (Rhee & Choi, 2014).

The discussions regarding negative social consequences of technology began in academia around 1960s (Cutcliff, 2000; Zeidler et al., 2005). The history of officially incorporating social issues in science education dates back to 1982, when the National Science Teachers Association (NSTA) published a position paper outlining the interdependency of science, technology and society (NSTA, 1982). Zeidler (2001) summarizes the reflections of this process as follows:

As the 21st century unfolds, professional associations (e.g., AAAS, 1989, 1993; National Science Education Standards, 1996; CMEC’s Pan-Canadian Science Project, 1997; Queensland School Curriculum Council, 2001) in science recognize the importance of broadly conceptualizing scientific literacy to include informed decision making; the ability to analyze, synthesize, and evaluate information; dealing sensibly with moral reasoning and ethical issues; and understanding connections inherent among socio-scientific issues (p. 357-358).

The science, technology and society (STS) movement constitutes a profound place in the field of science education (NSTA, 1982). In 1985, the yearbook of NSTA was

dedicated to STS teaching. Following the STS movement, Duschl (1988) emphasizing the social dimension of science stated the intended approaches to science education were humanistic. Stinner (1995) supported Duschl's argument by suggesting that understanding science education by its underpinning of humanistic characteristics emphasizes the human along with narrative and interpretive aspects of science.

Incorporating aspects of STS in science education required significant transformational implications for education in science and also teacher training as Bunting and Ryan (2010) suggest "the teacher needs to be able to integrate knowledge of the issue or topic with knowledge of ethical reasoning approaches" (p. 52). Rhee and Choi (2014) stressed the importance of the teacher's contribution in ethics education as "ethics education, more than any other area of education, entails authenticity, and so its effectiveness can be maximized when teachers not only deliver knowledge and ethical principles but also try to reflect on their own ethical awareness (p. 1126).

The implications of ethical issues arise typically in engineering, in other words the implication of science. Martin and Schizinger (1996) suggest that engineering ethics can be defined as:

Engineering ethics is (1) the study of moral issues and decisions confronting individuals and organizations engaged in engineering and (2) the study of related questions about the moral ideals, character, policies and relationships of people and corporations involved in technological activity (p. 2-3).

Engineering ethics is an example of an inter-disciplinary field that brings engineers and philosophers together, where both engineers and philosophers are funded by the National Science Foundation and private initiations.

Reilly and Strickland (2010) and Weidman and Coombs (2016) provide examples regarding the implications of ethics in science classes. Reilly and Strickland (2010) put focus of the study to elaborate the ethical issues that scientists face by promoting discussion in the classroom along with essay and paper writing activities on the ethical issues in the scientific community. Weidman and Coombs (2016) provides an entertaining and engaging way for students to tackle the kinds of ethical issues that scientist through a simulation game, called dodging marshmallows. Discussions, writing activities or simulation games would allow students to embark on ethical issues pertinent to scientists.

Alice deliberately brought up the ethical issues that may arise along with the advancements and implications of QM in everyday life. Her approach here was an appropriate example of blending pedagogical and content knowledge together, triggering the students' imaginations not only with the content knowledge of an abstract concept, but also with its ethical and social consequences. From my perspective, Alice's practice was an appropriate example of PCK in QM.

Having said that, despite the depth and breadth of the academic discussions around the topics of science, technology, society (STS) and ethics, these two concepts have never been effectively implemented and practiced in science education (Gaskell, 2001; Nashon et al., 2008; Zeidler et al., 2005; Waks, 1999). While Gaskell's (2001) approach offers a localized argument in BC based on the unsynchronized timing of this initiation with technological and economic transformations, Waks (1999) claims that the traditional, factory model of education was a hindrance for effective implementations of STS. Nashon et al. (2008) suggest the reason may be that while the efforts have been dedicated

to cultivating “tremendous rationale for policy” for STS, it was “left underdeveloped the will for practice” (p. 399). Zeidler et al. (2005) points out that STS integrating ethics approaches, STS(E), remained marginalized in science education because of another potential reason:

Traditional STS(E) education (or perhaps STS(E) education as currently practiced by and large) only “points out” ethical dilemmas or controversies, but does not necessarily exploit the inherent pedagogical power of discourse, reasoned argumentation, explicit NOS considerations, emotive, developmental, cultural or epistemological connections within the issues themselves (p. 360).

Here, Zeidler emphasizes that ethical issues of science exist within a complex framework and this complex dynamic is not acknowledged in science classrooms. Alice touched on the ethical issues in her classes what the technology of QM might cause in the future, but she has not explored the ethical issues in depth or within the above-mentioned complex framework. The reasons are twofold; first, she did not have enough time to expound on ethical conversation, second, she has not prepared a body of knowledge in ethics in relation to implications of science. Due to the potential encounter of ethical and societal issues that the technological advancements that QM would generate, incorporation of QM into the science curricula may aid revitalizing and transforming the concepts of society and ethics in science classes.

***Pre-PCK is required in introducing a new subject.***

Alice underlined that she always starts learning a new topic by setting the purpose for learning. She introduced the purpose of learning QM as being the new modern science that is the foundation of the technology her students use as well as a new subject

in the Grade 8 science curriculum. In her own learning experience, Alice realized that she also needed to keep her purpose in mind. Her purpose in learning the concepts of QM was primarily to teach it to her Grade 8 students with the goal of broadening their perspectives in science. By participating in this research however, she was not only preparing herself for the upcoming curriculum change, but she was also helping other teachers who will be facing similar challenges. According to her, having these multiple purposes created motivation in her learning process.

Alice announced that she was going to teach the topics of QM to her students three weeks prior her teaching. She intentionally announced it in a special way that as if QM classes were not going to be regular classes, rather a special science ‘event.’ Alice also advised her students to look at the video materials two days before the classes, so that she made sure that her students would have enough time reflect on the new topics. These deliberate actions contributed to her students’ level of readiness and anticipation for learning. In this vein, it can be viewed that Alice’s PCK development has started before her actual classes. I will refer to these attempts as pre-PCK, which contributed to her PCK development.

Pre-PCK refers to the pedagogical and content knowledge provoking activities that a teacher initiates prior to the class in order to improve the PCK development in the actual class. Pre-PCK activities can be understood as announcing the subject prior to the class, creating wonder and anticipation in students, explicitly articulating the purpose for the subject, encouraging students to get familiar with the subject through the suggested teaching materials. Pre-PCK activities require students to engage with the new topic on their own, thus mainly promote student-centered constructivist approaches. Although the

readiness of students is viewed as a positive contributor to learning and have been discussed in the literature (cite), the activities that are intended to physically and mentally improve preparation process for a new subject has not been discussed in the PCK framework. In this regard, the development of pre-PCK with its pedagogical and content knowledge aspect could be viewed as an integrated aspect of PCK.

***A model for introducing a new subject could be utilized.***

Pre-PCK activities would provide a basis to develop a more effective and student centered PCK in the classroom. In classroom teaching practice, it is recognized that incorporating a new subject into the school curriculum requires development of a new PCK; in that building a new content knowledge along with appropriate pedagogical approach for that specific topic would be needed, which is typically developed over time with practice. Rollnick et al. (2013) point out the challenge as follows:

The challenge of teaching new subject matter is a familiar one for most teachers. Teachers face an enormous challenge when confronted with the task of teaching a topic that is completely new to them. It has been comprehensively argued in the literature (e.g. Kind 2009) that the relationship between a teacher's content knowledge and the ability to transform it for teaching is complex (p. 1436).

There have been recommendations for an effective structure to introduce a new subject in the school curriculum. For instance, Layton's (1972) three-stage model of subject emergence on development of science in England in the 19<sup>th</sup> century, which seems compatible with the incorporation of the topics of QM into the BC's new Science 8 curriculum. According to his model, the first stage of introducing a new subject is its inclusion within a different subject only as a topic, typically with the initiation of

enthusiastic teachers. Layton (1972) suggests that this first appearance is usually based on a few hours in the classroom and then it might become a subject lasting an entire semester. In 2016-2017 education year only some topics of QM became mandatory within Grade 8 science classes, potentially showing that the BC Ministry of Education is currently in the beginning stages of introducing QM into the Grade 8 science curriculum. In the second stage of Layton's model, subject specialists would offer support in terms of teacher professional development. As the second stage of introducing a new subject, the Ministry can expect to provide support to teachers in the form of workshops or conferences. In the third stage teachers would gain a professional status such as that of 'QM teacher.'

Looking ahead, the establishment of QM as a subject in itself would make it strongly bounded from other areas of science. Until a newly introduced subject is strongly bounded, it will have an ambiguous identity and the settlement of the new subject will remain at risk (Bernstein, 1971). When considering the introduction of a new subject into school curriculum, it is expected that the subject would have an established department at universities, not only to give credibility to the subject, but also to provide a clear pathway to university for students (Goodson, 1985). Goodson (1985) points out a practical factor in establishing QM as a recognized subject, as it could inspire teachers and students to achieve further learning, when it possibly can lead to financial improvement and career prospects. Another argument on supporting the inclusion of a new subject would be to cultivate a holistic approach taking account the external factors in a broader perspective, such as informed parents, universities, employers, and the general public (Goodson, 1985).

Appleton (1995) adds that in the success of introduction of a new subject teacher confidence plays a major role. According to him, portraying self-confidence would create a positive self-image and contribute to the effectiveness of the class; otherwise, as he suggests the attempt to teach a new subject will fail. The findings of this study closely aligns with this statement as Alice heavily emphasized the importance of teachers' self-confidence and reciprocal trust between students and teachers for an effective teaching environment. Alice explained her learning experience to her students, humbly mentioning that she had no prior knowledge about these QM concepts. She presented herself as a co-learner in the class and developed a sense of self-confidence by sincerely sharing her vulnerability in learning a new subject as a teacher. Teaching in smaller groups as opposed to large university courses would also work more effectively when a teacher is introducing a new subject for the first time (Appleton, 1995); therefore, the size of a middle school class seems to be convenient to introduce a new subject.

**Theme 2: The student-centered approach mandated in the redesigned curriculum may be limiting**

In PCK development pedagogical approaches are shaped by the nature of content knowledge (Cochran et al., 1993; Hashweh, 2005; Shulman, 1987). As the data demonstrated, the development of PCK in QM might initially require traditional approaches. It is important to note that, this dissertation refutes the binary understanding pedagogical approaches as needing to be either traditional or constructivist. Traditional approaches do not necessarily confront and conflict with constructivist approaches. Given the human subjects and the complex nature of environment, even the same teacher who follows the same structured worksheet, will always be in an ever-changing

environment, and there will always be a new dynamic; not fixed, as the traditional approaches appear. For instance, although Alice utilized the same worksheet for three of her science classes, the lessons run by the same worksheet in each class were different. Firstly, Alice seemed more confident as she was teaching the same worksheet and it reflected to her tone as a sense of comfort and accessibility. She also seemed to be confident to include additional stories based on her learning experience and a couple of jokes. In all three classes Alice was sensing the class and adjusting the flow of the lesson and her responses in relation to student reactions, modes, answers, and even the general mood of the class. Alice was able to change her teaching in relation to student responses, which indicates that she was cultivating an evolving PCK with and in relation to student responses. Therefore, the PCK development through traditional approaches would be still in flux and inter-dependent to students' reactions in the class. In this sense, a solely traditional approach would not be possible. As a consequence, the term PCK used in this dissertation aligns with the constructivist framework of PCKing and should not be considered differently.

Although the redesigned curriculum in BC leaves the responsibility of ways of teaching and the time allocation for the topics of curriculum to teachers, it identifies student-centered approaches as the overarching pedagogy while promoting personalized learning styles (BC's New Curriculum, 2015). Alice acknowledged that her responsibility as a teacher is to use these contemporary approaches to guide her students as mandated in the redesigned curriculum (BC's Redesigned Curriculum, 2015). However, the findings showed that even engaging with so-called traditional approaches would leave room for student-centered adjustment emerging from the inter-related

dynamics between students and teacher. Therefore, it might not be useful to make exclusive distinctions between traditional and constructivist pedagogical approaches and a specifically mandated pedagogical approach by the Ministry may be limiting for science teachers who will be exploring effective ways of developing PCK in QM.

The challenge of fully adopting a student-centered, personalized learning approach in relation to QM curriculum is twofold. Firstly, it seems to be that there is scarce amount of age-appropriate and reliable online resources and hands-on activity ideas readily available for teachers thus without appropriate teaching material teachers' didactical employment of the content is inevitable. Additionally, due to lack of prior knowledge and experience in teaching QM following a worksheet is easier and safer for a teacher in introducing a new topic. However, it should be noted that following a worksheet in teaching does not necessarily exclude student-centered pedagogies. Looking ahead, science teachers would be able to fully adopt student-centered approaches in QM classes as they gain experience and improve their PCK in QM.

**Theme 3: The nature of learning QM is not different than learning other subjects.**

For Alice, the nature of learning the topics of QM was emerging from 1) engaging with a growth mindset, 2) cultivating conversations, 3) adopting a gradual, step by step learning including the history of the subject, and 4) making the subject relevant. These aspects are found to be mutual in learning any other subject, thus it is suggested that the fundamental requirements to learn about QM is not different than learning any other subject.

***Growth mindset is a prerequisite.***

Alice mentioned that she taught her students the benefits of having a growth mindset as opposed to having a fixed mindset. Growth mindset is a contemporary concept in science education that started to appear in the literature particularly after the year 2000 (Dweck, 2006; Shumow & Schmidt, 2013; Siegle & McCoach, 2005). Growth mindset is of particular important in learning environments, since “students with a growth mindset tend to embrace challenges, persist in the face of obstacles, perceive effort and study strategies as a means to learn, utilize feedback to improve, and find inspiration in the success of others” (Esparza et al., 2014, p. 6). These studies show that introducing the concept of growth mindset versus fixed mindset would improve students’ academic achievements, since growth mindset approach sets the focus on the learning process, rather than the learning outcomes. In this regard, having a growth mindset is viewed as the heart of all learning.

As Alice was learning about the concepts of QM, she realized that an open mind was needed in exploring the field of QM. She explained that the concepts of QM leave room for curiosity, mystery and different possibilities requiring a growth mindset or a sense of openness for transformation. QM may promote opportunities for growth in unexpected and unexplored directions. One needs to grow to an open mindset to capture the concepts of QM, since they are counter-intuitive and unfamiliar than anything we experience in every day world. The understanding of QM was shocking even for the scientists who made the discoveries putting them in a position where it was difficult for them to believe that what they have discovered was real. For instance, Einstein could not make sense of what he came up with when he discovered the notion of entanglement and called it “spooky action at distance.” When Alice linked learning about QM with the

concept of growth mindset, she was referring to the kind of growth and openness that is needed in order to accept another version of reality that confronts the known reality.

Although I was familiar with the concept of growth mindset, I had not made the connection with learning QM and developing growth mindset earlier. The growth mindset and QM connection could provide insight in understanding the influence of engaging with the concepts of QM on a personal level.

Given the potential positive contributions of growth mindset to learning, it seems beneficial to incorporate elements of teaching growth mindset in education as a meta-subject that would set the tone for learning all school subjects. In addition, rather than directly teaching the concept of growth mindset, the ideas of growth mindset could be indirectly instilled through the concepts of QM, while in learning QM students would be inevitably forced to step out of their comfort zone to embrace the challenge of opening their minds to a different reality.

***Conversation is vital in learning.***

In this study the words conversation and dialogue are used interchangeably. Conversation is particularly important to this study for two reasons: 1) Alice expressed that having conversations with me greatly helped her learning process, 2) in her PCK development, conversations created an opportunity where Alice left teacher-centered role and adopted a student-centered perspective. Therefore, both in Alice's and students' learning cultivating conversation regarding the new concepts enhanced the learning experience.

Alice emphasizes the importance of conversation in the process of learning the concepts of QM. She said that “bouncing ideas off, ” and “having a conversation” was

essential, particularly with the concepts that are not immediately accessible to everyday perception. In her learning process, cultivating dialogue seemed to have facilitated the development of Alice's thinking and enhanced her engagement with the topics of QM.

The importance of cultivating a conversation in learning environments has been studied widely through socio-cultural and dialogic theories (Bakhtin, 1981; Norris & Sawyer, 2012). Here, it might be necessary to note that the difference between a conversation and dialogue is outlined as follows: "the character of conversation varies according to context, topic or persons involved: it can be 'idle', 'relaxed', 'in passing', 'playful', or 'serious', while dialogue has always a serious, challenging and demanding character" (Kazepides, 2012, p. 915). At times, the notion of conversation has been replaced with the term "dialogue" particularly in Bakhtin's (1981) and Vygotsky's (1978) works. According to Cambridge Educational Dialogue Research Group, the term dialogue is distinguished from conversation because it can be both a pedagogic tool and an end in itself, and it is associated with, "...critical and higher level thinking, creative problem solving, making relevant links between and within subject disciplines, active and democratic citizenship and living peacefully" (Hennesy et al., 2016, p. 17). Cultivating conversations create productive learning environments in education, because knowledge can be co-constructed through explaining, contrasting, and criticizing ideas, in a conversation (Kubli, 2005; Littleton & Mercer, 2013; Michaels & O'Connor, 2013; Norris & Sawyer, 2004). Therefore, promoting conversation is essential in learning, not only the concepts of QM, but also any other school subject.

As mentioned above, conversations provide an enriching platform that thinking and re-thinking, evaluating opposing ideas, conceptualizing and developing new notions

could take place. Vygotsky (1978) suggested that talking and thinking are linked and that mental activities are rooted in society and social relationships. In Russian, the word consciousness is the combination of the two words, “together” and “knowledge.” It is suggested that promoting conversations, cooperation among peers and exchanging ideas in a group would enhance learning environments by promoting critical thinking and discursive reflection (McCormick & Pressley, 1997). Hennesy et al. (2016, p. 21) outline eight components of educational dialogue: 1) invite elaboration and reasoning, 2) make reasoning explicit, 3) build on ideas, 4) express or invite ideas, 5) positioning and coordination, 6) reflect on dialogue or activity, 7) connect, and 8) guide direction of dialogue or activity. In her PCK development in QM, the conversations that Alice promoted include some of the aspects of educational dialogue mentioned above, such as inviting elaboration and reasoning, expressing or inviting ideas, reflecting on dialogue, and guiding direction of dialogue. Therefore, effective learning could be enhanced for students by incorporating these aspects of educational dialogue.

Although Hennesy et al.’s (2016) educational dialogue framework was created for the purpose of better understanding students’ engagement in dialogue; it also applies to adult learners (i.e. science teachers) studying QM. For instance, Alice articulated some of these aspects of educational dialogue in her conversations when reflecting on teaching and learning QM. This speaks to the need for Grade 8 science teachers who are learning to teach QM to benefit from environments where learning through conversations would be provided, such as workshops or professional development programs that provide a platform for conversations and exchanging ideas among the learners.

***Gradual, step by step learning including the history of the subject.***

Alice mentioned that she was keen on learning new subjects, and her learning style is gradual, step by step learning as she expressed starting from A and moving to Z, even if she does not need to learn about A. For instance, when learning about electromagnetic waves, she looked first at the history of its development, then she learned about the concept. Making connections between a scientific concept and its historic background seems to provide the context that she needs to comprehend the scientific topic from a multi-dimensional perspective. When reviewing her notes as she learned each topic of QM, I realized that each topic began with a notation of the date or the name of the scientist who discovered that topic. Alice's learning style demonstrates an effective learning model for any subject matter, since studying a topic within its historical context provides a more complete picture of the topic while offering broader and deeper insights (Höttecke & Silva, 2012; Matthews, 1994; Oversby, 2009).

***Making QM relevant.***

Alice believes that making a topic relevant for students would improve their interest in that topic preparing an effective learning platform. This aligns with the studies which suggest that making topics relevant boosts students' interest in a topic (Broman & Simon, 2015; Welty, 1990). According to Alice, making a topic relevant needs to be connected with the purpose of learning that topic as well. Alice anticipates that the topics of QM would constitute a bigger part of everyday conversations in the near future, since the technology we use everyday emerges from the field of QM. By making the topics of QM relevant to students' lives, Alice aims to enable students making those connections, so that she could prepare her students for the future. As making topics relevant enhances

students' understanding independent from the field of study, this aspect of learning is not different than learning other school subjects.

**Theme 4: Middle school science education is inconsistent with the current level of scientific knowledge.**

The science education in schools and science practiced at the universities are not consistent with each other not only from the content knowledge perspective, but also with the embedded views of NOS, which likely to remain to reflect a narrower and incoherent understanding of science, unless necessary updates in science curriculum takes place. Incorporating the topics of QM would promote critical thinking skills and enable informed views of NOS. In the writing that follows I will elaborate this issue from two perspectives: 1) content knowledge in middle school science curriculum is outdated, so is the underlying views of NOS, and 2) teaching QM can instil informed views of NOS.

***Content knowledge in middle school science curriculum is outdated, so is the underlying views of NOS.***

During our interviews Alice mentioned the differences between science that is taught in K-12 schooling and in universities. She explained that in K-12 schooling science is presented as objective and factual and within a certain frame; however, at the university level the field of science is presented with an emphasis on its tentative and creative aspects, as it is studied and presented as a human activity.

For instance, in school science education the atom is demonstrated and taught with the Bohr atom model, which shows the electrons like planets in the planetary system revolving around the nucleus. The Bohr atom model belongs to the scientific knowledge of hundred years ago, and with the advancements in science, it was replaced by

Schrodinger's quantum atom model in 1926. In the quantum model electrons are considered to exist in a balloon-like clouds around the nucleus and due to the uncertainty principle electrons cannot have certain positions like the planets in the planetary system, rather the position of an electron can be thought from a probabilistic perspective, thus it can be anywhere in the cloud. From a visual and content perspective, quantum atom model is drastically different than the Bohr atom model. However, the updates and developments in scientific knowledge have not been entirely reflected in the science curriculum, despite the fact that some of school science topics like the Bohr atom model are not considered to be valid any longer from the 21<sup>st</sup> century scientific knowledge level. Therefore, not only is the content knowledge is outdated in the school science curriculum, the views of science embedded in this outdated content is also skewed. Consequently, unbeknown to the science teachers, their integrity seems to be at stake.

Alice had not realized that there was more current information regarding the atom model and regretted that she has not taught the quantum atom model in her classes, rather taught the Bohr atom model that was provided in the textbook. She wished that the quantum atom model had been included in a textbook, which she predominantly uses in preparing lessons. Alice explained that this dichotomy between schools and universities creates almost schizophrenic situation for the perception of science.

The literature supports Alice's views on the differences of the science education in K-12 and universities and demarcates the former as "low church" and the latter as "high church" (Fuller, 1993, p. xiii). The inclusion of NOS and the history and philosophy of science is essential in the high church, whereas low church, as the middle and high school science education, is "dismissed as non-academic" (Nashon et al., 2008, p. 388). The

dichotomy in teaching science in K-12 education versus universities seems to yield misrepresentation of the field of science, and consequently misconceptions in science education would naturally be expected (Didis, 2015; Ozcan, 2013; Savall-Aleman et al., 2016; Taber, 2008).

In terms of content knowledge Alice did not have any prior knowledge in QM. After exploring the concepts of QM, Alice said that she was surprised at how incomplete that her content knowledge in science had been. Alice believes that the challenge in teaching QM is that in the past, the science curriculum has not offered a complete representation of the field of science. She elaborated the difference as the content of the past science curriculum was fact-based and rational, while QM is counter-intuitive and requires imagination to grasp the concepts. Alice explained that teaching students rational, making sense aspect of science throughout elementary and middle school and then all of a sudden trying to inspire them to open their minds for conceptual understanding of QM seems “contradictory.” She said gradually introducing the general ideas of QM starting at younger ages would prepare students for more accessible QM lessons in Grade 8 classes.

Alice explained her feelings of fear by referring to standing behind the stage curtain and having to present a cutting edge science. Listening to her, I wondered if it was the nature of unknown territory and the notion of unfamiliarity that was frightening. I also wondered why she said that we enjoy the outcome of science, but do not want to be ‘behind the stage curtain’ referring to engaging with science. Is it because anything unknown can happen behind the curtain, and it is safer to stay on the known side of the curtain? Does the challenge of science come from willing to stay in the comfort zone?

She said science is perceived to be difficult, challenging and requiring relatively more time in order to feel confident about it. These might also be the common perceptions of science engrained in society, that science might be intimidating and viewed as being out of the comfort zone; and thus, it would be better to stay on the known, front side of the curtain and just watch the scientific performances taking place on the stage from safe, comfortable seats. This analogy refers to Alice's perception of the practice of science, where science is seen as a performance, scientists as actors, and general public as the audience in a theatre play that lacks inter-action. I noticed the alienation of science and scientists in her analogy, which I also witnessed as an articulated perception of science in general public. Incorporating inter-action between science as practiced at universities and science education at schools would help to eliminate this alienation and provide a more complete and realistic science education. Therefore, an update on the content knowledge in middle school science curriculum seems to be necessary and timely, which may include firstly quantum atom model and potentially other topics of QM to provide a more complete representation and sense of the field of physics.

***Teaching QM can instil informed views of NOS through critical thinking.***

Alice is clearly already aligned with the Ministry's goals of the redesigned curriculum; in that, she aims to raise her students as effective citizens by fostering critical thinking. She says students' future goal should not be getting a job and buying a car, but most importantly should involve being able to function in society and to cultivate an open mind for critical thinking in order to make informed decisions. She emphasized the significance and value of encouraging students to expand their imagination and open their minds. In the case of QM teaching, fostering imagination and creativity might create an

appropriate platform to engage with the informed views of NOS. Alice believed that learning and wrestling with the concepts of QM would enable students to be the critical thinkers that Alice and the Ministry of Education want them to be, and what society will need them to be.

Critical thinking is a meta-cognitive process (Bailin, 2002; Espinoza & Quarless, 2010; Gotoh, 2015) and active process for search of quality thoughts (Scriven & Paul, 1987). Problem solving, decision making, and cooperative learning are recognized as the traits of critical thinking skills, have been viewed as a goal of science education itself before 1980s, during the 1980s with an emphasis on encouraging the processes for critical thinking for pedagogical innovations, after the 1990s as an ability to employ critical thinking skills in diverse situations not only in school life, but also in students' personal lives (Terry, 2012; Vieira et al., 2011). From this perspective, promoting critical thinking skills could be viewed as the definition of education itself which may help to reduce egocentric attitudes by empowering abilities for conscientious participation in a pluralistic society with citizenship competence (Bailin, 2002; Wright, 1992). Developing critical thinking encourages students to approach controversial issues of science and technology in society with informed views of science, so that they can participate in scientific discussions and make informed decisions for themselves and for the future of the nation (Albe, 2007; KolstØ, 2001).

Alice views teaching the counter-intuitive aspects of QM as opening a new window for her students. Alice realized that students are more engaged when the material is not intuitive. It appeals to them, she thinks, because they find the conversations akin to talking about a science fiction movie or a video game. She says

that the counter-intuitive nature of QM leads to disruption of their pre-conception of science as being rational and making sense. It is mind opening for students when, for the first time, reality no longer makes sense. Alice recognizes that engaging with counter-intuitive concepts in a science classroom makes science playful and the learning process fun.

The counter-intuitive nature of QM has been discussed in different frameworks, in one of which Alice linked the counter-intuitive nature of QM, as in the topic of superposition, with subjectivity. According to Alice, the counter-intuitive nature of QM aligns QM with the field of humanities such as sociology and psychology; areas that she would not classify as objective, but like human focused studies, not completely linear and rational. For instance, in the social sciences, two seemingly different or even opposite attributes can be true at the same time. From a psychological perspective, a person can both love and hate another person, or they can be attracted and repulsed at the same time. In this sense, she said, QM is more akin to the social sciences with the concepts of superposition and uncertainty principle. Here, Alice refers to the “social and cultural embeddedness of science” which can be understood as a human enterprise where “science affects and is affected by various cultural elements and spheres, including social fabric, worldview, power structures, philosophy, religion, and political and economic factors” (Abd-El-Khalick, 2012, p. 357).

Alice’s perception of the nature of QM as subjective aligns with the Copenhagen interpretation of QM, which posits that even the apparatus used in the experiment is also a part of the understanding of the reality, thus the mere act of measuring a quantum system ultimately disrupts the system; consequently, objective pure information cannot

be acquired from the system. This aspect of QM could be interpreted as subjectivity. Since the outcome of a QM system depends on the perspective taken when looking at the data, Alice mentioned that QM is not fixed, linear and predictable. This creative and tentative understanding of QM can be seen in the field of astrophysics as well. For instance, as it was discussed in one of the interviews, while working with the same data and observations, some scientists claim the universe is expanding; others claim that it is shrinking. Despite the solid consensus regarding the laws of classical mechanics, astrophysics and QM might offer different schools of thought that exist within the same field all based on shared data. When I was trying to understand Alice's views on creativity in science, it appeared that she had come to understand that in scientific explorations there could be two different right answers at the same time. As another aspect of NOS, creativity can be defined as Abd-El-Khalick, (2012) suggests "creativity is involved in all stages of scientific investigation, including prior to, during, and following the collection of data, and is particularly relevant to interpreting data and generating conclusions from these data" (p. 357).

The dual nature of light was represented analogically with the image of the cylinder in the classroom. In my opinion, the cylinder demonstration was a remarkable analogy to raise profound questions in relation to the views of NOS. For instance, could this be true for the scientific knowledge? If so, would that make science a creative field of study? Can science education ever provide a platform to discuss this kind of questions? A deeper understanding of QM could have been explored by delving into these questions.

According to Alice many-world theory in QM also has the potential to initiate philosophical thoughts in science classes. She said, the philosophical approach "allows

for students to bounce ideas off each other, and to think creatively. Students are encouraged to think in a way that inspires them to ask ‘what if?’” This mode of thinking has not necessarily been explored in other school subjects, since the students have most likely been exposed to a predictable set of knowledge in their science classes; perhaps even hindered to think about other possibilities, so that the ‘what if?’ questions most likely have not arisen. By offering unfamiliar and intrinsically counter-intuitive perspectives, the topics of QM might encourage students to embrace unpredictable aspect of science and question the taken-for-granted notions of immediate reality.

In our interviews, I realized that Alice had already a preconception about paradigm shifts before this research due to her prior knowledge in the history of science. She explained paradigm shift with her own words as scientists “stepping out of their comfort zones and moving into something different” emphasizing the long process of proposing a paradigm shift in scientific community. Here, Alice unknowingly refers to the scientific crisis stage that Kuhn (1996) describes in his process of scientific revolutions. Apparently, Alice holds some aspects of the informed views of NOS by acknowledging the place of paradigm shifts in the development of science.

Alice also said, “we would not be able to learn it all, that science can never be perfect.” By suggesting that there will always be things left unknowable in science, once again Alice unknowingly referred to one of Kuhn’s (1996) notions in the field of philosophy of science that says that there is no ultimate level of knowledge in science; and thus, perfect science level is not possible. I was impressed that a science teacher would be able to so easily engage with one of the sophisticated notions that have been thoroughly discussed in the field of philosophy of science from informed views of NOS.

In this vein, Alice recognizes the human factor in developing scientific knowledge and refers to the social and cultural embeddedness aspect of NOS (Abd-El-Khalick, 2012) in the way that science interacts with a larger cultural milieu such as social fabric, worldview, philosophy and religion just to name a few, and these interactions could be complementary. Furthermore, by suggesting that science is time-dependent, Alice demonstrates that she has adopted tentative aspect of informed views of NOS.

Alice said that QM is more futuristic than the other science subjects. This may be because she has encountered the concepts of QM in science fiction movies. Science fiction differs from science facts in the way that science fiction offers an imaginary aspect of science, rather than the currently accepted and applied aspects in the field of science. The connection she made between QM and science fiction movies may have been because the concepts of QM reminded her of the imaginary, unattainable possibilities in science, which aligns with the open-ended aspect of informed views of NOS.

Alice said, “Learning about QM requires faith and belief, because it is not based on what you see” referring to the fact that QM operates in the subatomic realm and is not accessible by our naked sight. Alice’s statement corresponds to the inferential aspect of NOS, which is explained by Abd-El-Khalick (2012) as “inferences are statements about phenomena that are not directly accessible to the senses” and “most scientific constructs are inferential in the sense that they can only be accessed and/or measured through their manifestations or effects” (p. 357). This aspect of NOS refers to the epistemological perspectives embedded in informed views of NOS.

She also mentioned that teaching QM is different than teaching math or geometry

in the sense that QM is open to transformation. Other school subjects typically study the intuitive natural phenomenon, whereas QM offers counter-intuitive and unknown possibilities for the transformation of the field. Elaborating the difference between classical mechanics and QM seems to be fundamental to both learning and teaching QM. Making comparisons and learning about a new topic through differences demonstrates the implication of the variation theory. Alice implicitly utilized the variation theory in her learning process and also in her teaching practice, while comparing and contrasting the concepts and understanding of QM with her prior knowledge in science and everyday experiences.

Alice had inevitably encountered and pondered some concepts of NOS throughout her engagement with the topics of QM. Consequently, by drawing conclusions from her prior knowledge in NOS and what she has learned about the history of QM and QM concepts, she developed certain views of NOS, which showed elements of aligning with the aspects of the informed views of NOS that were elucidated in NOS literature (Abd-El-Khalick, 2012; Lederman et al., 2002). A prominent finding of this study was also that exploration of the views of NOS cannot be accomplished without incorporating HPS into the conversation. As Forato et al. (2012) suggest “the inclusion of history and philosophy of science (HPS) in the science curriculum is regarded as a suitable support to target some selected features of the nature of science (NOS)” (p. 658). Here, the selected features refer to the informed views of science, where it appears that providing the informed views of science may affect students in multiple ways, such as contributing to active citizenship, democratic decision making and furthering the best interests of society (Lederman et al., 2002; Gaskell, 2002; Matthews, 1994; Oversby, 2009). These broader

goals of science education seem to point to the importance of supporting teachers in learning and teaching the concepts of QM within a NOS and HPS framework.

Here it is important to note that the discussions regarding the detailed aspects of NOS that Alice holds might have been shaped by my interview questions, such as “Do you think renovations are allowed in science?” or “Can two scientists in different parts of the world generate different scientific knowledge based on the same data set?” The nature of these questions might have provided Alice with a space to more thoroughly ponder the concepts of NOS in a more refined and explicit way. The interview questions might have shaped Alice’s answers; however, without the interview questions an access to Alice’s views of NOS would not be possible. Here, the interview questions act like a measuring instrument in a QM experiment, where the act of measurement inevitably changes the nature of the outcome.

**Theme 5: The development of informed views of NOS requires an accumulation and synthesis of prior knowledge in HPS on that subject.**

In the writing that follows, I expound the inter-dependent relationship between the views of NOS and knowledge of HPS in order to elaborate this particular theme.

Alice spoke about the evolution of science starting from Aristotle’s times and how the body of knowledge and perspectives of science have changed. She then commented that as science has evolved so much since Aristotle’s time, it would most likely continue to evolve. Furthermore, she contrasts the field of science with other school subjects saying that unlike the rules of math and geometry, the field of science is able to transform. By understanding the history of science, where numerous paradigm shifts took place and transformations become explicit, Alice demonstrated that she is grasping

elements of philosophy of science. For instance, her perspective aligns with the open-ended, evolving nature of scientific endeavour, the stage of crisis and paradigm shifts in scientific developments as stated by Kuhn (1996).

History of science provides a multi-dimensional context where learners can make meaning of the scientific concepts in relation to human dimension of scientific developments. Teaching the history of science furthers students' ability to understand concepts, since "history allows students to situate and assess their own understanding of scientific concepts on the background of historical concepts and ideas (Oversby, 2009, p. 3). In addition, the integration of philosophy of science is intrinsic to the understanding of science, as Oversby states, "while science teaching and learning may be separated from history, they never can be separated from philosophy, (since) . . . philosophy supplies a meta-language to talk about science" (p. 2). Here, he refers to the philosophical understanding of science that provides a culture-like systematic framework that embeds certain ways of thinking. Promoting aspects of HPS in science education would enhance the meaning making process for students about the world and also about the self (Höttecke & Silva, 2007; Nussbaum, 1998; Oversby, 2009).

The philosophy of science typically refers to the ontological and epistemological understanding of science, which is indirectly and inevitably taught in science education; whether it is classical mechanics or QM (Forato et al., 2012; Savall-Alemany, 2016). In other words, the views of the nature of knowledge and the ways that knowledge is acquired are embedded in the understanding of the field of science. As Forato et al. (2012) suggest, "each way of presenting or teaching scientific knowledge conveys, implicitly or explicitly, a view of the nature of science" (p. 658). Therefore, the

embedded views of NOS and philosophical approaches in science education provide students with an understanding of not only science, but also a philosophical approach to a way of being in the world. For instance, teaching merely classical mechanics exclusively imposes deterministic views of the world and also sets the tone for a distorted understanding of science within a monolithic framework (Johnson, 2005; Nussbaum, 1998). QM promotes fundamentally different ontological and epistemological perspectives than classical mechanics; and thus, along with classical mechanics, QM has the potential to provide multi-dimensional ways of meaning making in science classes.

Alice recognizes that any contribution to science is valuable even if it is proven to be wrong over time, as were some of Aristotle's ideas. Here, unknowingly, Alice referred to Popper's (1959) notion of falsifiability in the field of philosophy of science, where all scientific theories can be accepted as only temporarily true until a falsifying test occurs. Alice said since writing was invented, the body of scientific knowledge has been passed on to the next generations and everything has been tested; however, this testing stage is a continuing process. After learning about QM, she speculated that even mathematical constants like the number pi might be updated. She admitted that she expects that future generations would change some scientific facts that we believe to be true today. Here, Alice refers to the tentativeness of science, which posits that "all categories of knowledge ('facts', theories, laws, etc.) are subject to change" (Abd-El-Khalick, 2012, p. 357). Over the course of our discussions, it was clear that Alice's perspectives of NOS were forming and re-forming through reflection and deliberation.

Alice's understanding of science enhances with her prior knowledge coming from history of science and reflects on her PCK development. History of science could be

incorporated in QM teaching in order to make physically inaccessible concepts more concrete and more relevant to the students by providing a contextual understanding of scientific enterprise and connecting the process of scientific discoveries with the real people who were involved. Alice says that the counter-intuitive nature of QM involves sociology and psychology, referring to the human dimension of science. Alice's perspectives here tie in to the STS approach, which has been set as one of the goals of science education (Allchin, 2011; Alters, 1997; McComas, 1998).

In order to implement STS approach in science education incorporating elements of HPS into science education would be essential (Nashon et al., 2008; Villani & Arruda, 1998). The conceptual understanding of science in relation to its philosophical and historical background would allow students to see the field of science in a more complete way. Einstein (1944) provides a helpful metaphor emphasizing the importance of history and philosophy of science in science education as follows:

I fully agree with you about the significance and educational value of methodology as well as history and philosophy of science. So many people today—and even professional scientists—seem to me like somebody who has seen thousands of trees but has never seen a forest. A knowledge of the historic and philosophical background gives that kind of independence from prejudices of his generation from which most scientists are suffering. This independence created by philosophical insight is—in my opinion—the mark of distinction between a mere artisan or specialist and a real seeker after truth.

Having seen thousands of trees, but never seen a forest summarizes the situation of science education practice that lacks the concepts of history of science along with philosophy of science. The benefits of incorporating HPS in science education has been extensively discussed in the literature. For instance, Matthews (1992) suggests that the inclusion of history and philosophy of science in science education can: a) make sciences more connected with personal, ethical, cultural, and political concerns, b) contribute to the fuller understanding of scientific subject matter, c) contribute to meaning making, d) provide a richer and more authentic epistemology of science, e) provide a greater understanding of the structure of science and its place in the intellectual schema of things.

HPS is intrinsically connected to NOS and incorporating a HPS approach would facilitate the informed views of NOS in science classes (Abd-El-Khalick & Lederman, 2000; Bell et al., 2001; Matthews, 1994; Solomon et al., 1992; McComas, 2000). In doing so, scientific concepts would be taught more effectively (Dedes & Ravanis, 2008; Galili & Hazan, 2001), the understanding of science in society could be enhanced (Solomon 1997; Osborne et al., 2002), students' interest towards science could be fostered (Kubli, 1999; 2005; Solbes & Traver, 2003) and potentially contribute to effective citizenship (Albe, 2007; Kolsto, 2008). As science and philosophy are interconnected (Matthews, 1994), "the separation of science from philosophy results in a distorted philosophy" (p. 84). It is suggested that an understanding of the philosophy of science through HPS and STS would enhance the foundational understanding of science subjects (Cutcliffe 2000; Matthews, 2000). Some aspects of NOS could be effectively taught by incorporating elements of history and philosophy of science into the science education (Forato et al., 2011; Irwin, 2000; Osborne et al., 2003).

Adapting the scientific literacy framework that was suggested by Project 2061 (AAAS, 1989), Nashon et al. (2008) proposed the components of scientific literacy as: a) nature of scientific content (concepts and facts), b) nature of scientific process and inquiry, c) nature of scientific enterprise (institutions, disciplines), e) nature of discovery and application, f) science and technology as culturally situated, and lastly, g) public attitude and outlook toward science. In this sense, the first five components of scientific literacy would have global applications, whereas the last component refers to local applications. According to this research (2008) pre-service science teachers found that teaching HPS and STS was more appealing through the topics of QM. Furthermore, Nashon et al.'s (2008) study suggests that "the history of quantum mechanics can address a range of components of scientific literacy" (p. 398). This statement emphasizes the criticality of this particular theme regarding the inter-relationship between QM and informed views of NOS with the components of scientific literacy.

A consensus supporting the inclusion of NOS, HPS, STS, and emphasis on scientific literacy have been developed as theory and policies in recent three decades (Bell, 2001; Lederman et al., 1998; Matthews, 1994; McComas et al.; 1998). Government documents and science education research posit that learning knowledge in, about and through science should be fundamental in science education (AAAS, 1990; 1993; Bell et al., 2001; Clough & Olson, 2008). However, mandatory policies are not always followed by practical implementations and consequently "HPS and STS have been marginalized in the curriculum" (Nashon et al., 2008, p. 387).

Given the extensive recognition of the value of HPS in the science education literature there is also plethora of studies that suggest why and how the inclusion of HPS

in practice is not working for teachers (Forato et al., 2012; Höttecke & Silva 2011; Oversby, 2009). In general, the challenges of why HPS has not been effectively implemented in science education have been identified as: the traditional fact-based culture of teaching science; lack of professional knowledge for teaching science; lack of support for teachers within their institutional framework; and lack of updated textbooks and teaching materials providing HPS content knowledge and appropriate pedagogies (Abd-El-Khalick et al., 2008; Höttecke & Silva 2011; Irez, 2006; 2008).

Alice also pointed out that despite the mandatory curriculum, she suspected that most of the Grade 8 science teachers would not teach the newly incorporated topics of QM. The literature provides reasons that explain the explicit dysfunction in practice ranging from skills, beliefs and attitudes of teachers to the lack of support from the institutional framework including unsatisfactory textbooks and fact-oriented science teaching culture (Höttecke & Silva, 2011; Gaskell & Hepburn, 1997; Nashon et al., 2008; Waks, 1999).

In order to overcome challenges in incorporating a HPS approach in science classes, Höttecke and Silva (2011) provides a framework that compares and contrast the culture of science teaching (Table 3), the content of textbooks that is designed to promote informed views of NOS and HPS (Table 4), and teachers attitudes and beliefs in incorporating a HPS approach in science classes (Table 5).

Table 3

*Culture of teaching physics necessary for implementing HPS compared to culture as it currently is (Höttecke and Silva, 2011, p. 299).*

Effective history and philosophy in science teaching	The current culture of teaching physics
Physics is demonstrated as a process historically	Physics is taught as truth and a collection of

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developed and influenced by a wider cultural and societal context	facts
Physics is demonstrated as a matter of empirical investigation, discourse, and negotiation among scientists that result in knowledge that has changed and may change in the future	Content is not a matter of negotiation and discourse among students
Students' conceptual development is supported. Processes of knowledge acquisition in science and in learning science are critically reflected	Teachers provide scientific content. Spaces are designed for enabling transmission of knowledge by teacher talk
HPS encourages students to express their own ideas	Students associate physics with heteronomy
Female role models are demonstrated	Physics is constructed as male

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Alice mentioned that she uses the textbooks as a primary source and guide in her teaching. For instance, she stated that if she had seen the quantum atomic model, she would have taught it; instead she taught her students the outdated and conceptually incorrect Bohr atom model, since it was the atomic model that the textbook was providing. Despite the availability of resources that can be easily accessed through the internet, textbooks seem to be still crucial source, if not primary, for teachers in preparing their lesson plans (Höttecke & Silva, 2011; Oversby, 2009). Textbooks are often the primary source of content, activities and instructional materials, and can shape the design of lesson plans, activities, and instructional materials (Höttecke & Silva, 2011; Oversby, 2009). As well, textbooks are viewed by both teachers and students containing reliable information (Höttecke & Silva, 2011).

#### Table 4

*Comparison of desirable HPS content of textbooks and the current state (Höttecke and Silva, 2011, p. 305).*

Desirable demonstration of HPS in textbooks	HPS currently conveyed by textbooks
Historical accounts that foster adequate views on NOS and portrays science as a social enterprise	Historical narratives that reinforce the naïve empirical inductive view of science. Social and cultural influences are rarely discussed.
Textbook content suitable for students and teachers' learning about HPS	Historical information resumes to dates, names and timelines
Historical content combined and integrated to scientific content	Historical content isolated in boxes that are dispensable for the learning of scientific content
Activities that foster explicit reflections on NOS	Notions about NOS are conveyed implicitly; activities addressing learning about the NOS are absent
Collaborative work of historians, philosophers and textbook writers	Historians and philosophers are not involved in textbook writing

Table 5

*Comparison of physics teachers' attitudes and beliefs necessary for teaching HPS to those empirically found (Höttecke & Silva, 2011, p. 302).*

Effective history and philosophy in physics teaching	Attitudes and beliefs of physics teachers
Teachers have to focus on NOS as an explicit objective for their teaching	Teachers do not focus on NOS as an explicit objective of their teaching
Teachers know how to use HPS to transform NOS into teaching practice	Teachers do not transform NOS knowledge into a reflective teaching practice
Students reflect on the NOS explicitly	Students do not reflect on the NOS, teachers often convey incorrect messages about it implicitly
Teachers' beliefs about classroom organization are progressive. They acknowledge students' ideas and epistemological beliefs. They dispose of pedagogical content knowledge for moderating discussions and	Teachers' beliefs about classroom organization, epistemological beliefs and beliefs about teaching objectives are likely to be traditional

negotiations among students, support students' meaning making, and transform reflected views of NOS during their teaching

Teachers appreciate learning content, context and process of science with HPS

Teachers have skills for teaching HPS like telling stories about science, moderating open-ended discussions and role-play

If teachers appreciate history of science, they focus mainly on learning about context, but feel unsafe about teaching science as a process

Teachers usually do not have skills for teaching HPS since valuing HPS does not belong to their subject culture

Incorporating informed views of NOS through HPS in science education would enrich ways of knowing and quality thinking leading to more informed ways of being in this world (Höttecke & Silva, 2011; Nashon et al., 2008; Matthews, 1994). In the longer perspective, providing multiple perspectives in science education and enhancing students' skills in critical thinking would contribute to active citizenship, informed decision making and democratic society (Oversby, 2009). Consequently, why, what and how science education is practiced has a profound impact on society, potentially shaping a nation's growth, since "political decision-making increasingly depends on scientific expertise" (Oversby, 2009, p. 4).

In the exploration of Alice's views of NOS the concepts of the history and philosophy of science, scientific literacy, and STS emerged throughout the interviews. On reflection, it occurred to me that HPS, STS and scientific literacy are intrinsically integral to the overarching framework of NOS. Abd-El-Khalick (2012) also suggests, "our understandings about NOS largely—though by no means solely, derive from scholarship in history, philosophy, and sociology of science" (p. 354). To this date, the

literature still falls short in providing examples of organically adopted and effectively internalized NOS, HPS, and STS approaches.

The insights emerging from this particular theme speak to the need for educating in-service and pre-service teachers in order to provide the necessary foundation in the contextual understanding of science and informed views of NOS within the PCK framework. A platform that would support teachers could be considered as professional development programs, workshops, and an online medium based on ongoing conversation focusing on the development of PCK (van Driel & Berry, 2012). Through these platforms the marginalized topics of science education—informed views of NOS, HPS, and STS—could be an integral part of science curriculum that could serve to provide a more complete, coherent and effective science curriculum. For instance, Vikström (2014) provides teachers with guidelines and examples on how to teach the particle nature of matter.

In this chapter, the themes that emerged from the data were elaborated. These themes provided critical insights for the research question in terms of the nature of PCK development and learning, positive contributors to the development of informed views of NOS for the teacher, and institutional roles and position in relation to the study. In the next chapter, I provide recommendations emerging from these insights.

## Chapter 6

### Recommendations

This study serves insights for the science education practice and the recommendations in various areas emerged through the data. In the writing that follows, I elucidate the recommendations that Alice mentioned along with what I made sense out of synthesizing the data.

#### **Updated teaching materials in QM.**

The predominant part of Alice's learning process was her engagement with searching online, where she was able to locate materials on QM. It was clear that as an experienced science teacher, she was able to access not many but some helpful materials for her students and gather an appropriate amount of QM content knowledge. Although the materials were carefully chosen, any Grade 8 science teacher potentially stepping into learning about QM without guidance might face some challenges including the reliability of online materials, since the accuracy of the information provided in these materials have not been tested or approved by scientific or educational authorities.

Therefore, given the likely lack of institutional support, teachers will most likely be left without guidance throughout their learning process and potentially might end up using teaching materials that might either work well or create misconceptions. Without expertise in the subject, how can they be expected to know the difference? A support group, a professional development program, evening classes, and workshops will be helpful in guiding teachers as they first encounter the topics of QM. These interventions would contribute to not only to the content and pedagogical knowledge in order to teach

QM, but also to the self-confidence of teachers—as the data suggested—one of the key elements in effectively introducing a new subject in the classroom.

### **Teacher-centered pedagogies.**

While developing her PCK in QM, Alice demonstrated elements of traditional teacher-centered pedagogical approaches, since she needed a safe and structured place for her teaching especially in her first QM classes. Although this changed to some extent in the second class, it was apparent that she had developed more self-confidence and a sense of ease in teaching QM. This might suggest that borrowing from traditional pedagogical methods might serve as an effective support, if teachers lack confidence in introducing a new topic.

### **Further study on the impact of QM on students' attitudes towards science.**

Throughout the PCK development, it was observed that teaching QM could create an unusual dynamic in the classroom as it did in Alice's classroom. It might be worthwhile to study the effects of learning QM on the class dynamics to see if academically less successful students in science might become active participants in classroom discussion, and even more significant, interested in pursuing the exploration of their QM questions after class with the teacher. It is Alice's opinion that learning of QM has the potential to level the playing field for all students, in that; they could have felt more confidence in discussing QM topics, since other students do not have enough prior knowledge to judge them.

### **Earlier introduction of the topics of QM in elementary school.**

In all the three classrooms, students expressed that they would have preferred to be exposed to QM ideas earlier in their schooling, some suggesting that Grade 3 would be

a good time to start to engage with the topics of QM. In the western world, the everyday perception of a human being aligns with the predictable and intuitive understanding of science and it builds a common sense of the world starting from childhood; consequently, the counter-intuitive nature of QM becomes more difficult to grasp as the classical common sense settles. In the literature it was found that one of the major hindrances for students in understanding the concepts of QM was that students were not able to abandon the classical perspectives they had learned both implicitly and explicitly, and were approaching the topics of QM from a classical physics perspective, which skews the essential understanding of QM. Here, the comments coming from students regarding the inclusion of QM into school curriculum starting from Grade 3 might serve to resolve this chronic problematic of approaching of QM from a classical perspective.

#### **Developing a new vocabulary for the conceptual understanding of QM.**

QM offers a different reality beyond human perception and language. Language falls short in explaining the concepts of QM. For instance, there is no correspondence of words to define the dual nature of matter. Matter co-exists as a particle and a wave at the same time; and thus, it becomes a both countable and uncountable noun according to grammar rules. Based on the chronological scientific discoveries about electrons, at first electrons were considered to be particles; however, with the insights from QM, it was found that electrons were also waves; and thus, as an uncountable word, the usage of plural for electrons is incorrect. This wrong use of plural form applies for all the sub-atomic quantum particles, such as protons, neutron, and photons. Therefore, using the word 'electrons' intrinsically instils a misconception in developing PCK in QM in science classes. As the literature suggest then, it is no surprise that students would have

difficulty in conceptualizing the dual, in other words co-existent, nature of electrons. In order to eliminate this particular misconception a new term is suggested: “particle-wave unity.” Science textbook authors, or professional development program designers to support teachers in learning and teaching the topics of QM should pay close attention to vocabulary and terminology that might instil misconceptions.

**Science curriculum needs to be more closely aligned with the field of physics.**

The misrepresentation of the field of science in the middle and high school level has been discussed in the literature and in this study. The dichotomy between K-12 science and university science has been identified as contributing to misconceptions about NOS. In middle and high school levels, the understanding of science present a narrower understanding of scientific enterprise, whereas it is only after high school that students more likely to have the opportunity to engage with informed views of NOS. Since one of the goals of science education is providing scientific literacy and promoting informed views of NOS, it would be beneficial for school science curriculum to be aligned more closely with the field of science as it is practiced.

**Promoting learning opportunities within a professional learning community is mandatory.**

The extensive elaboration of the informed views of NOS and HPS in science education literature and their absence in science curriculum point out a vital disconnect between research and practice in education. This disconnect could be eliminated by building a platform to bring education practitioners, policy makers and researchers together where they can collaborate and provide action oriented solutions. This mutual platform would allow to develop a professional learning community where conversation

would be essential between the stakeholders of science education. Science education practice and science education research would function more cohesively when the knowledge and communication gaps are closed between research and practice.

Alice doubted that most of the Grade 8 science teachers would skip the content of QM despite QM's mandatory position in the curriculum. This would speak to the need for providing an auditing system for policy-based actions, which would potentially contribute to the extent and quality of science education practices. As Alice suggested cultivating an ongoing conversation among science teachers through professional learning opportunities would also play a pivotal role in encouraging teachers to adopt the new topics mandated in the curriculum and fostering science education practice. Therefore, a second pathway to bridge this disconnect seems to be providing science teachers with professional learning opportunities.

In designing professional development programs, it is crucial that these programs should not be developed as a one-time initiation, but rather taught on a continuous basis, as well as the social context in which the subject is taught (Höttecke and Silva, 2011). In particular, it is suggested that the professional development programs that are designed to promote understanding of NOS should pay close attention to providing content knowledge along with appropriate pedagogies for science teachers (Höttecke et al., 2012; Schwartz & Crawford, 2004). Regarding NOS oriented professional development programs, Höttecke et al. (2012) state that “without professional development in this field, science teachers are in danger to fall back to conventional teacher-centered methods” (p. 1248). The implementation of NOS within the context of HPS in science education would be effective when the following elements (Höttecke et al., 2012) are

utilized:

1. Creative writing for understanding science and scientists
2. Role-play activities to engage with the multi-dimensional aspects of science
3. Reconstruction of the working replicas of historical science apparatus.
4. Explicit reflections on the views of NOS, where contextualized NOS issues are generalized for the purpose of promoting broader perspectives in and of science.

With the flexibility of pedagogical approaches suggested in the BC's new curriculum, teachers can shape and organize their science classes accordingly. In particular, role-play activities would enable the cohesive contextual understanding of science, since "role-play activities in general are methods for exploring the conceptual, epistemological, human, emotional and social aspects of science" (p. 1245). Role-play activities could be utilized in three ways. Analogical role-play activities provide each individual a role of a scientific element, such as a certain quantum particle. Metaphorical role-play activities allow individuals to re-conceptualize the historical science events by building a metaphorical monument providing insights about the setting or controversies regarding that scientific issue. Role-play; as a simulation of science would allow students to thoroughly understand the scientists and scientific concepts through drama.

From an institutional perspective Visser et al. (2010) offers some helpful recommendations in order to design an ideal professional development program when a new subject is being introduced:

- Teachers should develop their knowledge. Teachers should be given ample opportunities to acquire new knowledge and skills, for example science content,

instructional strategies, and assessment methods. Experts, colleagues, and specific literature can provide this knowledge.

- Teachers should cooperate with colleagues. Teachers should first be given opportunities to exchange and discuss experiences and ideas with colleagues. Discussion topics can be teaching methods and content, but also practical issues such as how to use a specific activity in class. Cooperation can be intensified by having teachers develop additional material or assessment instruments.
- Teachers should network. The result of the professional development program should be a well-organized network in which teachers from different schools participate in collaborative activities.
- The module should be made relevant and attractive for students. Teachers can design stimulating curricular elements to increase students' interest and motivation.
- Teachers should be well prepared and organized for their lessons. In the professional development program, teaching and learning difficulties can be discussed, and good practices exchanged. How to prepare practical activities and where to obtain certain equipment and materials also needs to be addressed (p. 639).

In understanding the key components for designing professional development program these components of desired teacher knowledge, skills and attitudes might be of assistance.

Therefore, the nature of professional learning opportunities should be ongoing, inter-active, and context-based with an emphasis on teacher knowledge that is provided

by experts, colleagues and the literature and teacher pedagogies and attitudes emerging from mutual discussions and collaborative activities. This speaks to the need of cultivating professional learning community in order to promote the desired continuous, effective and organically growing learning opportunities for science teachers.

In this chapter, I outlined recommendations that might be of interest to Grade 8 science teachers, curriculum makers, pre-service teacher educators, and experts in the field of science. In the following chapter, I provide concluding remarks for the study.

## Chapter 7

### Conclusion

When I began this study, I was highly motivated to share the topics of QM with a teacher who would in turn share these topics with students. As I explained in the background of the study, the understanding of QM has been a life long passion for me, being closely related to my sense of purpose in the world. The process of this research has not only been an academic endeavour, but has also been personally meaningful to me. It is hard to put into words how profound it was to learn the concepts of QM as a young person, but I can say that it continues to affect my being in the world, my development—my thinking, my perception and my actions. It is difficult to remain indifferent after learning about the notions of entanglement or the wave nature of matter. The concepts of QM not only inform about the unimaginable possibilities that could be perceived in everyday life, but also provide insights regarding a deeper understanding of scientific enterprise.

The purpose of this study has been to understand how a Grade 8 science teacher learns about QM and develops PCK in the topics of QM. Although the research question is actually divided into two parts—the first, how the teacher learns the topics of QM, and the second, after learning QM, how she develops PCK in QM in the classroom—it was acknowledged that these two processes cannot be separated, since the learning process was continuing as the teacher was developing PCK in the classroom. If the learning process could be summarized separately, it could be stated that it was an effective learning process for Alice, especially when taking into consideration the challenges she faced, such as not having been previously being exposed to the concepts of QM in her

pre-service teaching education. She also did not have the benefit of attending a workshop or a professional development program with other science teachers where ideas could be exchanged and discussed and peer learning could take place, but rather learned the topics of QM on her own with only occasional contact with me. The intention in the design of the study was to explore the authentic learning process of the teacher without external influence. However, although I provided minimum guidance throughout her learning process, she emphasized the significance of our conversations and how helpful my feedback and comments were for her learning process. The data regarding the learning process shows how a Grade 8 science teacher learns QM in relative isolation, since governmental support in aiding teachers to learn this new subject and providing updated textbooks has not been secured.

The analysis of the data provided insights to the study in relation to the nature of learning, the complex nature of PCK development in QM, inadequate content knowledge in science curriculum, the ways to develop informed views of NOS, and institutional roles in relation to the study.

The development of PCK in QM is complex for several reasons. Changing roles of the teacher contributes to the complexity of the PCK development, in that, the pedagogical standpoints shifted between teacher-centered to student-centered approaches. Developing self-confidence and building sincere and trusting relationship with students strengthen the PCK development. In teaching QM, new teaching styles such as utilizing metaphors, analogies and story telling in relation to historical and philosophical aspect of the science subject are required. PCK development for a new subject calls for a model to follow in introducing a new curricular content.

Two particular insights would uniquely contribute to the discussions regarding the PCK framework in the literature as it was found that the ‘allotted time’ for learning and teaching a subject matter is an integrated aspect of PCK framework. In addition, the concept of pre-PCK was coined as an integral domain of PCK development. Pre-PCK refers to the student-centered activities that take place before the class with the goal of promoting pedagogical and content knowledge in that subject matter, such as briefly explaining the subject to be taught ahead of time, informing students about the purpose of learning this subject, and making students engage with the introductory teaching materials before the actual class. Pre-PCK adopts constructivist approaches and as a sub-component of PCK fortifies the development of PCK.

As I was discussing the nature of QM as counter-intuitive, in my concluding remarks I have come to an understanding that the counter-intuitive nature of QM is not exclusive to QM considering other school subjects. The data showed that the counter-intuitive nature of QM requires engaging with creative imagination; however, creative imagination is not only in the realm of QM. For instance, the other school subjects such as art, literature, and history also require students to engage with creative imagination. Therefore, when teaching QM teachers can potentially draw on their prior experience in other subjects and may apply similar strategies.

The student-centered understanding mandated in the redesigned curriculum should not be understood as a rejection of traditional approaches, since a teacher is inevitably in inter-action with students and the flow of the class is a complex dynamic emerging from inter-related agents of students and teacher. The BC’s New Curriculum leaves the responsibility to organize instruction to teachers; in that, it explicitly defines

“the ‘what’ to teach but not ‘how’ to organize the time, space, and methods to teach it,” the overarching pedagogical approach in the curriculum is student-centered where personalized learning strategies are adopted (BC’s New Curriculum, Curriculum Info, 2015). This study shows that in teaching a new subject like QM, a teacher could use traditional pedagogical approaches, which may provide benefits in their teaching especially when introducing a new subject. The reasons for not adopting a fully constructivist approach could be viewed as the lack of accessible teaching materials to guide students in order to promote student-centered learning and the need for a structured and safe platform for the teacher to build self-confidence. In this particular study the teacher improved her PCK in QM by responding to a dynamic situation with her students and gradually adopting more student-centered approaches in the classroom.

Although student reactions were out of the scope of the study, the insights coming from observations and interviews showed that students were motivated to learn more about QM. From my observation, after the lessons students gathered around Alice and I to ask more questions and showed eagerness to continue the discussion beyond what had been said in class. Not only were there students with more questions, other with no questions were interested in listening to the discussion. In the third lesson, when Alice asked students at what age should the topics of QM first introduced, all of the students agreed that it should be earlier than Grade 8, where the earliest suggestion was Grade 3.

My observation in the classroom was confirmed when Alice mentioned that in general she found that her students were interested in the topics of QM, and she highlighted a particular student who had never participated in classroom discussion earlier, not only raised her hand and asked a question in the first QM lesson, but also

remained for further discussion after the class was over. Despite the structured and straightforward worksheet, the students' responses, excitement, interest, and questions were different in all lessons and subsequently so was Alice's teaching in response to students' reactions. The inter-relationship between the students and Alice created a unique flow in each class and aided the development of an on-going PCK.

This responsive and inter-dependent relationship can also be viewed as ethics of care, which was observed in two ways in this project. Firstly, Alice practiced ethics of care with her students as she was changing the flow of the class and shifting gears according to the reactions of the students in each class differently. In this sense, practicing ethics of care can be seen as an indication for the constructivist understanding of PCK. Secondly, as a researcher my approach toward Alice was to support her as she encountered challenges or had questions regarding her learning process. Alice mentioned that our conversations were invaluable in helping to form her thoughts about QM as she prepared to teach, which demonstrates the practice of ethics of care on the researcher's end.

The nature of learning QM is not different than learning other subjects. The insights demonstrated certain elements that fostered learning the topics of QM both for the teacher and students. These elements were namely, having a growth mindset, learning through conversation, step by step learning, and making the subject relevant. On reflection, it became apparent that these elements were not particularly necessary for QM learning, but to learning in general. Therefore, it was suggested that the nature of learning the topics of QM is not different than learning other school subjects.

QM concepts can be made relevant to people of different cultures. It may be that the teacher needs to draw connections or the students themselves may be able to link concepts from their cultures themselves in order to make QM relevant. For example, this summer I was fortunate to be able to teach science to Tla-o-qui-aht First Nations Community on Meares Island. I was thinking about the QM phenomenon, aurora borealis, how it might be an observable experience and be relevant for them. This was not my first experience teaching science to First Nations communities, but still I wanted to find out the insights of this particular community. I went on their website where I was drawn to the beautiful photo of the sea with the caption “His-shuk-nish-tsa-waak.” The English translation underneath reads, “everything is one.” Although I had discovered this connection years ago, I was once again pleased to see the acknowledgement of the metaphorical similarity between indigenous wisdom and QM. After all, the concept of non-locality, and thus *oneness*, is an ancient understanding of these communities long before the emergence of the concept of QM entanglement. As I have a personal interest in exploring these connections, it seems that the cultural and philosophical perspectives of ancient wisdom have parallels with the conceptual understanding of QM. The relevancy of QM can be associated with diverse groups through research and conversation and in the case of First Nations communities the relevancy may reveal itself as both philosophical underpinning and an observable phenomenon.

Middle school science education is inconsistent with the current level of scientific knowledge. Some of the content knowledge in Science 8 curriculum is outdated, which potentially creates misconceptions and hinders an adequate understanding in QM, such as the Bohr atom model. Incorporating the topics of QM in the new curriculum seems to

solve this problematic by more closely aligning science curriculum with the field of physics, yet more fine tunings are required. It was also found that teaching the concepts of QM might promote critical thinking skills by providing multi-dimensional modes of thinking/representation of reality and enable some aspects of informed views of NOS by providing insights on the creative, tentative, social and cultural embeddedness of science. A more finely updated science curriculum adopting the topics of QM seems to provide a more complete and effective platform both in content knowledge and informed views of NOS. Presently, as the content knowledge in Grade 8 does not necessarily align with the current scientific knowledge, and a more narrow understanding of science is presented, unbeknown to science teachers their integrity seems to be at stake.

The development of informed views of NOS requires an accumulation and synthesis of prior knowledge in HPS on that subject. Either naïve or informed, the views of NOS emerge from a contextual meaning-making process of scientific concepts and they are embedded in teaching any science concept. It was found that the more contextual knowledge about science expands and being synthesized, the more informed views of NOS could be developed. Consequently, the knowledge in history of science and making sense of the contextual knowledge from a philosophical perspective contribute to a more complete and coherent picture of science. With an analogy, this would help to provide a bigger picture of ‘the forest,’ rather than seeing individual trees. Therefore, informed views of NOS emerge from an accumulation of the prior knowledge in contextual understanding of history of science and synthesis of this knowledge from a philosophical perspective.

As discussed earlier QM provides an effective framework to address the variety of components of scientific literacy (Nashon et al., 2008). The findings of this study aligns with these components showing that teaching QM can contribute to understanding of the nature of scientific process and inquiry, nature of scientific enterprise, and the nature of discovery and application. Furthermore, through the concept of paradigm shift, the topics of QM may help to improve public attitude and outlook toward science, and cultivate an understanding that science and technology are culturally situated. Therefore teaching the topics of QM would address the components of scientific literacy on a global and local platform.

### **Limitations of the Study**

Limitations of the study emerges from the nature of qualitative study and pertinent to the dynamics of the study. Qualitative studies provide a deeper understanding regarding a phenomenon where human subject is the focus, naturally in order to acquire deeper understanding as opposed to general understanding, qualitative studies loose their quality for generalization and application for broader audience. The limitations pertinent to this study was firstly the time limitations that the participant faced throughout her learning process due to her busy schedule as a science teacher, and also the time limitations took place in her teaching experience due to the density of the curriculum and not being able to make enough time for the teachings of QM. Thus she could devote two and a half class to QM for each of her three classes.

Alice learned the topics of QM with minimal external support and in relative isolation. Although this was part of the design of the study, it might be that at least some teachers may have the opportunity to learn the concepts of QM in the company of

colleagues which might change and even improve their experiences in learning QM.

They might also have access to experienced physics teachers who might guide them in their teaching to Grade 8 students.

It cannot be clearly identified how and to what extent my presence affected the study. While it was my intention not to skew the study by offering my suggestions, I was there to help. She might have felt self-conscious when I was in the classroom, or my presence potentially altered her teaching or the responses of the students. Educational contexts embed complex dynamics and I believe, the data emerges from a unique set of these particular and complex dynamics. Therefore, it should be noted that by merely doing the research, I inevitably affected Alice's QM learning experience and her teaching practice.

From my experience, three main personal traits of Alice shaped and enriched this study: first, she is eager to learn and grow, second she is willing to take challenges showing perseverance, and third, she is generous in devoting her time, not only to provide the best she could to her students, but to the research process in terms of data, so that she could help other science teachers. For instance, I was expecting our interviews to last for about an hour; however, Alice was generous in the time that she devoted to learning and teaching, but also to me in our interviews, that the average time for each interview was two hours. I could not have been able gather this much data if she had not been generous with her time, effort and sincere contributions. While I was able to look deeply into Alice's experience, it is to be expected that had I studied a different teacher, I would most likely have found some variation in learning QM and PCK development processes.

## **Personal Reflections**

Throughout my research, I received reactions about my research some of which included criticism, which suggested that teaching QM in middle school would ruin the kids and it would not work. I realized that the majority of people providing feedback on my dissertation had pre-conceptions of QM as being complex and difficult. At times, the criticizing reactions made me question and re-evaluate what I was doing. Sometimes I take for granted what I know and forget to look at things from others' perspectives, so maybe they were right. However, eventually I came to understand that those particular reactions are only coming from the monolithic standpoint that has not been exposed to different perspectives. After re-evaluation, I became more trusting of my study and developed a deeper ownership about this work. My hope for the future is that public understanding of science will be enhanced after adopting the multi-dimensional perspectives of science and internalizing the understanding emerging from both classical and quantum physics.

I had some concerns and hopes about the research before starting this study. Firstly, I was concerned how a Grade 8 science teacher could learn the topics of QM in a month, which was a limited and relatively short amount of time. Given the busy schedule of science teachers, I feared that my subject would become overwhelmed and perhaps even give up and leave the study. Fortunately, the participant was intrinsically motivated and accomplished the task and exceeded my expectations. I learned through my participant that putting a meaning to a personal goal along with holding positive personal traits, such as having a growth mindset, naturally being interested in learning new areas,

feeling responsible regarding a given task, and willing to accomplish a better self and better teacher would improve the QM learning and teaching processes.

I was also concerned about whether I would gather enough data that would provide insight for other teachers to guide them in their learning and teaching processes. The nature of case study demands multiple sources of data and at the end of the research I gathered extensive data emerging from interviews, classroom observations, teaching recordings, journals, teacher's learning and teaching documents. I was fortunate that my participant was open minded, wholehearted, enthusiastic, willing to learn and take challenges. Despite her busy schedule and the limitations of time, she was eager to learn and devoted time and effort in engaging in the concepts of QM.

Due to the different ontological and epistemological approaches that QM offers, there is a potential for misconceptions in perceiving the concepts of QM. These misconceptions in engaging with QM most likely emerge from the classical ways of thinking, which is widely embedded in the culture of the Western world. However, with the new paradigm shift in science, it might be time to be liberated from this monolithic perspective and embrace multi-dimensional modes of thinking.

The insights emerging from this research would serve as a guiding framework for other Grade 8 science teachers and contribute to the science education practice. With my renewed passion, I am inspired to expand and further the understanding of the incorporation of QM into educational contexts. This might include exploring ways to develop effective Grade 8 learning materials in QM for both teachers and students. It might also be studying the Grade 8 student understanding of QM by identifying the dynamics of an effective QM learning environment. In order to do so, I would

incorporate the constructivist concept of PCKg as a guiding framework, since it has a major focus on student understanding. The design of this particular study focused on the teacher's perspective; however, directly adopting the PCKing components would provide an effective framework to study students' perspectives for further research.

In concluding this study, it is hoped that the insights regarding learning and developing PCK in QM will be useful in both science education practice and science education research. While the outlined recommendations will be of immediate interest to Grade 8 science teachers, they might also be of value to educational departments at universities, who are charged with developing programs for pre-service science teachers. The study may also be of use to the authorities in the Ministry of Education as they develop and initiate professional learning opportunities in QM. Through these avenues Grade 8 science teachers would gain competence as they embark on the task of teaching the topics of QM in relation to Alice's experience. This study is also an invitation to close the knowledge and communication gaps between the fields of science, science education practice and science education research.

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## Appendix A

BC Grade 11 and 12 (last updated 2006):

<https://www.bced.gov.bc.ca/irp/pdfs/sciences/2006physics1112.pdf>

Page 16 lists the topics to be taught through the years, and quantum physics is not among them. Page 28 mentions the word quantum, but it seems to indicate that students are to be aware of it in name only as one of the branches of physics, no requirement is given to actually teach anything about quantum physics at all. Quantum mechanics is not present as a curriculum requirement in BC.

Alberta Grade 11 and 12 (last updated 2007):

[https://education.alberta.ca/media/654853/phy2030\\_07.pdf](https://education.alberta.ca/media/654853/phy2030_07.pdf)

On page 54, in a section about electromagnetic radiation for Grade 12 students, students are expected to explain the photoelectric effect, using the quantum model. Further reading reveals that the quantum model refers to the particle theory of light, students are expected qualitatively and quantitatively explain the Compton effect as a part of particle-wave duality. The concept of quantum appears again on page 57 as students are asked to report about the early development of quantum theory and on page 58 students are asked to perform an experiment on photoelectric effect.

On page 60, the quantum mechanical model is listed as a key concept for Atomic Physics, but no information is given regarding how it will be taught or what it even really means. In context, atoms and nuclear reactions are mentioned, so they are unlikely to go into any sort of depth about quantum physics here.

On page 61, the correlation between cathode rays and development of atomic models are

given.

On page 63, quantum physics is mentioned as an explanation for the wave/particle duality of light (double slit experiment), so that's a start, but is really not a large part of the curriculum.

“Describe, qualitatively, how the two-slit electron interference experiment shows that quantum systems, like photons and electrons, may be modeled as particles or waves, contrary to intuition” (p. 63).

Saskatchewan Grade 11 and 12 (last updated 1992):

[https://www.edonline.sk.ca/bbcswebdav/library/curricula/English/Science/Physics\\_20\\_30\\_1992.pdf](https://www.edonline.sk.ca/bbcswebdav/library/curricula/English/Science/Physics_20_30_1992.pdf)

On page 24, quantum physics is mentioned in a historical context, in which they teach that each new theory builds on the previous theories. Past scientific knowledge should be viewed in its historical context and not be degraded on the basis of present knowledge (p. 24). They make the claim that the quantum theory of the atom built upon, rather than invalidating, the Bohr model of the atom.

On page 126, they mention the Heisenberg Uncertainty principle to state that even at absolute zero, there is some energy present due to quantum effects. By definition, absolute zero is the temperature at which all molecular motion ceases. But quantum mechanics (Heisenberg Uncertainty) states that even at absolute zero some energy must be present. If there is still some energy present, it is not, by definition, at absolute zero. The condition of zero energy cannot ever be met, so absolute zero cannot ever be reached (p. 126).

On page 263, they mention a quantum number. “Each orbit is assigned a quantum

number, with the lowest quantum numbers being assigned to those orbitals closest to the nucleus. Only a specified maximum number of electrons can occupy an orbital. Under normal circumstances, electrons occupy the lowest energy level orbitals closest to the nucleus. By absorbing additional energy, electrons can be promoted to higher orbitals, and release that energy when they return back to lower energy levels” (p. 263).

“Photons are used to describe the wave-particle duality of light. The energy of a photon depends upon its frequency. This helps to explain the photoelectric effect; only photons having a sufficiently high energy are capable of dislodging an electron from the illuminated surface” (p. 263).

On the same page they go on to mention quantum theory and the interesting shapes of electron probability clouds in quantum theory. “Quantum theory offers a mathematical model to help explain the nature of the atom (p.263).

Quantum theory describes a region surrounding the nucleus which has the highest probability of locating an electron. These orbital "clouds" have some unusual and interesting shapes” (p. 263).

On page 264 they mention quantum theory in the context of the wave/particle duality of light.

Learning outcomes (p. 264)

11. Explain how photons are used to describe the wave-particle duality of light.
12. Explain that quantum theory helps to explain the photoelectric effect, the Compton effect, and other important physical principles which earlier theories did not account for adequately.
13. State that quantum theory describes a region surrounding the nucleus which has the highest probability of locating an electron.
14. Describe some of the electron orbital descriptions provided by quantum theory.

Teaching Suggestions (p. 265)

The photoelectric effect and the Compton effect helped to give rise to quantum theory. Research these two phenomena. Attempt to explain why theories which were prevalent at the time failed to account for these phenomena.

### Optional Unit VIII: Atomic Physics E. Contemporary Physics (p.274)

This is a teacher-developed section, allowing teachers and students to explore other topics in contemporary physics which might interest them. As new research findings become available, they could be incorporated here.

The term "contemporary" may be somewhat misleading here. Some ideas which could be included, such as the Special Theory of Relativity, have been around for a long time.

Some ideas for topics to explore in this section include such things as elementary particles, particle accelerators, elementary particle classification, quarks, Special Theory of Relativity, quantum mechanics, lasers, solid state electronics, or models of the atom.

Teachers can add other topics to this list. Develop one or more of these topics to the extent possible in the remaining available time.

#### Learning Outcomes

Students will increase their abilities to:

1. Recognize that new discoveries in physics are ongoing.
2. Appreciate that learning is a life-long endeavour.
3. Research one or more specific topics in contemporary physics.
4. Assess the potential applications of new discoveries in physics.
5. Assess the potential benefits and risks of new discoveries in physics.
6. Appreciate the role that technology plays in scientific endeavour.

Manitoba Grade 11 (last updated 2003):

[http://www.edu.gov.mb.ca/k12/cur/science/found/physics30s/full\\_doc.pdf](http://www.edu.gov.mb.ca/k12/cur/science/found/physics30s/full_doc.pdf)

Page 163 Topic 2.2 16 the Notes to the Teacher section mentions quantum physics as the explanation for the particle/wave duality of light.

“At the end of the 19th century, James Clerk Maxwell combined electricity, magnetism, and light into one theory. He called his theory the electromagnetic theory of light.

According to Maxwell, light was an electromagnetic wave with the same properties as

other electromagnetic waves. Maxwell's theory, however, was unable to explain the photoelectric effect. In 1900, Max Planck suggested that light was transmitted and absorbed in small bundles of energy called "quanta." Albert Einstein agreed with Planck's theory and explained the photoelectric effect using a particle model of light. The quantum theory combines the two major theories of light, suggesting that light does not always behave as a particle and light does not always behave as a wave" (Topic 2.2.16)

Manitoba Grade 12 (last updated 2005):

[http://www.edu.gov.mb.ca/k12/cur/science/found/physics40s/full\\_doc.pdf](http://www.edu.gov.mb.ca/k12/cur/science/found/physics40s/full_doc.pdf)

"Historically, the fluid and particle models of charge accounted for experimental observations. However, as our ideas about the structure of matter evolved, the particle model provided a more reliable, predictive, and robust explanatory model" (18, sec. 2).

Questions should seek to examine observable results such as the following: whether students have understood what the particle model of matter is; whether they can give a short account of it; whether they can use it to explain everyday phenomena; and whether they can explain why it is an important idea in science (Millar and Osborne, 1998, p. 26) (in section 3, 13).

Ontario Grades 11 and 12 (last updated 2000):

<http://www.edu.gov.on.ca/eng/curriculum/secondary/science1112curr.pdf>

Overall expectations for the section Electrochemistry students are expected to "demonstrate an understanding of quantum mechanical theory, and explain how types of chemical bonding account for the properties of ionic, molecular, covalent network, and metallic substances" (p. 64).

The page later goes on to explain that the student is expected to understand electron

probability clouds from the quantum model of the atom. “Describe the quantum mechanical model of the atom (e.g., orbitals, electron probability density) and the contributions of individuals to this model (e.g., those of Planck, de Broglie, Einstein, Heisenberg, and Schrödinger)” (p. 64).

Use appropriate scientific vocabulary to communicate ideas related to structure and bonding (e.g., orbital, absorption spectrum, quantum, photon, dipole) (p. 64).

Overall expectations for the Matter-Energy Interface references "early quantum mechanics" in a section talking about the relationship between matter and energy. Some mention is made of "matter waves" and mass-energy equivalence. They also mention "quantum energy" in reference to the particle theory of light. “Demonstrate an understanding of the basic concepts of Einstein’s special theory of relativity and of the development of models of matter, based on classical and early quantum mechanics, that involve an interface between matter and energy” (p. 111).

Define and describe the concepts and units related to the present-day understanding of the nature of the atom and elementary particles (e.g., radioactivity, quantum theory, photoelectric effect, matter waves, mass-energy equivalence) (p.111)

Describe the photoelectric effect in terms of the quantum energy concept, and outline the experimental evidence that supports a particle model of light (p.111).

Describe and explain in qualitative terms the Bohr model of the (hydrogen) atom as a synthesis of classical and early quantum mechanics (p.111).

Describe the Standard Model of elementary particles in terms of the characteristic properties of quarks, leptons, and bosons, and identify the quarks that form familiar particles such as the proton and neutron (p.111).

Compile, organize, and display data related to the nature of the atom and elementary

particles, using appropriate formats and treatments (e.g., using experimental data or simulations, determine and display the half-lives for radioactive decay of isotopes used in carbon dating or in medical treatments) (p. 112).

Describe how the development of the quantum theory has led to scientific and technological advances that have benefited society (e.g., describe the scientific principles related to, and the function of, lasers, the electron microscope, or solid state electronic components) (p. 122)

Describe examples of Canadian contributions to modern physics (e.g., contributions to science and society made by Bert Brockhouse, Werner Israel, Ian Keith Affleck, Harriet Brooks, Richard Taylor, or William George Unruh) (p. 112)

Page 113 says students will "describe how the development of the quantum theory has led to scientific and technological advances that have benefited society (e.g., describe the scientific principles related to, and the function of, lasers, the electron microscope, or solid state electronic components)"

Quebec Grade 12 (last updated 1992):

<http://www.learnquebec.ca/export/sites/learn/en/content/curriculum/mst/documents/phys534a.pdf>

\*\*\* NOT MENTIONED \*\*\*

The table of contents lists The Nature of Light, Optical Devices and Mechanics.

Nova Scotia Grades 11 and 12 (last updated 2002):

[http://www.ednet.ns.ca/files/curriculum/physics11\\_12.pdf](http://www.ednet.ns.ca/files/curriculum/physics11_12.pdf)

Students will be expected to:

Quantum Physics (p. 18)

1. Apply quantitatively the law of conservation of mass and energy using Einstein's mass-energy equivalence (326-9)
2. Explain how quantum physics evolved as new evidence came to light and as laws and theories were tested and subsequently restricted, revised, or replaced and use library and electronic research tools to collect information on this topic (115-7, 213-6)
3. Describe how quantum energy concept explains both black-body radiation and the photoelectric effect (327-9)
4. Explain qualitatively and apply the formula for the photoelectric effect (327-10)

Compton and deBroglie (p. 19)

1. Explain how a photon momentum revolutionized thinking in the scientific community (115-3)
2. Apply and assess alternative theoretical models for interpreting knowledge in a given field (214-6)
3. Explain quantitatively the Compton effect and the de Broglie hypothesis, using the laws of mechanics, the conservation of momentum, and the nature of light (329-1)

Particles and Waves (p. 19)

Summarize the evidence for the wave and particle models of light (327-11)

Bohr Atoms and Quantum Atoms (p. 19)

1. Explain quantitatively the Bohr atomic model as a synthesis of classical and

quantum concepts (329-2)

2. Explain the relationship among the energy levels in Bohr's model, the energy difference between levels, and the energy of the emitted photons (329-3)
3. Use the quantum mechanical model to explain naturally luminous phenomena (329-7)

Page 26 mentions Quantum Physics as 3 hours of study in the context of Waves and Modern Physics. Compton de Broglie (p. 132) as 2 hours of study, Particles and Waves (p. 134) and in the same section, Bohr Atoms and Quantum Atoms (p. 136) are an additional 3 hours of study.

Page 28 expands that students will learn about Einstein's mass-energy equivalence, how quantum physics evolved as a response to new evidence gathered over time, how quantum energy explains both black-body radiation and the photoelectric effect.

Page 130 expands even further on the "Quantum Physics" 3-hour course, reiterating many of the same points about black body radiation and the photoelectric effect. New Brunswick Grade 12 (last updated 2003):

<https://www.gnb.ca/0000/publications/curric/physics12.pdf>

\*\*\* NOT MENTIONED \*\*\*

Prince Edward Island Grade 12 (last updated 2010):

[http://www.gov.pe.ca/photos/original/edu\\_phy621A2010.pdf](http://www.gov.pe.ca/photos/original/edu_phy621A2010.pdf)

\*\*\* NOT MENTIONED \*\*\*

Newfoundland Grade 12 (last update 2004):

The only sections in the table of contents are "Force, Motion, Energy", "Fields", and "Matter-Energy Interface". The first two make no mention of quantum physics, but the third one references quantum physics as an explanation for black-body radiation and the photoelectric effect. This outline borrows heavily from the Nova Scotia one and tries to explain quantum physics from a historical context, how it grew from the discovery of new evidence, and how it compares to the Bohr model of the atom.

## Appendix B – NOS Questionnaire

### Views of Nature of Science Questionnaire: Part 1 and Part 2

Figure 1. Views of nature of science questionnaire, Part 1 (Lederman et al., 2002).

1. After scientists have developed a theory (e.g., atomic theory), does the theory ever change? If you believe that theories do change, explain why we bother to teach scientific theories. Defend your answer with examples.
2. What does an atom look like? How certain are scientists about the structure of the atom? What specific evidence do you think scientists used to determine what an atom looks like?
3. Is there a difference between a scientific theory and a scientific law? Give an example to illustrate your answer.
4. How are science and art similar? How are they different?
5. Scientists perform experiments/investigations when trying to solve problems. Other than the planning and design of these experiments/investigations, do scientists use their creativity and imagination during and after data collection? Please explain your answer and provide examples if appropriate.
6. Is there a difference between scientific knowledge and opinion? Give an example to illustrate your answer.
7. Some astronomers believe that the universe is expanding while others believe that it is shrinking; still others believe that the universe is in a static state without any expansion or shrinkage. How are these different conclusions possible if all of these scientists are looking at the same experiments and data?

Figure 2. Views of nature of science questionnaire, Part 2 (Lederman et al., 2002).

1. What, in your view, is science? What makes science (or a scientific discipline such as physics, biology, etc.) different from other disciplines of inquiry (e.g., religion, philosophy)?
  2. What is an experiment?
  3. Does the development of scientific knowledge **require** experiments?
    - If yes, explain why. Give an example to defend your position.
    - If no, explain why. Give an example to defend your position.
  4. After scientists have developed a scientific theory (e.g., atomic theory, evolution theory), does the theory ever change?
    - If you believe that scientific theories do not change, explain why. Defend your answer with examples.
    - If you believe that scientific theories do change: (a) Explain why theories change? (b) Explain why we bother to learn scientific theories? Defend your answer with examples.
  5. Is there a difference between a scientific theory and a scientific law? Illustrate your answer with an example.
  6. Science textbooks often represent the atom as a central nucleus composed of protons (positively charged particles) and neutrons (neutral particles) with electrons (negatively charged particles) orbiting that nucleus. How certain are scientists about the structure of the atom? What specific evidence **do you think** scientists used to determine what an atom looks like?
  7. Science textbooks often define a species as a group of organisms that share similar characteristics and can interbreed with one another to produce fertile offspring. How certain are scientists about their characterization of what a species is? What specific evidence **do you think** scientists used to determine what a species is?
  8. It is believed that about 65 million years ago the dinosaurs became extinct. Of the hypotheses formulated by scientists to explain the extinction, two enjoy wide support. The first, formulated by one group of scientists, suggests that a huge meteorite hit the earth 65 million years ago and led to a series of events that caused the extinction. The second hypothesis, formulated by another group of scientists, suggests that massive and violent volcanic eruptions were responsible for the extinction. How are these **different conclusions** possible if scientists in both groups have access to and use the **same set of data** to derive their conclusions?
  9. Some claim that science is infused with social and cultural values. That is, science reflects the social and political values, philosophical assumptions, and intellectual norms of the culture in which it is practiced. Others claim that science is universal. That is, science transcends national and cultural boundaries and is not affected by social, political, and philosophical values, and intellectual norms of the culture in which it is practiced.
    - If you believe that science reflects social and cultural values, explain why. Defend your answer with examples.
    - If you believe that science is universal, explain why. Defend your answer with examples.
  10. Scientists perform experiments/investigations when trying to find answers to the questions they put forth. Do scientists use their creativity and imagination during their investigations?
    - If yes, then at which stages of the investigations you believe scientists use their imagination and creativity: planning and design, data collection, after data collection? Please explain why scientists use imagination and creativity. Provide examples if appropriate.
    - If you believe that scientists do not use imagination and creativity, please explain why. Provide examples if appropriate.
-

## Reference

- Lederman, N. G., Abd-El-Khalick, F., Bell, R. I., & Schwartz, R. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching*, 39(6), 497-521.

## **Appendix C – Consent Form**

### **Purpose of the Research**

The purpose of this research is to explore the experiences of Grade 8 science teachers in learning to teach quantum mechanics (QM), in the hopes that describing this experience will help those who will be teaching QM as the mandatory aspect of the new Grade 8 science curriculum in British Columbia (BC). You have been approached because you are a Grade 8 science teacher, presently employed with the greater Victoria School Districts 61 and 62.

The motivation of this study is a draft curriculum in the works, which includes QM as a curriculum Prescribed Learning Objective (PLO) for Grade 8 science classes in British Columbia. I hope to uncover a rich narrative that will speak to all those who wonder what it is like studying, learning and teaching QM for teachers and how would teachers develop lesson plans in QM, especially the ones who do not have a background in QM. It is also hoped that you will benefit from the process of articulating your experience and that your subsequent discussions about this topic will be stimulating. Overall the experience of participating in this project is designed to be an affirmative and informative experience in itself.

### **What you will be asked to do in the research**

As a participant, you will be asked to volunteer your time to this study. The research will take place through the weekly focus group meetings. Time spent on the project must be outside working time, as you will not be paid from any source for participating.

- You will sign an informed consent form.
- You will participate in the weekly focus group meetings over a ten week time period (March-April-May 2016) and then two classes of QM teaching in your classes.
- You will keep and submit a research journal that will reflect your QM learning experience.

- The research process throughout conversations regarding your experience including learning and teaching QM will take five to eight hours a week over a three month period.
- You will review the research findings to make sure that you feel comfortable with the content, that confidentiality has been protected, and that your thoughts have been expressed completely and correctly. You will provide feedback and give your verbal consent that you wish to continue and to have your material included.

### **Data Collection**

The data for this study will be the conversations that emerges in our weekly focus group meetings, the email conversations, lesson plans in QM, and your personal research journal. Your individual responses will be presented anonymously in the final research paper. Confidentiality will be provided to the fullest possible extent.

Teachers' journals: Throughout the research process participant teachers will keep a personal journal, where they will write down their insights. For example, their feelings as they were learning, thoughts that might help them to teach, connections they are making between what they learned about classical mechanics in their own training and what they are now learning in QM as well, as anything related the questions posed during the focus group meetings. The journal will also be used to track their teaching experience and they could take notes; for instance, on their mode of teaching, the content and the responses of the students that might help them adjust their next lesson. During the focus group meetings the time allocated for journal entries will be 15-20 minutes in each workshop session. Please see Appendix F – Research Design Weekly Schedule for the journal questions for each week.

Written communication via email refers to the potential yet unplanned conversations that might take place between the researcher and one or more teachers throughout the research process. The subject of this communication might vary, possibly exchanging insights or questions.

Researcher's field notes refers to the notes that will be taken by the researcher during the focus group meetings. These notes can vary from little reminders for the workshop or personal insights that could be viewed as the researcher's personal journal.

Teachers' in-class practices involve the participant teachers' QM teaching experiences in their own classrooms. After in-class practices, the teachers will write about their QM teaching experiences in their journals. Please see Appendix F – Research Design Weekly Schedule for the in-class journal questions for each week.

In the focus group meetings, the teachers will create posters regarding particular topics of QM and they will design lesson plans to be presented as posters to the group (see Appendix F for the poster activity details). These posters will be collected each of the eight weeks as data contributing to the database. The researcher's weekly narratives at the end of the data collection process constitute the last part of a database, which develop open-ended answers for the case under study, which means that the researcher will be examining all pieces of the database, and then through a self reflexive process, the researcher's experiences will form a narrative in response to the research questions.

### **Inconveniences**

The time commitment required to engage in this research will require approximately 3-4 hours for 10 weeks, two classes of QM teaching, and 3-4 hours to review the research narratives at the end of the research process. Should the need arise the timeframe can be reduced or extended by mutual agreement of the participants. Interaction will be primarily by weekly meetings. The researcher will be available for email and phone conversations as needed throughout each of the 12 weeks.

### **Risks and Discomforts**

You will be introduced to new ideas in the topic of QM. Gaining insight about this branch of physics may be challenging on the mental level, possibly disrupting your world-view. You may also face emotional discomfort through a QM paradigm shift. Studying QM may also create a need to expand your teaching content and material. The research design itself is such that the process of the weekly meetings is likely to ameliorate any discomfort, and might provide support as each teacher works their way

through the material. This might be an enhancement to learning QM independently in isolation from colleagues.

Science teachers can have demanding schedules. Participating in research such as this might be experienced as tiring. For this reason, the schedule has been spread out over a three month period and the researcher has committed to being responsive to your request for changes in the time line.

There are no social risks as it is up to you to disclose your participation. The researcher is not in a power position with the teachers. The results of the study will in no way affect your job security or your pay. Since the researcher is not employed by the school board, should you decide to discontinue their participation in the research there will be no consequences in terms of employment.

Although minimal harm is expected, should you become distressed for any reason the researcher will be immediately available to discuss concerns. The researcher has gone through this process, so will be able to relate and empathize with the teacher experience. Another potential harm is that you might in some way feel uncomfortable about an aspect of your process of learning QM or about your writing. I want to assure you that you are in control of what I see. You can review your writing before sending it to me and delete any content that you don't want to share. The purpose of your writing is to understand your experience, not to evaluate the writing itself or your practice.

### **Researcher's relationship with participants**

I am a former physics teacher, which may make it easier to discuss sensitive material, and add to a sense of trust and confidence. It might also mean that more is at stake, should for any reason, the research not be experienced in a positive and affirming way.

### **Benefits of the research and benefits to you**

By participating in this research it is my hope that the science teachers who volunteer to participate in this study will have the opportunity to study, learn and teach QM while in discussion with other teachers who have an interest in QM. Because of the nature of the research method, it can be anticipated that the conversations about QM

might develop your scientific thinking. This method of studying and learning QM might be considered a particularly engaging way of learning material that may be required of you, since the draft curriculum including the topics of QM will be implemented next year. Furthermore, learning a new subject by this method, you might learn new skills that will help you to learn any new subject introduced by the BC Ministry of Education in future. It is possible that you may increase your confidence and interest in science content knowledge by your participation. Participating in this science education research provides a platform in which participants can contribute to the body of knowledge of science education.

### **Voluntary participation**

Your participation in this research is completely voluntary and you may choose to stop participating at any time. Deciding not to participate or withdrawing your consent at any time will not influence your relationship with me, or the University of Victoria, either now or in the future.

### **Withdrawal from the study**

You may stop participating in the study at any time, for any reason, if you so decide. Your decision to stop participating or to decline answering particular questions, will not affect your relationship with me, the University of Victoria. In the event that you withdraw from the study, you will be consulted about whether you want all or part of the data that has been collected thus far to be included or destroyed. If at any time you wish to withdraw from the study contact the researcher at [goksenins@gmail.com](mailto:goksenins@gmail.com).

### **Dissemination of results**

I intend to disseminate results in the form of a PhD dissertation. Additionally, I intend to publish results in academic journals and at academic and professional development conferences and workshops, and I may decide to rewrite my dissertation as a book, immediately following graduation. The results, as synthesized in the dissertation, will be made available to participants.

### **Anonymity and Confidentiality**

In this research anonymity and confidentiality will be protected. In signing this form you agree to keep the identity of the people you interact with confidential. If you choose to discuss your contributions with other colleagues then it might be possible for them to identify those comments in the final written version of the research, I will use pseudonyms in order to hide your identities. The group members who will participate in the research will know each other. The supervisors may guess the identity of the participants as the researcher will contact the participants through them. Nonetheless, every effort will be made to protect the identity of participants in this study. In the final documentation neutral gendered language will be used. All teacher participants will choose their own neutral gender nicknames and assign pseudonyms for the names of the related middle schools.

### **Maintenance and Disposal of Data**

Password protected computers will be used for further discussion after the focus group meetings. These potential conversations after the focus group meetings will take place by email. Each participant is expected to use a password protected computer. Some communication may be between the researcher and each individual participant, while others may be between both participants and the researcher. I will take hand written field notes during and after the focus group meetings, and then transcribe and transfer them to my computer as soon as possible after the events occur. I will then shred my hand written notes. Annotated bibliography of the documents and possible artefacts and documents created by the research team also contribute to the database. In the focus group meetings, you will create posters regarding particular topics of QM and you will design lesson plans to be presented as posters to the group. These posters will be collected as tabular materials, contributing to the database. My narratives at the end of the data collection process constitute the last part of the database, which develop open-ended answers for the case under study. In this process, I will be examining all pieces of the database, and then through a self reflexive process, my experiences will form a narrative in response to the research question. Posters will be stored in a locked filing cabinet. The research data will be kept for a period of five years, after which it will be destroyed. All data and copies will be deleted. Tabular materials will be manually destroyed through shredding.

### Questions about the research

If, as a research participant, you have questions about the research in general, or in your role in the study, please contact me at [goksenin@uvic.ca](mailto:goksenin@uvic.ca) or contact my co-supervisors at the University of Victoria: Dr. Kathy Sanford - [ksanford@uvic.ca](mailto:ksanford@uvic.ca) and Dr. Todd Milford - [tmilford@uvic.ca](mailto:tmilford@uvic.ca)

This research has been reviewed by the University of Victoria Human Research Ethics Office and conforms to the Canadian Tri-Council Research Ethics guidelines. You may verify the ethical approval of this study, or raise any concerns you might have, by contacting the Human Research Ethics Office at the University of Victoria (250-472-4545 or [ethics@uvic.ca](mailto:ethics@uvic.ca)).

Your signature below indicates that you understand the above conditions of participation in this study, you have had the opportunity have your questions answered by the researcher and that you consent to participate in this research project.

Name of Participant	Signature	Date

A copy of this consent will be left with you, and a copy will be taken by the researcher.

Informed consent forms: Participants

Study name: Grade 8 Science Teachers' Experiences in Learning to Teach Quantum Mechanics

Researcher: Goksenin Sen, PhD Candidate, University of Victoria, Department of Curriculum and Instruction

Contact: [goksenin@uvic.ca](mailto:goksenin@uvic.ca)

Co-supervisors:

Kathy Sanford: [ksanford@uvic.ca](mailto:ksanford@uvic.ca)

Todd Milford: [tmilford@uvic.ca](mailto:tmilford@uvic.ca)

### Appendix D: Draft Interview Questions

1. What is the view of NOS for a Grade 8 science teacher who does not have any QM background?
2. In anticipating learning the concepts of QM, how difficult do you think it would be for you to engage with QM ideas?
3. What is your experience as you learn the quantum atom model?
  - a) In terms of concept, what did you find most encouraging and interesting?
  - b) In terms of material, what did you find most encouraging and interesting?
  - c) Did you engage with history and philosophy of science?
  - d) What are the challenges you faced in learning QM and how did you overcome those challenges?
  - e) What do you need in order to learn the concepts of QM? How can you be best supported?
4. What is your experience as you learn the uncertainty principle?
  - a) In terms of concept, what did you find most encouraging and interesting?
  - b) In terms of material, what did you find most encouraging and interesting?
  - c) Did you engage with history and philosophy of science?
  - d) What are the challenges you faced in learning QM and how did you overcome those challenges?
  - e) What do you need in order to learn the concepts of QM? How can you be best supported?
5. What is your experience as you learn the concept of entanglement?

- a) In terms of concept, what did you find most encouraging and interesting?
  - b) In terms of material, what did you find most encouraging and interesting?
  - c) Did you engage with history and philosophy of science?
  - d) What are the challenges you faced in learning QM and how did you overcome those challenges?
  - e) What do you need in order to learn the concepts of QM? How can you be best supported?
6. What is your experience as you learn the dual nature of light?
- a) In terms of concept, what did you find most encouraging and interesting?
  - b) In terms of material, what did you find most encouraging and interesting?
  - c) Did you engage with history and philosophy of science?
  - d) What are the challenges you faced in learning QM and how did you overcome those challenges?
  - e) What do you need in order to learn the concepts of QM? How can you be best supported?
7. How has learning QM affected your views of NOS?
8. How have you developed PCKg in the understanding of NOS in terms of:
- a) Content
  - b) Teaching materials
  - c) Pedagogical approaches
  - d) Student characteristics
  - e) Teaching goal and values

Journal Writing Questions:

1. What have you learned from creating a lesson plan on a counter-intuitive concept? In terms of pedagogy what are the pros and cons of the lesson plans that were presented?
2. What have you learned from creating a lesson plan on the quantum atom model? In terms of pedagogy what are the pros and cons of the lesson plans presented?
3. What have you learned from creating a lesson plan on the uncertainty principle? Pedagogy-wise what are the pros and cons of the lesson plans presented?
4. What have you learned from creating a lesson plan on the concept of entanglement? In terms of pedagogy what are the pros and cons of the lessons presented?
5. What could you use from our focus group discussion and the expert video in drafting a lesson plan on the dual nature of light for your students?
6. What have you learned from creating a lesson plan on the dual nature of light? What did you learn from the other lesson plan presentations?
7. What have you learned from creating a lesson plan on NOS? Pedagogy-wise what are the pros and cons of different lesson plans?
8. Based on your experience in teaching the dual nature of light, in your assessment what worked well in your lesson plan, was there anything else that didn't work well? How would you change your lesson plan, if at all? Is there anything else that you need to learn before to teaching it again? How do you anticipate difficult it will be to learn the concepts needed?
9. What's your experience in teaching the informed views of NOS?

June 1 &amp; 3, 2016

Nom : Teacherdiv 8-10Introduction to Quantum Mechanics (Mécanique quantique)

- A. We are going to explore and learn about Quantum Mechanics. What does it mean?  
Hypothesis :

\*\*There will a mix of technical terms, images and video clips to help approach this topic.

1. Quantum : - Small quantity of energy proportional to the frequency of radiation  $\lambda$ .

\* - minimum amount of any physical entity involved in an interaction. (it has a discrete value - it leaps!!)

2. Mechanics : - Math branch that deals with "motion" and the forces that produce "motion".

\* - It is the way something is made or how something works.

3. Some history found in Wikipedia :

- One of the field of study in Physics.
- Specifically for very small particules (atomic or subatomic parts).
- It began around 1910.
- About 10 physicists (Europeans & Americans).
- Max Planck is considered the father of Quantum Mechanics.

4. Why creating a new branch of Physics ?

Those physicists were trying to explain phenomenons that could not be explained with classic Physics.

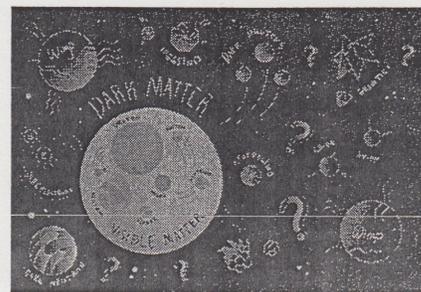
Ex a. Dark Matter :

- 27% of the Universe has a mass but...

... - no interaction with light

... - Cannot be seen

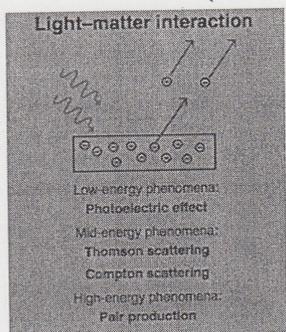
... - Can be made of black holes.



\* The matter that we know and makes up the stars and galaxies only accounts for 5% of the content of the Universe.

2

Ex b. Photoelectric effect (or photoemission)



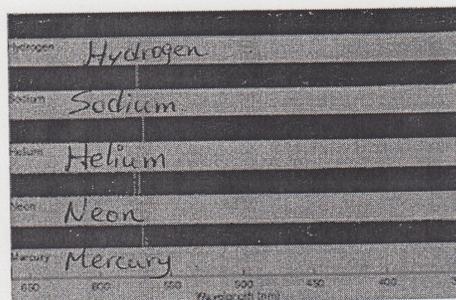
This was observed in 1839.

- Electrons are produced when a light shines upon a material
- It requires a certain amount of light (energy) to produce these photoelectrons

Einstein (1905) called it 'Photon'  
\*particle that has no mass!!

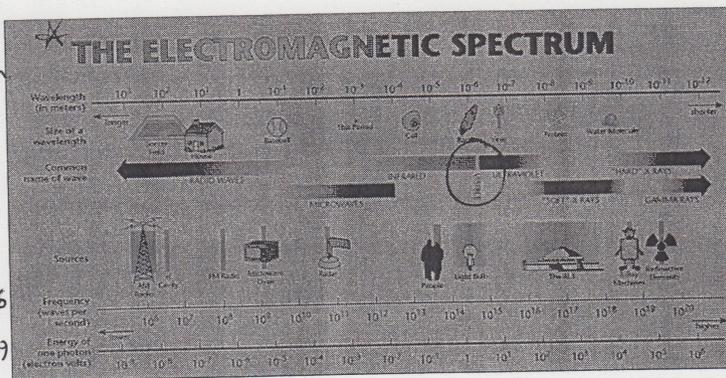
Ex c. Spectrum Rays :

- Each element (atom) has some kind of genetic code.
- It is a serie of dark or light lines (coloured).
- It depends on the interaction of the atoms.



The sodium spectrum was discovered in 1752

\*  $10^3$  m



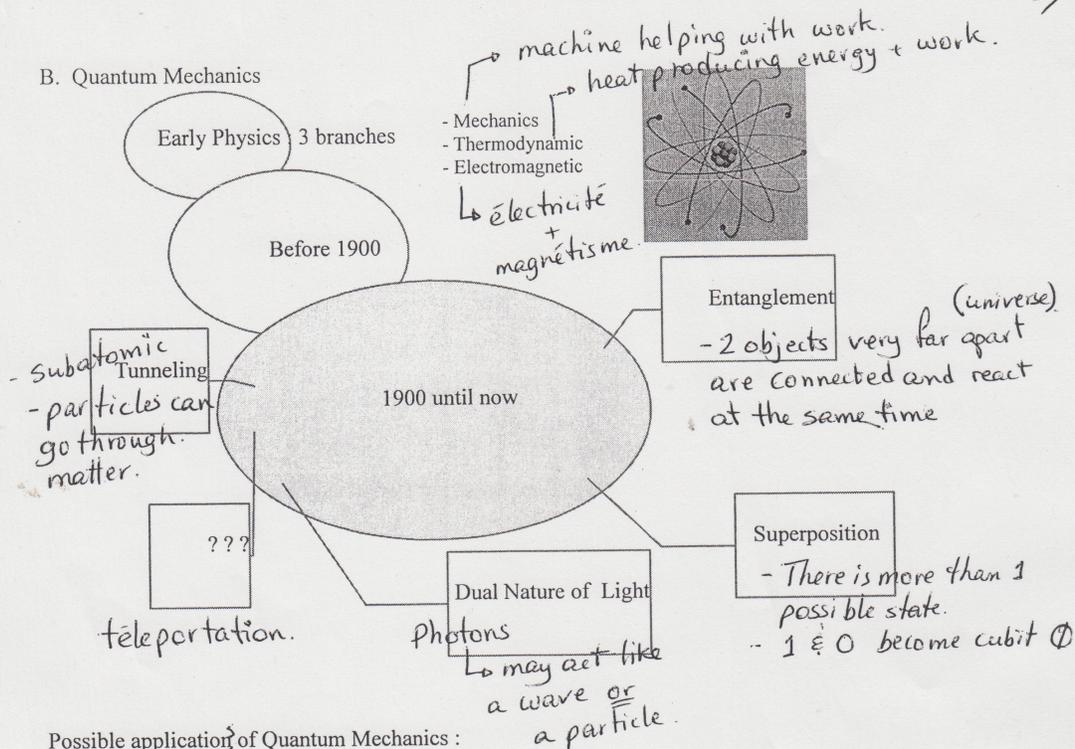
$10^{-12}$  m.  
} all made of photons  
 $10^{20}$  Hz (waves/s)  
 $10^6$  electron volt. (pour 1 photon)

\*\*\* We can see the visible light which is a very small part of the Electromagnetic Spectrum.

\*\*\* We cannot see the other waves but we feel or see the effect of the other rays (Microwaves, Infra Red - UV, Radio waves, etc)

All the research done during the 1900 until today helps to explain :  
the construction and the behaviour of the atom and its parts.

B. Quantum Mechanics



Possible applications of Quantum Mechanics :

- Superconducting Magnets
- Light-emitting diodes and laser (everyday electronics)
- Transistor & semi-conductors (microprocessors, Magnetic Resonance Imaging and electron microscopy)
- Explanations for many biological and physical phenomena (Photosynthesis, bioluminescence, ...)

C. Atomic and Subatomic particles :

Protons : 2 up Quarks  
1 down Quark.

Neutrons : 1 up Quark  
2 down Quark.

- electrons, neutrinos  
muons  
tau.  
light particles

UP QUARKS	U	C	T	Q	H
	up	charm	top	gluon	Higgs boson
DOWN QUARKS	D	S	B	Y	
	down	strange	bottom	photon	
LEPTONS	E	M	T	Z	
	electron	muon	tau	Z boson	
	$\nu_e$	$\nu_\mu$	$\nu_\tau$	W boson	
	electron neutrino	muon neutrino	tau neutrino		
				GRAVITON	

- made of particles
- 4 Forces : ① Strong atomic Force  
g = gluon.  
② Electro-magnetic  
Y  
③ Weak Force  
Z & W

3 Generations of Fermions until 2008

④ G - Graviton

\*\* 2012 Higgs Bozon → makes the Higgs Field → gives a mass to matter

## D. Dual Nature of Light :

Some phenomena that Quantum Mechanics can or attempt to explain :

Dual Nature of Light (La dualité onde - particule)

un objet quantique peut être à la fois ...

... une particule (électron) == acts like a ball ○ →

ou / or (onde) (vague)  
... a wave (électron) == acts like a wave ~~~~~

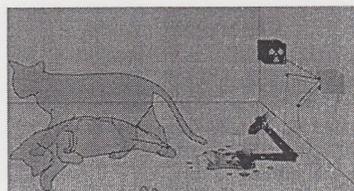
Video clips :

We are going to watch some videoclips and pull out some of the information we may understand and also write down some questions that come to mind.

1) What can Schrödinger's cat teach us about quantum mechanics? ( 5: 23 min)- Josh Samani (bilingue)

2 cats in universe & rule of entanglement ( applying subatomic info and applying it to macroatomic world) as as superposition.

<https://www.youtube.com/watch?v=z1GCnycbMeA>



- the Physics that we observe everyday is different than the Physics at the atomic / subatomic level. (This is Quantum Mechanics world)

- The cat can be both alive <sup>and</sup> ~~or~~ dead (It is called a superposition state)

\*- Electron is everywhere around an atom (ex. hydrogen). To know where the electron is, we need to observe it....

- Entanglement " same goes for the cat, ... we need to open the box.

2) What is a Higgs Boson? ( 4 min) in 2011 before it was discovered or proven !!

<https://www.youtube.com/watch?v=RIg1Vh7uPyw>

3) The Higgs Boson Simplified Through Animation (4 min)

<https://www.youtube.com/watch?v=L6AN6UwTTjU>



LHC  
1964  
in Geneva.

Hypothesis :

A field (Higgs) would give a mass to some subatomic particles and less to others (the smaller one) (large)

Comparison with a fish in water vs a human,

class # 1

smaller particles → field  
↳ less interaction.

bigger particles  
↳ more interaction  
↳ more mass

5

4) Quantum Theory Made Easy [2] 0:00 – 8:00 (premiers modèles des atomes)

[https://www.youtube.com/watch?v=FIrgE5T\\_g0](https://www.youtube.com/watch?v=FIrgE5T_g0)

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5) Quantum Theory Made Easy [1] 0:00 – 10:15

[https://www.youtube.com/watch?v=e5\\_V78SWGFO](https://www.youtube.com/watch?v=e5_V78SWGFO)

Duality of Matter

Origin of Quantum Theory

originated from electromagnetic forces (Wave lengths and frequencies)  
 Light is a disturbance of electric field and magnetic forces  
 It was declared that Light was a WAVE !!!

Planck was looking for a light 'bulb' that maximize emission of light with a minimum of heat.

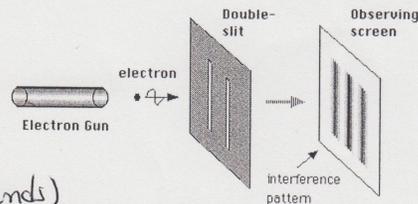
Looking for something, Planck ended up searching for something else  $E = nhf$   
 He discovered 'quanta' energy that comes in discrete amount (not a continuum like a wave) !

Here comes the expression « Quantum Leap »

Photoelectric effect 14:00 – 15:00

6) Dr Quantum - Double Slit Experiment (5:03) animated

<https://www.youtube.com/watch?v=DfPeprQ7oGc>



①

Macro

- Particles → create 1 or 2 lines behind the plate with slit. (bands)
- Waves → create an interference pattern with many bands.

② Quantum

- electron = tiny bit of matter / very small marble
- ↳ 1 slit ~~beho~~ electrons behave like marble → 1 band.
- ↳ 2 slits → ~~be~~ electrons behave like a wave !!! How?

Matter ⇒ !!  
 wave ✗

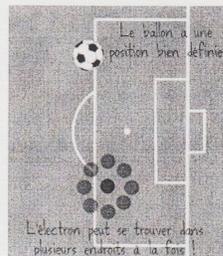
It doesn't make sense → leave as 1 and behave like 2.  
 to interfere like a wave.

→ When observed/spied upon = electron behaves like a particle

6

7) Quantum Mechanics for Dummies 2015  
 (22 minutes)  
 London City Girl (animated)  
 Excellent pour expliquer les différentes composantes d'un atome

<https://www.youtube.com/watch?v=JP9KP-fwFhk>

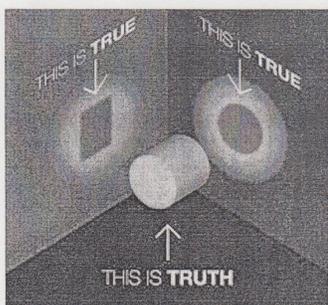


Subatomic Particles: electron/proton/neutron.  
 + Leptons + Quarks. → Matter  
 Personal Notes: Forces

Review → Double slit → interference pattern  
 ↳ Superposition → electron at various places at once  
 ↳ with the detector on, superposition collapses and the electron is in one location

Schrodinger's cat experiment was done to illustrate how odd the law of Quantum Mechanics are.

Smaller objects may follow the law of QM.  
 Qubits: deux valeurs à la fois



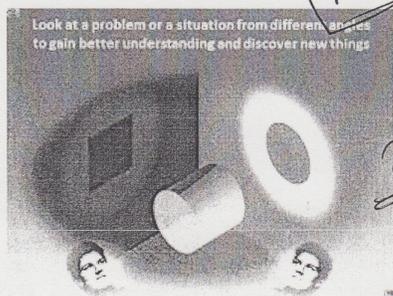
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Les ordinateurs que nous utilisons actuellement codent les informations en séries de bits (0 ou 1). Un ordinateur quantique utilise des qubits, qui peuvent prendre deux valeurs à la fois (0 et 1) selon le principe de « superposition » qui permettent les propriétés quantiques de la matière. Au sein du qubit, la part du 1 peut varier entre 0 % et 100 % (de gauche à droite de la première série), et de la même manière la part du zéro (de gauche à droite de la deuxième série).

↳ electrons are smart!!  
 ↳ they change their behaviour

Philosophy

↳ Many world theory  
 ↳ anything that can happen does happen.



↳ Entanglement → reaction happens at a speed faster than the speed of light.

Tunneling

Quantum ↳ Particle wave function.  
 proton will act like wave to tunnel to the

He

→ Sun

H

→

H