Characterizing Teachers' Incoming Science Content Knowledge in a Professional Development Program

Joyce M. Parker
Michigan State University

Tom J. McConnell
Ball State University

Jan Eberhardt
Michigan State University

A paper presented at the 2013 Annual International Conference of the National Association for Research in Science Teaching, Rio Grande, Puerto Rico, April 9, 2013.

This material is based upon work supported in part by the National Science Foundation, under special project number ESI – 0353406 as part of the Teacher Professional Continuum program. Any opinion, finding, conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of any of the supporting institutions.

Abstract

While research shows that improving science teachers' content knowledge is important in changing teaching practice, offering professional development that meets the needs of a diverse population of teachers is challenging. Teachers enrolling in a professional development (PD) experience come with different educational backgrounds, different teaching certificates, and different levels of experience. Just as we expect teachers to pre-assess so they can focus instruction on the needs of their students, PD planners should also base their instruction on the prior knowledge of participating teachers. The Problem Based Learning Project for Teachers implemented a pre-assessment strategy that includes instruments in seven content strands for K-12 teachers who elected to study a science topic they had identified as an area of need. In this paper, we give a qualitative summary of the patterns in teachers' content knowledge for each strand. Findings suggest that teachers entered the PD program with no more than the level needed to answer recitation types of questions about science content in their selected strands. Many of the elementary teachers and elementary-certified middle school teachers lacked even foundational knowledge of the core concepts (NRC, 2012) they teach. Teachers across all levels struggled to connect idea and explain their application to real-world contexts. We discuss the implications of the patterns in the design and delivery of professional development for science teachers.

Keywords: teacher content knowledge, assessment, pre-assessment, problem-based learning, professional development.

Characterizing Teachers' Incoming Science Content Knowledge in a Professional Development Program

Introduction

Effective science teachers possess several types of knowledge (Loughran, Mulhall, & Berry, 2004), but central to the understandings they must master is content knowledge. PCK (Park & Oliver, 2008; Shulman, 1986; van Driel, Verloop, & DeVos, 1998) encompasses many of these types of knowledge, including knowledge of content, knowledge of learners, and knowledge of pedagogy. For this paper, the authors focus on content knowledge, and the qualitative assessment of it in the context of a teacher professional development program. In order to design effective instruction, assess the accuracy of student writing (Ball, 1997), and explain complex scientific concepts (Ma, 1999), science teachers need to have a deep understanding of the topics they teach. A deep understanding not only includes definitions and recognition of patterns in scientific phenomena, but also the mechanisms and explanations for why these patterns are present and how they apply to students' lives (Windschitl, 2009). Especially as the *Framework for K-12 Science Education* (National Research Council, 2012) is being implemented, teachers need a firm understanding of the core concepts they teach, the interactions of these concepts across subjects, and the processes and practices of science that lead to theories and practical applications of these theories.

Research on the characteristics of effective science teachers highlights the importance of a deep understanding of science content to support change in teaching practice (Jeanpierre, Oberhauser, & Freeman, 2005; Traianou, 2006; Darling-Hammond & Richardson, 2009) and increase student achievement (Hill, Rowan, & Ball, 2005; Mundry, 2005). For example, Goldhaber and Brewer (1997) found that whether teachers were teaching in versus out of certification correlated with student performance. (Ball & Darling-Hammond, 1998).

But do practicing teachers have the appropriate content knowledge to implement the *Framework for K-12 Science Education* (NRC, 2012)? Studies of teacher content knowledge suggest that teachers of science do not have an adequate understanding of the science content they are asked to teach. Especially those who have only taken introductory science courses or are teaching out of their fields, have "ideas of science content that may not reflect accurate conceptions" (Akerson, 2005, p. 245). Even teachers assigned duties within their area of licensure may not be prepared to teach the content included in the standards for a specific grade level. For instance, teachers with a license to teach grades K-8 in Michigan may be assigned to teach middle school science courses without having had more than a few introductory science classes in college. In addition, because of changes in state graduation requirements that moved earth science from the high school curriculum into the middle grades, middle school teachers certified several years ago have found themselves required to teach standards for which they are unprepared.

The importance of teacher content knowledge becomes more important as the Next Generation Science Standards [NGSS] (NRC, 2012) are adopted by states. The structure of these standards places an emphasis on the core ideas of science and the crosscutting concepts that build a network of connections. If teachers have only a superficial level of understanding of these core ideas, they may lack the ability to identify the way students' verbal and written comments may reflect misconceptions, making it less likely they will address those misconceptions in class. These teachers may also struggle to present the correct models and multiple examples to demonstrate the relevance of the core ideas and crosscutting concepts described in the

Framework (NRC, 2012). Even if a teacher knows the content well enough to pick the correct answer from a multiple choice test question, the NGSS (NRC, 2012) calls for teachers to help students make connections between related concepts. The ability to make links and apply science ideas in this way requires more than just a recall level of knowledge. Teachers need to know how the concepts in chemistry relate to biology, physics, and earth science, for instance. Our minimum expectations should be that teachers understand the content to *at least* the level expected for graduation from high school science courses.

There is clearly a need to help strengthen the science content knowledge of teachers, especially in inner cities, rural schools and elementary classrooms where teachers have taken fewer science content courses than other teachers of science (Akerson, 2005; Howley & Howley, 2005; Irving, Dickson, & Keyser 1999). This need points to the importance of science teacher professional development (PD) that focuses on deepening content knowledge.

Professional development (PD) for in-service teachers often addresses science content (Diaconu, Radigan, Suskavcevic, & Nichol, 2012; Phillips, Desimone & Smith, 2011). However, very little has been written that gives a qualitative description of the types of content knowledge teachers have when they enter a professional development program. Because different PD programs focus on different concepts or teaching strategies (Gerard, Varma, Corliss, & Linn, 2011; Hartshorne, 2008), and because they target teachers from different grades or content areas, it is nearly impossible to characterize the gaps in content understanding across programs. Most studies have been based on standardized tests that are effective at quantifying the level of knowledge within specific science disciplines (Tretter, et al., 2007). There is scarce literature about the qualitative nature of the knowledge and teachers' ability to explain and apply concepts across a wider range of content areas.

However, it is crucial for PD planners to consider prior knowledge when working with teachers. As in K-12 education, constructivist learning theory (Vygotsky, 1978) indicates that in order for learners, in this case teachers, to achieve deep and enduring understanding, we need to identify their initial understanding in order to build on it and connect to it. This study examines the science content knowledge of a group of K-12 teachers with varying amounts of experience and training entering an extensive summer PD experience. Participants in the PD program selected content strands in which they felt they needed a deeper understanding of core ideas. We used an assessment strategy that asked teachers to use their understanding of science concepts to write about patterns and formulate explanations of general concepts and apply those concepts to particular situations (McConnell, Parker, & Eberhardt, 2013). Therefore, this study examines both teachers' content knowledge and their ability to diagnose their own areas of weakness. We present a summary of the content knowledge and gaps in understanding found across several content strands and among teachers with varying levels of experience, education, and grade level taught.

Research Questions

The research questions that guided the design of this study include:

- What patterns do we see in the science content knowledge teachers?
- How well do teachers identify the topics in which they need more content knowledge?
- How does teacher science CK correlate to factors such as experience, education, and grade level taught?

Context - The Professional Development Program

Characteristics of effective PD

The Problem-Based Learning (PBL) Project for Teachers (McConnell, et al., 2008) was an NSF-funded project that offered professional development for K-12 science teachers. The goals of the program were to use PBL as a strategy to help develop deep content knowledge, support teachers in the development of inquiry-based curricula based on their content knowledge, and facilitate collaborative inquiry into teaching practice with the goal of improving instructional practice. For this article, we focus on the content learning aspect of the PBL Project.

Effective professional development needs to address the practical needs of teachers (Wei, Darling-Hammond, Andree, Richardson, & Orphanos, 2009). Among these needs, professional development that is most effective for improving student achievement has been shown to support teachers' content knowledge and instructional practices (Saxe, Gearhart & Nasir, 2001).

During the summer of 2008, 65 participants from schools across central Michigan enrolled in the program. Participating teachers selected a content topic, or "strand," in which they felt the need to improve their content understanding. Participants took part in a seven-day summer program consisting of three days of content learning in their chosen strand, followed by four days of curriculum development. Most of the summer participants also took part in yearlong professional learning communities to collaboratively analyze classroom practice. Before and after the summer workshop, researchers administered pre- and post-assessments of content knowledge for each strand (McConnell, et al., 2008).

By examining teachers' prior concepts in each strand, teacher educators can design PD activities that address the practical needs of the teachers in a PD program. In this article, we will discuss the design of the assessment instrument, the findings of the pre-assessment, and the implications of these findings on the design of professional development.

Participants

In the summer of 2008, 68 participants enrolled in the program. The participants included teachers in all grades from K-12. The teachers ranged in age from 23 to 61 years, with a range of teaching experience from one to 32 years. About 89% of the participants were female. Based on the areas of need identified in teachers' applications, seven content strands were selected for the summer workshops. Table 1 shows the distribution of teachers in these content strands organized by grade taught.

Methodology

Design of the Assessments

The assessment instruments used in the PBL Project were designed to reveal teachers' ability to identify, explain and apply concepts related to the specific content strand chosen by the participant. In the first cohorts, researchers examined different approaches to assessing teacher content knowledge, including concept inventories and open response questions. The findings of each cohort led to the version tested in the 4th cohort of teachers.

The assessment instrument for this final cohort included two different types of open-ended questions: general knowledge questions and application questions. Examples of each of these types of questions, taken from the Geosphere Secondary Strand are shown in Figure 1.

Table 1

Number of Teachers by Strand And Grade Band

Strand\ Grade	***Elementary K-2***	***3-5***	***Middle 6-8***	***High 9-12***	***Total***
Astronomy	0	6	4	0	**10**
Cell Bio	0	0	2	7	**9**
Ecosystems	0	8	4	0	**12**
Genetics	0	0	4	7	**11**
Geosphere Elementary	8	3	0	0	**11**
Geosphere Secondary	0	1	8	1	**10**
Weather	1	0	4	0	**5**
Total					**68**

General Explanation Question	**Application Question**
It is said that the history of the Earth is written in the rocks. How do rocks tell the geologic history of an area? Include the rock type, age, texture of the rock (at the hand specimen level as well as regional scale), the general composition, relationship to other rocks in the environment, and the rock forming processes involved.	The theory of plate tectonics proposes that plates come together at convergent plate boundaries and spread apart at divergent boundaries. Explain how all the parts of the rock cycle happens at both of these boundaries a. The East African Rift Valley (a divergent boundary) b. Japan (a convergent boundary)

Figure 1. Example general and application questions from the Geosphere Secondary Strand.

In each content strand, the assessments included at least one general question prompting participants to write about the broad theme for the strand. In the geology question in Figure 1, this question asks about the types of information a scientist can infer by studying the rocks in a given area. The prompts after the initial sentence were found to be helpful in drawing out the details in a teachers' understanding. Questions written for earlier cohorts did not include these prompts, and the responses written by teachers were much shorter (McConnell, et al., 2013).

We also found that in response to the general questions, participants often only provided a list of concepts with which they were familiar. In order to assess participants' ability to use the information, application questions were written for each strand. Early trials led to a design that included at least one question asking for an explanation of a specific scenario, issue or phenomenon. For instance, the Geosphere question in Figure 1 describes the difference between divergent and convergent plate boundaries and identifies a particular example of each. The question then asks participants to explain the connection between the conditions at tectonic boundaries and the rock cycle. The application questions were designed specifically to reveal the teacher's ability to explain concepts and events, something an objective test cannot achieve.

The questions written for each strand were aligned with national and state standards for the content strand that matched the participants' self-identified areas of need (AAAS, 1993; Michigan Department of Education, 2006; NRC, 1996, NRC, 2012). The facilitators for each strand were content experts for each topic, including university faculty and expert teachers. The facilitators also wrote ideal responses and used these to identify the "Big Ideas" addressed by each question. Other facilitators reviewed the questions and ideal answers prior to administering the assessments.

Level of understanding assessed

Based on the researchers' prior experience with teacher PD, the problem-based learning activities and assessment questions were aimed at the boundary between teachers' strong and weak explanatory content knowledge. Therefore the project Big Ideas (see Methodology) include concepts identified as targets for middle and high school students in national (AAAS, 1993; NRC, 1996) and state standards (MDOE, 2008) available at the time, as well as concepts that explain these ideas. We have since mapped the Big Ideas onto the Disciplinary Core Ideas (DCIs) of *The Framework for K12 Science Education* (NRC, 2012). For the most part, project Big Ideas correspond to middle school and high school DCIs. The correspondence and the exceptions are explained in more detail in the Findings.

Data Collection and Analysis

The pre-assessment questions were administered in April prior to the summer workshop. Teachers at an orientation meeting were asked to write their responses, and given about 45 minutes to complete their writing. The same instruments were administered after the 7-day summer workshop to assess teachers' learning. The responses were then transcribed, de-identified, and mixed so coders could not distinguish between pre- and post-assessment answers. For each strand, a team of three facilitators met to code responses to assess their accuracy against an ideal answer written by the expert facilitator. Each team included the strand's facilitators who wrote the question, and one other content expert not directly involved in the strand.

When coding responses from earlier cohorts, we tried to establish inter-rater reliability. Because of the small sample sizes within each strand, this was difficult to assess. Once coders had reviewed enough responses to begin establishing a shared interpretation of codes, nearly all the responses had been scored. In the last cohort, the teams of three coders met to reach a consensus on codes assigned to responses.

To code the responses, researchers were given a list of the Big Ideas addressed in each question. They then read the responses, and assigned a code for each idea. The codes are shown in Table 2 (McConnell, et al., 2013). The coding team then discussed the codes and reached a consensus that was then recorded in the table.

Table 2

Coding scheme for analyzing open-response items
(From McConnell, Parker, & Eberhardt, 2013)

Code	***Definition***	***Description***
NP	Not Present	Concept is not present in the response
I	Inaccurate	Concept is inaccurate; exhibits misconception.
C	Confused	Answer is confused, vague, or offers too little information to understand what the respondent knows about concept
AI	Accurate, but Incomplete	Response is accurate, but lacks important information;
AC	Accurate	Response is accurate and completely addresses Big Idea

Codes were compiled for each teacher for each Big Idea (McConnell, et al., 2013). In the compilation, when teachers' scores for a particular Big Idea differed in response to different questions, the "lower" score was given. The exception was that if teachers' scored "not present" in one of the responses, they were given the other score for that Big Idea. The tables for each teacher in a strand were compiled showing the number of teachers with each code for each Big Idea. Summaries of teachers' incoming knowledge described in the Findings section are based on the latter tables and careful reading of individual responses.

Limitations of assessments

To understand how the assessments are useful, it is helpful to identify some limitations of the assessments. In some cases, the answers written by teachers to the open response items were limited to phrases or bulleted lists that did not reveal very much about the connections teachers could make between concepts. Other teachers also failed to address parts of questions. Because of this, the codes listed in Table 2 may be difficult to interpret. For instance, a code of "Not Present" (NP), does not necessarily suggest that a teacher does not know the concept. It only indicates that the written response did not address the idea. If the teacher skipped the concept or did not write in a coherent manner, his or her understandings may not be adequately reflected in the response. In other cases, the teacher may have clearly stated that she did not know a particular concept. In the example below, Mrs. Duggan's response to the general question from astronomy wrote:

> *Q: Why do we see the moon go through phases, and why do they change? Explain clearly in words and support your explanation with a well-labeled diagram.*
> *A: I don't really know why the moon goes through each of it's* [sic] *stages like waning, waxing, etc.*

Similarly, the "Confused" (C) code could suggest that the teacher has confused understandings, or that his or her writing is not clear. Still other teachers who received this score approached a question much as their students would; they began by restating the question and adding a vocabulary term in a vague connection. Interpreting what the teacher knows is difficult in this case. However, the "Confused" code does indicate that a student receiving such an explanation would have difficulty interpreting it.

In our discussion of the findings, we present examples of responses to illustrate the patterns found to be common across the content strands. In the discussion of the results, we present interpretations of these findings.

Findings

Teachers' Incoming Science Content Knowledge

Table 3 shows the level of teachers' incoming knowledge by grade level. Teachers' incoming knowledge was categorized as "None" if their response did not contain any accurate ideas. Responses with 1- 3 Big Ideas scored as accurate and incomplete or accurate and complete were categorized as containing "Some" knowledge. Responses with 4 or more accurate ideas were categorized as indicating "High" content knowledge. In each grade band, teachers' content knowledge ranged from none to high. High school teachers were most likely to come with a lot of knowledge, while middle school teachers were most likely to come with essentially no knowledge.

Table 3

Level of Teachers' Incoming Knowledge by Grade Level

		Incoming Knowledge		
Grade	Total	None	Some	High
HS	15 22.1%	4 12.5%	6 22.2%	5 55.6%
MS	31 45.6%	20 62.5%	9 33.3%	2 22.2%
ES	22 32.4%	8 25.0%	12 44.4%	2 22.2%
Total	68	32	27	9

These data suggest that more middle school teachers entered the program with low content knowledge, while high school teachers entered with higher content knowledge. This might be related to the level of education for the teachers. Some of the middle school teachers were elementary generalists certified for grades K-8, but were assigned to teach science. Our sample resembles teachers in a study reported by Hobbs (2012) of about 50% of middle school teachers teaching out of field. We hypothesized that education level and grade taught were predictive of content knowledge. To test this idea, researchers examined the relationship between incoming content knowledge and teacher variables. Factors that may influence familiarity with science content were tested using Pearson's R correlations include grade taught, the type of degree (non-science, bachelors in science content, graduate degree in science content), age, and years of teaching experience. The data in Table 4 show that only the degree held by the teacher had a small but significant (p = .046) correlation to incoming content knowledge.

Table 4

Correlations between Incoming Content Knowledge and Teacher Variables

Variable	Correlation to Incoming Content Knowledge
1. Grade Taught	0.169
2. Degree	0.258*
3. Age	-0.064
4. Teaching Experience	0.009

Summaries of Qualitative Responses by Strand

While above data are helpful in identifying patterns in incoming content knowledge across participating teachers, a more telling source of data is the written responses to the assessment questions analyzed by content strand. In the following section, for each content area, we offer a brief description of the Big Ideas that were the focus of the assessment, how these ideas matched state and national standards, and a summary of the patterns in the responses with examples of teachers' written responses. It should be pointed out that, with a few exceptions as noted, teachers were assessed on their use of concepts appropriate for middle or high school students as defined by the national standards (NRC, 2012).

Weather. The big Ideas in the Weather strand included the water cycle driven by uneven heating of the earth by the sun and the connection between air temperature and pressure and wind. Most of the Big Ideas for this strand are addressed in the national (ESS2.D, PS1.A) and state standards for grades K-8. The exception is the concept that thermal energy is redistributed when water changes phase.

Five teachers participated in the weather strand. Four of these were middle school teachers, while the fifth teacher taught kindergarten. The teachers were asked the following general question: Using the words thermal energy and radiation explain why we have weather? (Think about seasons, the water cycle, air masses and predicting the weather.) The kindergarten teacher answered with one sentence fragment. One of the middle school teachers (Ms. Uther) wrote general sentences apparently based on the terms given in the question. "*Weather is a result of natural conditions affected by seasons, air pressure and air masses. The thermal energy from the sun can warm air masses. Radiation is the transfer of the heat energy.*" The remaining three teachers had statements that connected some, but not all of the components of weather. Ms. Brinkman's response is an example of this.

> *The atmosphere gets warmed by the sun's radiation and conduction(?). Warm air is less dense and rises. Cool air is more dense and sinks. In high pressure areas – cool air sinks and is warmed. The air can hold more moisture. In low pressure areas – warm air rises and cools and can't hold as much moisture. I know an air mass is a body of air with a certain temperature and fronts are what separate air masses.*

The teachers were also asked the following application question: Using the diagram [of a side view of Lake Michigan and the coast of Michigan with Holland shown close to the coast and Lansing farther inland], explain why Holland experiences greater lake-effect snows than Lansing. In your explanation discuss phase changes in water, air pressure and density, land water and air temperatures, and movement of air. In response, all of the teachers wrote about air moving across Lake Michigan and picking up moisture and then dropping that moisture on Holland in the form of snow. The kindergarten teacher and Ms. Uther did not explain why the snow would fall once the air reached Michigan. Two of the remaining teachers had incomplete explanations. For example, Ms. Brinkman wrote, "*Cold air moves across the lake. The lake is warmer than the air. As water evaporates off the lake and mixes with the cold air, this change in density causes precipitation. If temps are cool enough, snow is produced.*" The fifth teacher gave a fairly complete explanation.

> *Evaporation occurs over Lake Michigan. This creates a moist air mass that is moving, generally, from west to east. When the moist air mass moves over the land the air is pushed up by cooler air (because the water in the lake held on to its heat?). As the air mass rises it cools, condensation happens and snow falls. By the time the air mass gets to Lansing it has lost moisture.*

Genetics. The Big Ideas of the Genetics Strand focused on using cellular processes such as meiosis, transcription, and translation to explain patterns of inheritance. This approach reflects both national (LS3.A-B) and state standards. The one exception is that differential gene expression as the mechanism for production of specialized cells is not mentioned in the state standards. The level of detail in the Big Ideas for the project is somewhat higher than that of the national standards, since they include the nature of the genetic code (a redundant triple code in the sequence of nucleotide bases) and the structures involved in the processes of transcription and translation which are not mentioned in the *Framework* (NRC, 2012).

There were 11 teachers in the Genetics Strand – 4 middle school and 7 high school. A modern high school understanding of genetics includes a connection between cellular functions (such as meiosis and protein synthesis) and inheritance of traits. In one general question, teachers were asked to explain the central dogma of biology – how genetic information in DNA is used to guide synthesis of proteins (Explain the simple statement: DNA → RNA → protein). Seven teachers gave detailed narratives of the steps of protein synthesis. However, two did not explain the form that the genetic information took. Only two of the seven described how the structure of nucleic acids contributes to the processes of transcription and translation. Two other middle school teachers and one high school teacher described the processes in very general terms ("*DNA codes for RNA which in turn codes for protein synthesis.")* One middle school teacher wrote that she only understood genetics at the macro level.

When asked to explain Mendel's laws, two teachers gave partial, accurate responses connecting what Mendel observed to what we now know about meiosis and fertilization. An example of this is Ms. Atlas' response below which identifies meiosis as the process that segregates homologous chromosomes, but does not explain that different traits are independently inherited if they are on different chromosomes.

> *Mendel's Law of Segregation asserts that homologous chromosome pairs are divided and distributed evenly during meiosis so that each daughter cell receives one of the pair. The end result (in humans) is that each daughter cell gets 1 full set (haploid-1n) of chromosomes. Mendel's Law of Independent assortment states that one trait is inherited independently of others. That is that one trait/gene does not have any influence or impact on how another is passes on or inherited.*

Each of the remaining teachers attempted to explain at least one of Mendel's laws, but their writing was characterized by confusing combinations of ideas as illustrated by Ms. Webb's response below. In her first sentence, it is not clear if "chromosomes break apart" refers to recombination of chromosomal material or segregation of homologous chromosomes. In the last sentence, "assortment varies the chromosome order which also varies the DNA sequence" is difficult to interpret and probably inaccurate.

> *Law of Segregation explains the way the chromosomes break apart to ensure variety in the genes in organisms. This segregation allows the chromosomes to code for amino acids to produce particular proteins. The Law of Independent Assortment explains the way the chromosomes change positions to also increase diversity of organisms. The assortment varies the chromosome order which also varies the DNA sequence further creating the RNA sequence also affecting the amino acid order and the protein sequence.*

When asked to explain why liver cells and muscle cells have different arrays of proteins, four teachers explained that not all genes are expressed in all cells resulting in different proteins, but only one explained how this occurs.

> *Since the liver & muscle cell need different parts of the DNA, the proteins made through transcription & translation will be different as well. Gene regulation helps control which genes are expressed in a cell & which are not. The regulation depends on the cell.*

Four teachers gave confusing or inaccurate accounts of why cell types differ as exemplified by Ms. Joy's response. "*Each type cell is coded by a different protein, which is why they look different.*"

Six teachers recognized that the inheritance of coat color in Labrador retrievers is non-Mendelian. Three of these gave at least partial explanations of how this happens. The remaining teachers gave Mendelian explanations such as incomplete dominance or co-dominance that did not account for the data.

Astronomy. The Big Ideas included using a model of the solar system to predict, describe and explain the patterns of the phases of the moon, what people on the earth see of a lunar eclipse, and the appearance and apparent motion of the planets against the celestial sphere. All of these Big Ideas are in both the state and national standards (ESS1.B) for grades K -8.

Six of the ten teachers in the Astronomy Strand taught 4th or 5th grade. The other four teachers taught middle school. Ms. Tran, the fourth grade teacher was the only teacher who explained the phases of the moon accurately and completely. Three middle school teachers and one 5th grade teacher gave very general and brief explanations such as, "*It depends on where it [the moon] is in relationship to the earth and sun.*" Their diagrams did not add information. Two 5th grade and one middle school teacher had brief explanations that contained some accurate information such as, "*The visible portion of the moon is a result of the sun illuminating*." However, they also contained misconceptions such as the phases resulting from the tilt of the earth's access. The two remaining teachers attributed moon phases to the earth's shadow falling on the moon.

Ms. Tran and a 5th grade teacher were the only two teachers to give an accurate and complete explanation of why we see Venus only in the morning or evening, but never in the middle of the night. One middle school teacher gave an incomplete explanation that did not include why Venus is out of our line of sight at night. One 5th grade teacher inaccurately described Venus' orbit saying, "It moves quicker and therefore comes into view in the morning and continues revolving around the sun and then returns by evening." The remaining six teachers wrote nothing, said they did not know the answer, or volunteered a brief and inaccurate answer after saying they did not know.

Ms. Tran was the only teacher who correctly predicted whether the moon seen overhead in the evening would be visible in the morning. One teacher did not respond to this question and the remaining teachers gave vague answers ("*It depends on how early you get up*") or incorrect answers ("*Yes, but only until the sun rises*.") When asked how the same moon would look to people in Australia, Ms. Tran and two other teachers made correct predictions, but only Ms. Tran explained her answer. Two teachers did not respond and the remaining five teachers gave incorrect responses, predicting that Australians would see a different moon phase or a different part of the moon.

Ms. Tran and two other teachers correctly explained how longitude and latitude would affect what people in Michigan, New York and New Orleans see of a lunar eclipse. Three teachers did not respond and one gave a vague answer. Two teachers incorrectly predicted the effects of longitude and latitude. No teachers indicated that through powerful binoculars Venus would appear to have phases.

Cell Biology. The Big Ideas focused on explaining the energetics of photosynthesis, respiration, and fermentation in terms of bond energies and oxidation and reduction. These Big Ideas are somewhat more specific than the state and national high school standards. The national high school standards use bond energies in a generic way, but not oxidation/reduction to explain the energy transformations of metabolism. (LS1.C: *For example, aerobic cellular respiration is a chemical process in which the bonds of food molecules and oxygen molecules are broken and new compounds are formed that can transport energy to muscles*.) The state standards are less specific in the nature of the explanation that high school students should be able to give. (B2.1A *Explain how cells transform energy (ultimately obtained from the sun) from one form to another through the processes of photosynthesis and respiration. Identify the reactants and products in* *the general reaction of photosynthesis*.) Learning progression studies of students' understanding of matter and energy transformations in carbon-transforming processes describe association of more energy with C-C and C-H bonds than with C=O bonds as an upper anchor approach to bio-energetics (Hui and Anderson, 2012)

There were nine teachers in the Cell Biology Strand. Two of these were middle school teachers, while the remaining teachers taught high school. Teachers were asked to explain the energy transformations and transfers in a plant from sunlight to cellular work. Two middle school and one high school teacher accurately and simply explained that in the process of photosynthesis the energy in sunlight is transformed and stored in the resulting sugars. The sugars are used in the process of respiration when a cell needs to do work. The remaining six high school teachers gave more or less detailed and accurate accounts of the energy transformations in photosynthesis. However they all left out cellular respiration, because they had the misconception that the ATP produced during photosynthesis is used for cellular work.

In explaining why yeast grows faster in aerobic versus anaerobic conditions, four teachers described, but did not explain, the larger output of ATP molecules produced from each sugar molecule. However, they did not explain the role of ATP in growth. The remaining four teachers said only that the difference was due to the presence of oxygen or that aerobic respiration was more efficient.

When asked about metabolic symbiotic relationships between microbes and cows, all but one of the teachers talked in general terms. Three teachers described the microbes breaking down cellulose as an energy source resulting in products that were used by the cow as energy sources. However they were not specific about the relative amounts of energy or the products. Three teachers talked about microbes producing metabolic products that could be used by cows without accounting for the energy needs of the microbes. One teacher erroneously indicated that the cow and microbes used different parts of the grass as food. The one teacher who used more specific terms said that the microbes produced ATP as they broke down cellulose into sugar.

Teachers were asked to explain why compost piles are warm and lose volume. One high school and one middle school teacher indicated that microorganisms breakdown the material producing CO_2 or gas (respectively) which is lost. Four high school and one middle school teacher indicated that microorganisms were using the compost material for energy, but did not explain the loss of volume. One high school teacher attributed the volume loss to loss of water.

In explaining the mechanisms of chemical breakdown, two teachers erroneously said that breaking chemical bonds releases energy.

Ecology. The Big Ideas focused on the concept that populations are limited by availability of resources, such as food, space, water and sunlight and using this idea to explain how changes in food webs, invasive species, key species, succession, and habitat quality affect ecosystems and ultimately biodiversity. If we consider succession to be a specific case of how species interact, all of these Big Ideas are addressed in both national (LS2.A – C) and state standards. These standards span all grade levels.

The twelve teachers in the Ecology Strand taught grades 3 – 7. In contrast to the situation in other strands, all of the teachers in the Ecology Strand addressed most of the Big Ideas, though not always accurately and rarely completely. Many teachers' responses to a question about natural and manmade causes of biodiversity decline named, but did not explain the causes. However, the question did not specifically ask for explanations. The most common inaccuracies were somewhat vague statements that implied that invasive species and pollution directly harm indigenous species, rather than competing with them or degrading their habitat. The one idea that no teachers addressed was that of succession despite the question specifically asking for natural as well as manmade contributions to decline in biodiversity. Instead teachers cited global warming and geological and weather-related events such as earthquakes and floods or droughts as natural cause of decline in biodiversity. One teacher mentioned evolution.

Teachers were asked to explain why seepage of organic matter from septic tanks into a lake led to decreases in productive fishing. Three teachers explained that this led to increased plant/algal populations. However these teachers gave inaccurate explanations of the effect of the increased plant growth on animals saying that the plants of the surface shaded out other plants or the plants crowded out the animals. Four teachers gave vague statements about changing conditions in the lake and four other teachers did not respond to this question.

When asked to explain how loosestrife takes over marshes, six teachers mentioned that its root system squeezed out cattails and/or that loosestrife is not eaten by any indigenous species. Three of these teachers talked about the indigenous cattails as being less hardy or unable to adapt quickly. One teacher erroneously said that loosestrife "*sucks the nutrients/water that cattails needed*." One teacher knew that cattails were affected but said she did not know why. Teachers were also asked to explain how changes in plants in the marsh might affect other organisms. Seven described the loss of cattails as affecting other species dependent on them for food and/or shelter. Three teachers did not respond to this question.

Geology Elementary. These Big Ideas used conservation of matter as an overarching concept for exploring water and rocks cycling, tectonic formation of major landform types, and humans' use and disposal of earth materials. These ideas are covered by the state and national standards (ESS1.C, ESS2.A-C, PS1.A-B) for grades K – 8, with the exception of the following – solar energy and gravity cause the earth's surface to be broken apart and moved to new locations.

There were eleven teachers in the strand addressing geology for elementary schools. Teachers were asked about people's use of earth materials and the effects of that use on the geo-, hydro- and atmospheres. Eight teachers responded in generic form mentioning mining and general harm to the environment or pollution. When they gave specific examples of materials that are mined, they mentioned particular metals, gems, and coal. Ms. Summer's response is representative.

> *One way people obtain materials from the earth is through mining. The copper mines in Michigan's Upper Peninsula are an example of mining. People use machines and explosives to create holes in the Earth. They dig the minerals out from the rocks around them. Mining is a benefit because people use the minerals for making things or selling for money. Mining can be hard on the environment because of pollution that can occur.*

In contrast, one kindergarten teacher, Ms. Passmore included soil as a resource from the earth and identified, but did not explain some links between mining to environmental harm. Two additional teachers' responses were in between these two examples in completeness. Ms. Passmore's response is shown below.

> *People use earth materials for food, shelter, and manufacturing. Ores and minerals can be mined, diamonds, marble, and salt are examples. Homes are built*

> *using clay, concrete, and marble. Soil is used to grow food. The Geosphere is impacted when mining is used to remove earth solids. The hydrosphere is impacted by erosion and pollution. The burning of coal impacts the atmosphere and affects global warming.*

Teachers were asked to explain how the Rocky Mountains and Central Plains formed, the rock types associated with each, and how they will change over time. Seven teachers associated mountain building with tectonic plates coming together and identified various kinds of weathering and erosion as destructive forces that change them. Two teachers correctly attributed the Central Plains as the remnants of an inland sea. Two teachers associated the Plains with glaciers, one with erosion products from the Rockies and one with the biblical flood. Two teachers only identified destructive forces, one only explained what tectonic plates are, and one's response contained only cues from the question. None of the teachers identified rock types associated with the landforms.

Teachers were asked to explain why fossils of marine organisms can be found in the Himalayas. Two teachers explained that movement of tectonic plates pushed up mountains and weathering and erosion exposed the fossils. One teacher described only the mountain building parts of this scenario. Four teachers hypothesized that at one time sea level was higher. One of these teachers attributed the high seal level to the biblical flood. Two teachers gave scenarios that included only erosion and weathering without uplift and one teacher explained that glaciers had moved the fossils.

When asked to connect "reduce, reuse, recycle" plastic water bottles to natural resources, energy consumption, and conservation of matter, three teachers gave simple, strong responses. Four teachers explained what it means to reuse or recycle plastic water bottles, but took "reduce" to apply to harmful environmental effects (for example, "*reduce the amount of non-biodegradable objects in landfills*.") Three teachers did not explain the meaning of "reduce" and made no connection to energy consumption. One response was difficult to interpret.

Six teachers described two ways (one via the atmosphere and one not involving the atmosphere) in which rain water falling in Michigan can reach the ocean. However only one of these explained that an energy input is needed to get water into the atmosphere. One teacher cited the water cycle without elaborating and humans moving water. Two teachers said they did not know the answer.

Geology Secondary. The big Ideas of the Geology strand for Secondary teachers focused on using plate tectonics to explain basic landforms and associated rock assemblages. All of these Big Ideas are found in the national (ESS2.B) and state standards for grades 5 – 12. However the project Big Ideas are more specific in that they address some rock characteristics such as crystal size as an indicator of cooling rate which are mentioned in the standards.

When asked about how rocks tell us about the history of the earth, none of the teachers connected rock types with tectonic events except in general terms such as, "*Rocks can tell Earth's story of floods, earthquakes, volcanic eruptions*." Eight of the ten teachers identified and in some cases described the three rock types. Five teachers explained that rocks' ages can be determined because older rocks are found below younger ones. Four teachers indicated that fossils in rocks can tell about environments or ages of rocks. Two teachers explained that big crystals are indicative of rapid cooling. Only one teacher responded with all of these ideas. One teacher wrote that she did not have much knowledge of this topic and another teacher offered only general or inaccurate ideas such as, "*Brittle rocks have been around longer around more areas of dampness*" or the history of the earth can be determined from "*the colors of the rock from the inside out*."

Teachers were asked to explain what part(s) of the rock cycle occur in the African Rift Valley which they were told was a divergent plate boundary. Three teachers mentioned that igneous rocks would form from the magma that came through the rift. Two of these teachers went on to explain how uplifted rocks would weather and erode and the resulting sediments might form rock. They said that metamorphic rocks would form under conditions of high heat and pressure, but did not explain where these conditions might occur. Seven teachers said they had no knowledge of this topic or offered a simple sentence with no reference to the three rock types.

Teachers were also asked to explain what part(s) of the rock cycle occur in Japan, a convergent plate boundary. One teacher gave sound explanations of how subduction zones produce igneous rocks, which can be eroded and weathered to form sedimentary rocks. As in the question about the rift valley, she and two other teachers explained the conditions for metamorphism, but not where they would occur in Japan. One teacher associated mountain building with convergent plate boundaries but did not mention rock types. The remaining teachers did not attempt answers.

Discussion and Implications

The seven content strands described above included teachers from grades K-12, who were entering a professional development program in which they elected to study science content in a topic in which they felt they need to learn. The patterns seen in their pre-assessment responses can reveal trends relating to teachers' incoming content knowledge (CK). These patterns help answer the original research questions. The findings do not suggest that the teachers are not knowledgeable about science in general, but rather that there are specific science concepts in which each teacher lacks a deep understanding. In this section, we will discuss the importance of the trends in the teachers' responses and the implications these trends have for informing the design and delivery of science teacher professional development.

RQ1: What patterns do we see in the science content knowledge teachers?

In analyzing the results, it is important to remember the context. As described in the Methodology section, the Big Ideas against which teachers' responses were scored, were identified in state (MDE, 2007) and national documents (NRC, 2012) as ideas that middle and high school students should understand. Teachers had taught or would be teaching the topic in the fall. This does not mean that teachers taught the particular ideas on which they were assessed. Finally, teachers chose the particular content strand in which they were working as one where they would benefit from PD.

We looked first at what teachers did include in their responses. Many of the teachers recognized important terms, rules or concepts, and could often provide definitions of those ideas. For instance, teachers in the Genetics Strand were able to state Mendel's laws of inheritance, and teachers in the Geology Secondary could describe how sedimentary and igneous rocks are formed. These are the types of ideas we might describe as "recitation" knowledge: the ideas we expect students to be able to recite in class or on a test. The level of this "recitation" knowledge also varied across strands. Participants in strands that included mostly secondary teachers (grades

6-12) wrote more responses coded as AC or AI than teachers from strands made up of mostly elementary teachers. This is not surprising considering the requirements for more science courses in secondary science teaching programs at the university level.

We looked next at what was not in teachers' responses. What is most striking is that even the most detailed accounts lacked important explanatory connections between pieces of information. For example, many teachers in the Genetics Strand were able to state Mendel's laws of inheritance. Several mentioned, but none explained how the process of meiosis results in segregation and independent assortment. In Cell Biology, many of the teachers knew that anaerobic fermentation is less efficient that cellular respiration, but none explained why. Most knew what cellular respiration is, but did not describe its role in plants. Teachers in the Geology Secondary Strand described how sedimentary and igneous rocks are formed, but did not link them to particular tectonic conditions. In the Ecology Strand, teachers wrote about direct interactions between organisms and factors in an ecosystem such as food webs or pollutants directly harming organisms, but none described less direct interactions such as habitat degradation. Only one teacher in the astronomy strand consistently explained observations of the moon, planets, and stars using a model of the solar system. In the Weather Strand, teachers at best described some, but not all of the connections between components of weather such as air pressure, temperature, and density. In the Geology Strand for elementary classrooms, teachers did not describe the connections between human activities or natural processes in the geosphere and effects in the atmosphere or hydrosphere.

Another way to view these results is that teachers' content knowledge is not organized around crosscutting concepts (NRC, 2012). For example, genetics is a topic that can be organized around the idea of cause and effect: mechanism and explanation. In particular, the idea that a mechanism should be part of an explanation of how a cause results in a specified effect clarifies what is important in an explanation. Alternatively, structure and function could be used to in a similar way to standardize what constitutes a satisfactory explanation. In the case of Geology for elementary classrooms, the crosscutting concept of matter and energy: flow, cycles, and conservation provides an organizing framework. Tracing the fate of different types of atoms taken from different layers of the earth and the energy needed to move and recombine them supports connection making.

Did teachers not include connections in their responses, because the connections were not specifically asked for? For example, teachers in the Genetics strand were asked to "Explain Mendel's Law of Segregation and Law of Independent Assortment, using in your explanation what we now know about genes/chromosomes and traits/proteins." They were not specifically asked to include a mechanism or the process of meiosis in their answer. However many of the questions, as exemplified by the following question from the Secondary Geology strand, did ask for particular connections:

> *It is said that the history of the Earth is written in the rocks. How do rocks tell the geologic history of an area? Include the rock type, age, texture of the rock (at the hand specimen level as well as regional scale), the general composition, relationship to other rocks in the environment, and the rock forming processes involved.*

In either case, the hope is that teachers are thinking about and therefore volunteer explanations that include connections. A complete set of the assessment questions is found in McConnell, Parker, and Eberhardt (2013).

RQ2: How well do teachers identify the topics in which they need more content knowledge?

In the planning of the PD program, the research team was advised not to let teachers select the strands in which they would study. Colleagues suggested that learners, including teachers, are not able to identify topics in which they need to improve. The findings of this study contradict this idea.

Across all the strands, the assessment instruments revealed gaps in teachers' understanding. As described above, the gaps were sometimes in foundational knowledge, put almost always in participants' ability to connect concepts. With few exceptions, teachers did need help with the content area that they chose. We do not know if the state of their knowledge of that topic was representative of their overall science content knowledge for teaching, but we can be confident that teachers can identify their own content knowledge deficiencies.

For PD planners, this suggests that we need to include participating teachers in the planning process. If we ask teachers about topics in which they need help, we can develop programs that meet the specific needs of our learners. For the PBL Program, this meant creating smaller learning groups, each with their own content focus, in order to meet the needs of a diverse population of learners. We posit that PD programs should adopt this approach rather than assuming all teachers in a school or district share the same needs.

RQ3: How does teacher science CK correlate with factors such as experience, education, and grade level taught?

Another question that must be asked is how incoming CK is related to a teacher's experience, educational history, and grade taught. Before analyzing data, the researchers hypothesized that incoming content knowledge would be higher among the high school teachers, and lowest among elementary teachers. When we analyzed the level of content by grade taught, we found that there were a significant number of teachers at each grade band with no CK. High school teachers were least likely to fall into this category (12.5%). However, 62.5% of middle school teachers had no accurate responses or several confused or inaccurate statements. This group was the most likely to be identified as having "no CK" as seen in Table 3. Further examination of this pattern found that many of the middle school teachers who lacked content knowledge held elementary certifications (grades K-6 or K-8) and were assigned to teach science in grades 6 or 7.

In order to understand the reason behind this pattern, we used Pearson's R correlation methods to look for the relationships between the demographic variables. The only factor that was significantly correlated to incoming CK was the degree earned. Teachers who had science degrees, including both bachelors and graduate degrees, were more likely to show "high content knowledge" than teachers with degrees in other areas, including graduate degrees. This result was expected, and supports the idea that schools need to employ highly qualified teachers for the science classroom.

But the research team also expected the more experienced teachers to show a higher degree of content knowledge. We accept the adage that the best way to learn is to teach, and familiarity with science concepts over many years should result in a deeper understanding. Despite a sample of teachers who ranged in experience from 1 to 43 years (the most experienced secondary science teacher had been teaching for 32 years), there was no correlation between either age or teaching experience and incoming CK.

This pattern is likely related to the design of the program and the assessment instrument. Each teacher was asked to identify a science topic in which he or she wished to learn more, specifically connecting the choice to state science standards they teach. The teachers were self-selecting into strands in which they were weak, so the scores might be expected to be lower.

Each strand also answered assessment questions written specifically designed to probe the limits of the teachers in the group. Strand facilitators wrote the assessments to address the standards expected for the band of grades represented by the enrolled participants, with some questions that reached beyond those standards to require more explanation of the concepts. In essence, the instruments were stacked to ensure that teachers were likely to be unable to answer all the questions.

If all the teachers were given a common assessment that included a broad scope of science concepts, it seems likely that participants with the most science courses would show the most CK. But the purpose of the assessment was to gauge the depth of content knowledge around a defined set of Big Ideas. We propose that this method is more effective than concept inventories when used to design professional development because it informs planners of the needs of the learner, just as we try to teach prospective science teachers to do in their own classrooms.

How representative is the content knowledge of participants?

A trend showing a lack of content knowledge or the connections between concepts could suggest that the participants in this study were weak in CK compared to teachers who chose not to take part in the study. However, demographic data about the participants (gender, ethnicity, age, type of school (urban, rural, suburban designations and socioeconomic standing designations) and collaboration with the teachers' classroom indicates that the participants were highly motivated and very professional. They were the teachers who actively pursue PD opportunities, even when enrolling in the program meant dedicating extensive time during the summer and after school during the school year. We posit that these teachers were typical for the teachers in Michigan, if not a sample that is unusually high performing.

Recommendations for PD and Science Teacher Education

Based on the findings of this study, we offer some recommendations for the planning and delivering professional development. We also suggest that these recommendations may also hold true for pre-service teacher education.

While many professional development programs address a specific teaching strategy or activity, planners need to address the deep understanding of the science concepts included in the topics we present to teachers. We cannot assume that teachers come to our programs with an understanding of the detailed mechanisms that produce the phenomena their students will see or the relevance to other concepts in the curriculum. The science we teach does not exist in discrete packets, each independent of the others. If we do not make these connections explicit, teachers may be unable to help their own students learn about the relationship between concepts. The new NGSS described in the *Framework* (NRC, 2012) places an emphasis on these crosscutting concepts, so it is important to ensure teachers know what those concepts are and how to best introduce them to students in the science classroom.

We also suggest that any professional development must start with an assessment of the participants' content knowledge. This assessment should take place before development of learning activities takes place. If we teach a topic and our participating teachers already know the concept, we waste their time. If we teach topics for which the teachers are unprepared, we also waste ours. We also cannot assume that all the teachers in a program come to the first session with the same science knowledge. Just as we should pre-assess young learners, we should find out what teachers know before we teach them new ideas.

With this understanding of the nature of teachers' content understanding and a strategy for assessing their ability to explain and apply science concepts, professional development is more likely to result in changes in teachers' ideas and practice. The findings of this study suggest a strategy for assessing prior knowledge in a way that reveals a more qualitative picture of teachers' understanding of science concepts than can be achieved through a multiple choice concept inventory (McConnell, et al., 2013).

Future research

Pre-assessments not only help us design programs, but are essential for demonstrating that teachers have learned. Future research stemming from this study will include examining the efficacy of the PD program. The researchers in the PBL Project are currently using the assessments described here to measuring the gains in understanding teachers achieved during the PD program. This data will also reveal information about which subjects or concepts teachers find most challenging, information that will be helpful in planning future PD opportunities to meet the needs of teachers.

This analysis may also be helpful in developing learning progressions that offer sequences of topics that build on each other for both teacher and student learning. Analysis of this research topic should include a more detailed description of teachers' ability to implement the new standards included in the NGSS (NRC, 2012). Curriculum development for K-12 classrooms and teacher professional development should both be based on research in this area.

In order for science teacher educators to plan the most effective PD programs, it is critical to consider what the learners already know. Pre-assessment can guide the selection and development of learning activities that target the specific disciplinary concepts in which teachers need to improve their knowledge. The findings of this study also show that teachers are aware of gaps in their own knowledge, and their perceived needs should be included as part of the planning of PD in order to engage teachers. As new state standards are adopted or developed, these pre-assessments and professional development activities should be aligned with the new NGSS (NRC, 2012). The assessment strategy described here offers PD planners a tool that has been shown to provide a rich qualitative description of the conceptual understanding, misconceptions, and gaps in content knowledge of PD participants.

References

Akerson, V. L. (2005). How do elementary teachers compensate for incomplete science content knowledge? *Research in Science Education, 35*, 245-268.

American Association for the Advancement of Science [AAAS]. (1993). *Benchmarks for Science Literacy.* New York: Oxford University Press.

Ball, D. (1997). What do students know? Facing challenges of distance, context, and desire in trying to hear children. In B. J. Biddle et al. (Eds.), *International handbook of teachers and teaching*, vol. II, (pp. 679–718). Dordrecht, Netherlands: Kluwer Press.

Darling-Hammond, L. & Ball, D. (1998). *Teaching for high standards: What policymakers need to know and be able to do.* CPRE Joint Report Series, co-published with the National commission on Teaching and America's Future, JRE-04.

Darling-Hammond, L., & Richardson, N. (2009). Teacher learning: What matters? *Educational Leadership, 66*(5), 46-53.

Diaconu, D. V., Radigan, J., Suskavcevic, M., & Nichol, C. (2012). A multi-year study of the impact of the Rice Model Teacher professional development on elementary science teachers. *International Journal of Science Education, 34*(6), 855-877.

Gerard, L. F., Varma, K., Corliss, S. B., & Linn, M. C. (2011). Professional development for technology-enhanced inquiry science. *Review of Educational Research, 81*(3), 408-448.

Goldhaber, D., & Brewer, D. (1997). Evaluating the effect of teacher degree level on educational performance. In W. Fowler (Ed.), *Developments in School Finance* (pp. 197-210). Collingdale, PA: Diane Publishing.

Hartshorne, R. (2008). Integrating hypermedia in professional development opportunities for elementary teachers of science; A literature review. *Journal of Educational Technology Systems, 37*(2), 175-194.

Hill, H.C. Rowan, B. and Ball, D.L. (2005). Effects of Teachers' Mathematical Knowledge for Teaching on Student Achievement. *American Educational Research Journal 42*(2), 371-406.

Hobbs, L. (2012). Teaching out-of-field: Factors shaping identities of secondary science and mathematics. *Teaching Science: The Journal of Australian Science Teachers Associations, 58*(1), 21-29.

Howley, A., & Howley, C. B. (2005). High-quality teaching: Providing for rural teachers' professional development. *The Rural Educator, 26*(2), 1-5.

Irving, M., Dickson, L. A., & Keyser, J. (1999). Retraining public secondary science teachers by upgrading their content knowledge and pedagogical skills. *The Journal of Negro Education, 68*(3), 409-418.

Jeanpierre, B., Oberhauser, K., & Freeman, C. (2005). Characteristics of professional development that effect change in secondary science teachers' classroom practices. *Journal of Research in Science Teaching, 42*(6), 668-690.

Jin, H. & Anderson, C.W. (2012). A Learning Progression for Energy in Socio-ecological Processes. *Journal of Research in Science Teaching, 49*(9), 1149-1180.

Loughran, J.J., Mulhall, P, & Berry, A. (2004). In search of pedagogical content knowledge in science: Developing ways of articulating and documenting professional practice. *Journal of Research in Science Teaching, 41*(4), 370-391.

Ma, L. (1999). *Knowing and teaching elementary mathematics: Teachers' understanding of fundamental mathematics in China and the United States.* Mahwah, NJ: Lawrence Erlbaum Associates.

McConnell, T. J., Eberhardt, J., Lundeberg, M. A., Parker, J. M., Koehler, M. J., Urban-Lurain, M., & Stanaway, J. C. (2008). The PBL Project for Teachers: Using problem-based learning to guide K-12 science teachers' professional development. *MSTA Journal, 53*(1), 16-21.

McConnell, T. J., Parker, J. M., & Eberhardt, J. (2013). Assessing teachers' science content knowledge: A strategy for assessing depth of understanding. *Journal of Science Teacher Education.* DOI: 10.1007/s10972-01309342-3

Michigan Department of Education [MDOE]. (2007). *Grade level content expectations*. Available at http://www.michigan.gov/mde/0,1607,7-140-28753_38684_28760---,00.html. Retrieved May 25, 2008.

Mundry, S. (2005). Changing perspectives in professional development. *Science Education, 14*(1). 9-15.

National Research Council [NRC]. (1996). *National science education standards.* Washington, D.C.: National Academy Press.

Park, S., & Oliver, J. S. (2008). Revisiting the conceptualization of pedagogical content knowledge (PCK): PCK as a conceptual tool to understand teachers as professionals. *Research in Science Education, 38*(3), 261-284.

Phillips, K. J. R., Desimone, L, & Smith, T. M. (2011). Teacher participation in content-focused professional development and the role of state policy. *Teachers College Record, 113*(11), 2586-2630.

Saxe, G., Gearhart, M., & Nasir, N. S. (2001). Enhancing students' understanding of mathematics: A study of three contrasting approaches to professional support. *Journal of Mathematics Teacher Education, 4*, 55-79.

Shulman, L. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*(1), 4-14.

Stewart, J., & Dale, M. (1989). High school students' understanding of chromosome/gene behaviour during meiosis. *Science Education, 73*, 501-521.

Traianou, A. (2006). Teachers' adequacy of subject knowledge in primary science: Assessing constructivist approaches from a sociocultural perspective. *International Journal of Science Education, 28*(8), 827-842.

Tretter, T. R., Brown, S. L., Bush, W., Saderholm, J., & Moore, B. (2007, April). *Valid and reliable physical, life, and earth science content assessments for middle school teachers*. Poster presented at the National Association for Research in Science Teaching Annual Conference, New Orleans, LA. April 15–18 2007.

Van Driel, J. H., Verloop, N., & de Vos, W. (1998). Developing science teachers' pedagogical content knowledge. *Journal of Research in Science Teaching, 35*(6), 673-695.

Wei, R. C., Darling-Hammond, L., Andree, A., Richardson, N., & Orphanos, S. (2009). *Professional learning in the learning profession: A status report on teacher development in the United States and abroad*. Dallas, TX: National State Development Council.

Windschitl, M. (2009). *Cultivating 21st century skills in science learners: How systems of teacher preparation and professional development will have to evolve.* National Academies of Science Workshop on 21st Century Skills. Washington, D.C. February 5-6, 2009.

Vygotsky, L. S. (1978). *Mind in society.* Cambridge, MA: Harvard University Press.