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# STEM Touchstones for Teacher Professional Learning: An Analysis of Teacher Content and Pedagogical Content Knowledge in a Place-based Professional Development Program

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**ABSTRACT**

The Vermont STEM Leadership Institute (VSTEM) was designed to provide professional learning and leadership opportunities for K-12 educators teaching primarily in high-need schools. The fundamental premise of the program was to actively engage teachers in constructivist curriculum and pedagogy coupled with authentic scientific research experiences within the context of local environments or "places." This study investigated changes in content and pedagogical content knowledge that teachers exhibited in their science teaching practice over the course of their program participation. Data analysis revealed that teachers' science content knowledge and pedagogical content knowledge were enhanced by VSTEM program participation with moderate to strong indications about place-based education, project-based learning, and the importance of engaging students in authentic scientific research. The study found that participants learned new content-specific teaching strategies and implemented standards-based units and lessons that aligned with constructivist theories of teaching and learning.

*Keywords:* in-service teacher professional learning, pedagogical content knowledge, science content knowledge, pedagogical knowledge, project-based learning, place-based education

## Introduction

Despite national efforts to highlight science, technology, engineering, and mathematics (STEM) education and careers in the U.S. over the last 60 years, U.S. students still perform marginally on National Assessment of Educational Progress (NAEP) evaluations of mathematics and science knowledge, and a comparatively small percentage of U.S. students pursue STEM postsecondary degrees and careers (Atkinson & Mayo, 2010). Nationally, 41% of fourth graders and 34% of eighth graders are proficient in mathematics compared to 29% of fourth graders and 29% of eighth graders demonstrating proficiency in science (National Center for Education Statistics, 2019). In Vermont, mathematics achievement is comparable to the national average with 39% of fourth graders and 38% of eighth graders achieving proficiency in mathematics. Comparatively, the results are significantly better in science with 48% of fourth graders and 44% of eighth graders demonstrating proficiency in science in Vermont (National Center for Education Statistics, 2019).

Over the past nine years, as a response to the continued need for ongoing improvement and support of STEM teaching and learning in the U.S., national learning standards have been updated to promote STEM curriculum, teaching, and achievement goals more broadly. The Common Core State Standards for Mathematics (National Governors Association Center for Best Practices, 2010) and Next Generation Science Standards (NGSS Lead States, 2013) call for STEM teaching and learning that advance scientific and computational thinking practices, evidence-based and inquiry-based teaching and learning, and critical and creative problem solving across the K-12 spectrum, particularly for underrepresented and underserved students in high-need schools. Federally funded programs such as the Mathematics and Science Partnerships (MSP) program (Merrill & Daugherty, 2010) have responded to this call for improved STEM instruction and student achievement by supporting educational partnerships between state education agencies, higher education institutions, and high-need school districts with the long-term goal of improving teacher quality and academic achievement and learning in mathematics and science for all students.

The quality and success of inquiry and project-based teacher professional learning programs is dependent on evidence-based best practices that focus on a number of essential factors that improve classroom teaching and student learning (Banilower et al., 2007; Loucks-Horsley et al., 2003; Meiers & Ingvarson, 2003). Ingvarson (2005) identified five key characteristics that suggest that effective STEM professional development should be content focused, involve active learning, provide feedback, involve collaborative examination of student work, and have long-term follow-up. Researchers also recommend extensive support and mentoring in methods of implementing inquiry-based approaches as well as models and actual experience in implementing these approaches before teachers attempt to do so within their own STEM classrooms (Fitzgerald et al., 2019).

The Vermont STEM Leadership Institute (VSTEM), an MSP-funded professional learning program, was designed to provide professional learning and leadership opportunities for K-12 educators teaching primarily in high-need schools in Vermont. VSTEM functioned to model content knowledge and pedagogical content knowledge (Park & Oliver, 2008; Shulman, 1986; Van Driel et al., 2002) aligned to the Next Generation Science Standards (NGSS) disciplinary core knowledge and scientific practices for teaching and learning. The fundamental premise of VSTEM was to actively engage teachers in authentic inquiry and research practices aligned with constructivist curriculum and teaching methods within the context of local environments or "places". The long-term goal was for teachers to develop deeper knowledge of scientific principles and concepts supported by student-centered pedagogies in order to transform their own classrooms into dynamic and stimulating places of interdisciplinary STEM inquiry for students. See Appendix A for a summary of VSTEM goals, objectives, and outcomes.

This mixed methods study examines changes in K-12 teacher content knowledge and pedagogical content knowledge resulting from participation in the VSTEM program. Using a convergent parallel mixed methods design (Creswell & Plano Clark, 2011), qualitative and quantitative data were collected and analyzed separately over the two-year project (2015-2017), and then combined to answer the two interrelated research questions:

(1) What pre-post differences in teachers' science content knowledge were evident over the course of participation in VSTEM?

(2) What evidence of pedagogical content knowledge (PCK) did teachers demonstrate as an outcome of their participation in VSTEM?

## Literature Review

### Social Constructivist Theories of Teaching

Social constructivist theories of teaching and learning (Julyan & Duckworth, 2005; O'loughlin, 1992; Palinscar, 1998; Solomon, 1987) inform the theoretical and conceptual framework of VSTEM. Program tenets and practices are grounded in the notion that knowledge is socially constructed from prior knowledge and experiences and that students and teachers learn best when learning experiences are contextualized, reflective, research-based, inquiry-based, and relevant to everyday experiences (Prawat & Floden, 1994). VSTEM pedagogy exemplifies best practices of reflective teaching and assessment by eliciting the prior knowledge and conceptions (Duckworth, 2006; Graves, 1999; Wandersee et al., 1994) that teachers have about science content and pedagogy and engaging them in authentic local scientific research that embodies many of the NGSS disciplinary core ideas, practices, and cross-cutting concepts.

### Research on Teacher Knowledge

As an MSP-funded project with a focus on improving teacher quality, we were interested in examining the impact of VSTEM activities on teacher content knowledge and pedagogical content knowledge. Content knowledge or subject matter knowledge pertains to the depth and breadth of teachers' understanding of the concepts, principles, and theories that constitute the disciplines that they teach (Magnusson et al., 1999). Pedagogical knowledge pertains to general knowledge of the practices, strategies, and methods that teachers employ in their curriculum, instruction, and assessment. Pedagogical content knowledge (PCK) is the critical junction where content knowledge and pedagogical knowledge intersect, and where teachers organize, represent, and formulate their subject matter for student understanding and learning (Shulman, 1986). PCK refers to the connections that teachers make between what they know about "how" to teach the content with "what" they teach (Cochran, 1997). According to Shulman (1986), PCK includes:

> the most regularly taught topics in one's subject area, the most useful forms of representation of those ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations—in a word, the ways of representing and formulating the subject that make it comprehensible to others. Pedagogical content knowledge also includes an understanding of what makes the learning of specific concepts easy or difficult: the conceptions and preconceptions that students of different ages and backgrounds bring with them to the learning. (p. 9)

Cochran et al. (1993) extended Shulman's theory of pedagogical content knowledge to include two additional components: (1) teachers' knowledge of students' abilities and learning strategies and (2) teachers' understanding of the social, political, cultural, and physical environments. According to Cochran (1997), PCK is highly specific to the concepts being taught. In the following excerpt, Cochran (1997) describes how a teacher integrates the different components of PCK through their planning and instruction.

> The teacher critically reflects on and interprets the subject matter; finds multiple ways to represent the information as analogies, metaphors, examples, problems, demonstrations, and/or classroom activities; adapts the material to students' developmental levels and abilities, gender, prior knowledge, and misconceptions; and finally tailors the material to those specific individual or groups of students to whom the information will be taught. (p. 1)

Although the construct of PCK has had a profound influence on science education (Berry et al., 2015) the current consensus among education researchers—including Shulman himself (Shulman, 2015)—is that PCK is more complex than first imagined. Numerous models for PCK have been developed to account for this complexity (Kind, 2009). In this study we draw on the model proposed by Magnusson et al. (1999), which is the most widely adapted/adopted PCK model in the field (Kind, 2015; Park & Oliver, 2008). Building on Grossman (1990) and Tamir (1988), Magnusson et al. (1999) conceptualized pedagogical content knowledge for science teaching as having five components: (a) orientations toward science teaching, (b) knowledge and beliefs about science curriculum, (c) knowledge and beliefs about students' understanding about specific science topics, (d) knowledge and beliefs about assessment in science, and (e) knowledge and beliefs about instructional strategies for teaching science (pp. 96-97).

Of the five PCK components identified by Magnusson et al. (1999), two are particularly germane to this study: (a) orientations toward science teaching and (b) knowledge and beliefs about instructional strategies for teaching science. Orientations toward science teaching refers to the goals of teaching science that a particular teacher would have and the typical characteristics of instruction for a teacher having that orientation. This particular study focuses on a project-based orientation to teaching science (Krajcik et al., 2007; Tal et al., 2006), the goal of which is to involve students in "investigating solutions to authentic problems" (Magnusson et al., 1999, p. 100). Knowledge and beliefs about instructional strategies includes both subject-specific strategies and topic-specific strategies. Subject-specific strategies are "general approaches to or overall schemes for enacting science instruction" while topic-specific strategies refers to "strategies that are useful to helping students comprehend specific science concepts" (Magnusson et al., 1999, pp. 110-111). Magnusson et al. (1999) suggest two categories of topic-specific strategies: *representations* (e.g., illustrations, examples, models, analogies) and *activities* (e.g., problems, demonstrations, simulations, investigations, experiments) (pp. 111, 113).

Research on PCK typically focuses on teacher knowledge of a specific science content area (Bayram-Jacobs et al., 2019; McNeill & Knight, 2013; Beyer & Davis, 2012; Falk, 2012; Van Driel et al., 2002). To make PCK visible, researchers combine observations of content-specific instructional practice—PCK in-action (Bayram-Jacobs et al., 2019)—with opportunities for teachers to discuss, analyze, and reflect on their content-specific teaching. For example, McNeill and Knight (2013) examined the impact of professional development on teachers' PCK of scientific argumentation by asking teachers to design a lesson to introduce argumentation to students and reflect on their experience teaching that lesson. Similarly, Bayram-Jacobs et al. (2019) examined PCK development regarding teaching socio-scientific issues (SSI) by having teachers prepare, teach, and reflect on a specially designed SSI lesson. Over time, science education researchers have adopted a more dynamic conception of PCK that emphasizes how teachers use PCK in practice (Bayram-Jacobs et al., 2019; Beyer & Davis, 2012; Falk, 2012; McNeill & Knight, 2013; Van Driel et al., 2002).

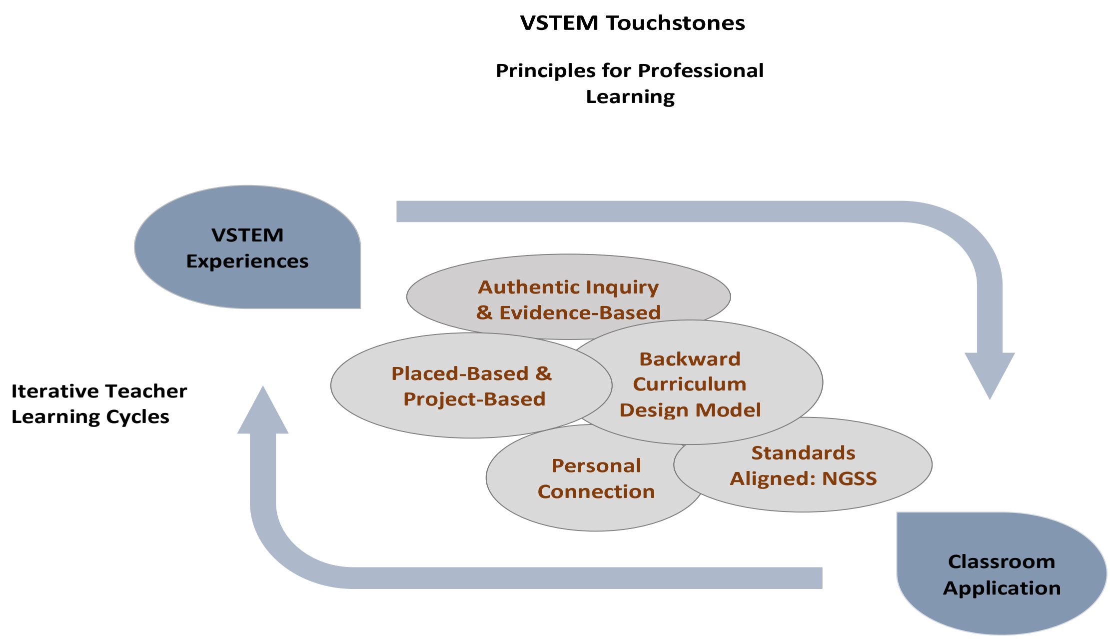
## VSTEM Touchstones

The VSTEM touchstones are fundamental standards or criteria aligned with constructivist theories of teaching and learning (Julyan & Duckworth, 2005; O'loughlin, 1992; Palinscar, 1998; Solomon, 1987) that serve as foundational principles for teacher professional learning in the program (See Figure 1). The touchstones support a shared understanding of best curriculum and teaching practices that increases the likelihood that the curriculum work teachers are engaged in will have purpose, meaning, and persistence over time (Rice, 2012).

Key touchstones such as project-based learning (Krajcik et al., 1994; Tal et al., 2006) and place-based education (Demarest, 2015) promote problem-solving and authentic inquiry (Blumenfeld et al., 1991; Cuevas et al., 2005; Geier et al., 2008; Kahle et al., 2000; Krajcik et al., 2008) within the context of "local places" resulting in a project, product, or artifact that is interdisciplinary in nature and has personal connection and meaning to both students and teachers. In order for teachers to understand how to design place-based projects outside the boundaries of the classroom, many of the VSTEM activities take place in and around local lakes, quarries, and streams as well as in science and engineering laboratories at the university. Principles of backward design (Wiggins & McTighe, 2005) are central to the VSTEM curriculum framework and serve as the foundation for the project planner that teachers utilize in the development of a place-based project required for program participation.

**Figure 1**

*VSTEM Touchstones*




## Research Methods

### Research Context

The VSTEM program was designed to engage teachers in authentic research alongside scientists, graduate students, and teacher educators during a week-long summer institute followed by monthly workshops and school-based lesson studies during the academic year. The summer institutes consisted of field trips to local quarries or aboard the University of Vermont (UVM)'s *Melosira Research Vessel* and workshops conducted at UVM's Ecosystem Science Labs. The field trips were designed to facilitate a shift in teachers' orientation towards science teaching and exposure to topic-specific instructional strategies. For example, teachers investigated the reproductive success of lake trout in Lake Champlain, the history of ocean basin opening and closing and the formation of the Appalachian Mountain chain, and optimization of animal forging behavior. Teachers also investigated how big data informs quantitative reasoning and analysis in the context of these questions.

The summer institute experiences were bridged to academic year programming by engaging teachers in content-focused workshops in chemistry, ecology, and geology; facilitating field trips to Lake Champlain and local geology and stream sites; and hosting lesson studies at participating schools that focused on, for example, school-based composting efforts or local bird population studies. Coupled with these professional learning experiences were opportunities for teachers to reflect upon ways to meaningfully integrate the NGSS, as well as project-based and place-based principles or *touchstones* into their teaching practice. As part of program requirements, teachers kept a reflective journal of VSTEM experiences, developed and implemented a long-term project aligned to the NGSS and VSTEM touchstones, participated in school-based lesson studies and the VSTEM spring conference, and facilitated STEM professional learning communities (PLCs) in their home schools during the academic year.

**Participants**

During the period between 2015-17, thirty (30) K-12 teachers from rural, urban, and suburban school districts in Vermont participated in the VSTEM program. In Year 1, sixteen (16) teachers representing five school districts spanning grades K-12 participated in the program. Ten first-year cohort teachers returned to the program joined by ten new teachers in Year 2. Four of the five participating school districts are high-need designated school districts as defined by federal free and reduced lunch measures (U.S. Department of Agriculture, 2020). All of the VSTEM teachers are White. Teacher demographics aggregated by grade level and gender are represented in Table 1.

**Table 1.**

*VSTEM Teacher Participant Demographics*

| | **2015-16** | **2016-17** |
|---|---|---|
| **No. of Teachers** | 16 teachers representing 5 school districts | 20 teachers representing 5 school districts |
| **Grade/Gender** | 6 elementary – all female<br>6 middle school science – all female<br>4 high school – 3 male, 1 female (2 Biology, 1 Earth Science, 1 Physics) | 7 elementary – all female<br>9 middle school science – 7 female, 2 male<br>4 high school – 2 male, 2 female (2 Biology, 1 Earth/Environmental Science, 1 Physics/Environmental Science) |

**Data Collection and Analysis**

This mixed methods study examined changes in K-12 science teacher content knowledge and pedagogical content knowledge resulting from participation in the VSTEM program. Using a convergent parallel mixed methods design (Creswell & Plano Clark, 2011), qualitative and quantitative data were collected and analyzed separately over the two-year project (2015-2017), and then combined to answer the two interrelated research questions:

(1) What pre-post differences in teachers' science content knowledge were evident over the course of participation in VSTEM?
(2) What evidence of pedagogical content knowledge (PCK) did teachers demonstrate as an outcome of their participation in VSTEM?

Quantitative and qualitative data sources are illustrated in Table 2.

**Table 2**

*Quantitative and Qualitative Data Sources*

| Research Question | Data Source |
|---|---|
| What pre-post differences in teachers' science content knowledge were evident over the course of participation in VSTEM? | • Pre-Post Assessments of Science Content Knowledge<br>• Participant Project Plans<br>• Post-Program Surveys |
| What evidence of pedagogical content knowledge (PCK) did teachers demonstrate as an outcome of their participation in VSTEM? | • Participant Project Plans<br>• Classroom Observations<br>• Post-Program Surveys<br>• Reflection Journals |

Quantitative pre-post assessments of science content knowledge were used as measures of change in content knowledge and ratings of classroom practice were used as evidence of pedagogical content knowledge (PCK). Qualitative notes from classroom observations, along with participant project plans, post-program surveys, and participant reflection journals provided additional evidence of both types of knowledge along with description and explanation. These data were collected and triangulated to gain a deeper understanding of knowledge change across multiple sources. Data from each source were analyzed separately and results were then merged to answer the research questions (Creswell & Plano Clark, 2011).

### *Pre-Post Assessments of Science Content Knowledge*

Pre and post content assessments were used to measure change in participant content knowledge. The assessments were designed by project faculty to align closely with module learning objectives, and thus considered to have content validity. Participants completed pre and post assessments for each content specific module during the program. The pre and post assessments consisted of short and extended response questions primarily designed to assess basic knowledge of chemistry, geology, and ecology concepts. Most assessments contained too few items to establish reliability as measured by Cronbach's Alpha (Graham, 2006). When the data format allowed, results of pre and post assessments were analyzed using Wilcoxon signed rank tests as per project funder requirements.

### *Participant Project Planners*

Development and implementation of an NGSS aligned project to be implemented as an instructional unit with their students was one of the key requirements for VSTEM participants. During the July institute, teachers were introduced to a project planner (see Appendix B) that served as a template for project design. During the summer institute, participants consulted with institute faculty and collaborated with VSTEM peers. As part of the project planning process, staff reviewed the principles of backward curriculum design (Wiggins & McTighe, 2005) and supported participants in project goal articulation, selection of standards, and development of enduring understandings and essential questions aligned to the overall project design. Completed planners were analyzed for evidence of content knowledge and content-specific instructional and assessment strategies.

### *Classroom Observations*

To more fully examine the degree to which the VSTEM program impacted teacher instructional and assessment practices, classroom observations of the 10 teachers who participated in both Years 1 and 2 were conducted early, mid-way, and at the end of the VSTEM program utilizing the Diagnostic Classroom Observation Tool (DCO) (Saginor, 2008). The DCO was initially developed at The Vermont Institutes, subsequently validated by Mathematica, Inc. and the Northwest Regional Labs, and modified in 2014 to better align with new math and science standards. Utilization of the DCO allowed researchers to study both lesson implementation and lesson content. A summary of the 14 DCO indicators used in this study are listed in Table 3.

**Table 3**

*Summary of Diagnostic Classroom Observation Indicators (Saginor, 2008)*

| Implementation Indicators | Content Indicators |
|---|---|
| **Teacher Confidence**<br>Teacher demonstrates confidence as a facilitator of math/science learning and growth. | **Academic Standards**<br>Academic standards are central to the instructional program. |
| **Teacher – Student Interactions**<br>Periods of teacher-student interaction are probing and substantive. | **Teacher Content Knowledge**<br>Teacher demonstrates an understanding of the concepts and content of the lesson. |
| **Instructional Choices**<br>Instructional choices are effective in engaging students in active and thoughtful learning. | **Formative Assessment**<br>Teacher collects and assesses evidence of student progress to enhance teaching and learning. |
| **Opportunities to Construct Knowledge**<br>Students have opportunities to construct their own knowledge. | **Student Engagement**<br>Students are intellectually engaged with concepts contained in the activities of the lesson. |
| **Lesson Pace**<br>Lesson pace is appropriate for the developmental level of the students with adequate time for wrap-up. | **Content Connections**<br>Concept connections and applications to the real world are made within and across lessons. |
| **Student-Student Interactions**<br>Periods of student-student interaction are productive and enhance individual understanding of the lesson. | **Abstractions, Models, Theories**<br>The lesson incorporates abstractions, theories, and models as appropriate. |
| **Teacher Technology Integration**<br>Teacher models technology integration. | **Student Strategic Use of Tools**<br>Students use appropriate tools strategically. |

One complete science lesson per teacher was observed at each data collection point (fall 2015, spring 2016, and spring 2017). At each observation, each indicator was rated on a scale of 1 to 5 (no evidence to extensive evidence). Each DCO indicator includes a list of evidence that might be observed during the lesson. For example, "Instructional Choices" focuses on the connections between student engagement, clarity of learning objectives, and inquiry-based pedagogy. "Opportunities to Construct Knowledge" focuses on how the learning environment provided students with the opportunity to actively explore questions or concepts, and integrate new learning with prior experience and understanding. A detailed description of these two DCO indicators is found in Table 4. The observer noted whether any of these examples were observed, and took detailed notes of teacher and student actions during the lesson. The scale ratings were analyzed for shifts in frequencies and means across the three data collection points. At the end of the project, a paired sample t-test was used to test for statistically significant change in mean ratings for each of the 14 indicators. Field notes were used to describe the observed changes in more specific detail.

**Table 4**

*Samples of DCO Indicators Used for VSTEM Observations (Saginor, 2008)*

| Indicator | Evidence | Examples of Evidence |
|---|---|---|
| **Instructional choices** are effective in engaging students in active and thoughtful learning. | 1 - no<br>2 - limited<br>3 - moderate<br>4 - consistent<br>5 - extensive | • Students are engaged and excited about finding answers to questions posed by the activity.<br>• Objectives are clearly stated.<br>• Activities are likely to lead to student learning in the stated objectives.<br>• Teacher does not dominate discussion.<br>• Tasks are challenging; teacher sets high expectations.<br>• Both teacher-directed instruction and constructivist methods are used as appropriate for task and diverse learning needs. |
| **Opportunities to construct knowledge** Students have opportunities to construct their own knowledge. | 1 - no<br>2 - limited<br>3 - moderate<br>4 - consistent<br>5 - extensive | • Investigations are essential elements of the lesson.<br>• Curiosity and perseverance are encouraged.<br>• Students apply existing knowledge and skills to new situations and integrate new and prior knowledge.<br>• Students make notes, drawings, or summaries in a journal or lab book that becomes part of their ongoing resources.<br>• Students have opportunities to do more than follow procedures; they ask their own questions, choose their own strategies, or design investigations.<br>• Students manipulate materials and equipment.<br>• Teacher and students discuss which technologies to use for various products and processes and why. |

### *Post-Program Surveys*

At the end of each program year, each participant responded to an anonymous online survey about their program experiences. Survey topics included participants' perceptions of the impact of the VSTEM program on their knowledge of science content and pedagogy. Data analysis included creation of charts and tables from the raw data for each closed-response question and description of the results. Open-response items were analyzed for themes and patterns.

### *Reflection Journals*

Each participant completed a daily journal reflection that prompted them to consider what they had learned about science content and pedagogy from VSTEM program activities. The journals were designed to provide evidence of participants' PCK for teaching the specific science topics addressed by the institute faculty and were analyzed for evidence of teachers' developing knowledge of instructional strategies for teaching science.

## Research Results

The VSTEM program was built on two overarching foci pertaining to participating teachers' science content knowledge necessary to facilitate learning for all students and evidence of improved pedagogical content knowledge (PCK). A detailed summary of the analysis pertaining to changes in science content knowledge and PCK of participating teachers follows.

### Science Content Knowledge

Pre-post content tests administered during workshops and field trips suggest a moderate increase in science content knowledge for teacher participants. For example, in Year 2 of the program, 13 of the 20 participants completed pre-post tests for the chemistry module. The pre-post data were analyzed using Wilcoxon signed ranks test which showed eight teachers posting significant gains ($p$=.006). It is important to note that the five teachers (mostly high school teachers) who did not score significant gains were already knowledgeable in the content area and completed the pre and post content tests with no errors. Fourteen teachers completed pre and post tests for the geology module. Test results were not in a format that allowed for use of Wilcoxon signed ranks (the standard MSP analysis); however, of the 14 teachers tested, 11 or 79%, showed positive gains in geology content knowledge from pre to post-test.

The ceiling effect observed in the pre-post content tests corresponds with participant responses to a question on the post-program survey about perceptions of increases in content knowledge. All survey respondents reported that participation in VSTEM deepened their knowledge of science content with increases ranging in degree from small to large. Comments suggested that this range is attributable to some participants having begun the project with deeper background in science, particularly those high school teachers who had STEM degrees.

That participants developed a deeper understanding of each of the VSTEM content areas is also evident in the analysis of their project planners. This analysis revealed that science content had been acquired and applied in a unit planned, taught, and evaluated by each of the teachers. Unit topics included forces and interactions, exploration of waves and sound, Earth science and engineering design, chemical processes and thermal energy, bridge design, and ecosystems and environmental change. Analysis of project planners also revealed an understanding of specific science content and the integration of content knowledge into meaningful science learning experiences. Table 5 represents examples of project planners designed by four of the VSTEM teachers.

## Pedagogical Content Knowledge (PCK)

Our analysis of PCK focused on teacher knowledge of content-specific teaching strategies documented in participants' online journals, project planners, classroom observations, and online surveys. In our analysis, we explored evidence that teachers learned new strategies for teaching specific science content—for example, learning to use a local field site to teach students about human impacts on ecosystem biodiversity or learning novel ways for students to represent their understanding of energy conservation. To 'count' as PCK gained through this project necessitated evidence that teachers had learned these strategies through their participation in VSTEM activities specifically. For this reason, teachers' reflective journals—which prompted them to reflect on lessons learned from workshops and fieldtrips —were particularly useful.

**Table 5**

*Teacher Designed Project Planner Descriptions*

| Title | Level | Essential Understandings | Project Experiences |
|---|---|---|---|
| Forces and Interactions | Middle School | Relationships between force, energy, and mass | Explore forces on encapsulated egg dropped from the roof and apply learning to the design of a helmet to prevent brain injury. |
| Exploration of Waves and Sound | Middle School | Properties of simple waves<br>Sound transmission | Explore sound waves and apply learning to the design of musical instruments made from everyday materials. |
| Local Community Recreational Trail Project | High School | Water's movement causes weathering and erosion. Humans can negatively impact the environment. Models can generate data for iterative testing. | Using a local recreational area as an outdoor laboratory, observe weathering, collect data, build models, and experiment with trail design. |
| Bridge Design | Elementary School | Relationship between balance and force. Engineers consider materials, setting, purpose, and motion when designing bridges. | Students use the engineering design process to design a bridge for their school campus. |

### *Reflective Journals and Project Planners as Evidence of PCK*

Teachers' reflective journals revealed that the VSTEM workshops and fieldtrips —where university faculty modeled content-specific teaching strategies—were a primary source of VSTEM teachers' PCK. For example, multiple instances were found of energy-related PCK that resulted from a 2016 summer institute workshop led by chemistry faculty. Several VSTEM participants mentioned learning two new strategies—*Energy Theater* (Daane et al., 2014) and *Energy Tracking Diagrams* (Scherr et al., 2016)—for modeling energy transfers and transformations within systems and assessing students' understanding of energy types. Other participants mentioned learning to use water as an agent for demonstrating the relationship between temperature and kinetic energy while simultaneously addressing the common misconception among students that energy is only transferred through objects. The following excerpt from a high school teacher's journal denotes the energy-related PCK that resulted from this particular workshop:

> *I learned lab activities that will get students thinking about energy (mass and heating of water, electrolysis of water, and a variety of other activities mentioned by other teachers in the class). I also started to think more about total vs. average energy in a system and how students might think about that. I also got many ideas about how students could modify the lab activities that we did today (salt water, different energy sources, etc.) to turn these activities into individual investigations.*

Additional instances of PCK were found where teachers reported learning new strategies for teaching ecology and Earth science topics. For example, teachers reported learning from environmental science faculty how to model food webs, graphically represent population density, and investigate the effect of species size on ecosystem functioning. For example, several teachers wrote in their reflective journals about learning new strategies for modeling fish predation and the idea that big fish can only eat little fish.

> *What I found fascinating today—and I had never thought of it before—is that fish can only eat what fit in their mouth. They do not have hands or paws to push things in. They do not have a way to make their food smaller. They cannot chew. They just open and swallow. Totally amazing and quite obvious, but I never thought about it. I love the idea of sorting-by-size because third graders can do it and understand it and understand that little things need to eat littler things.*

A middle school teacher mentioned learning the same topic-specific strategy.

> *Today I learned about the ecology and food webs of Lake Champlain. It was interesting to learn that certain fish will eat the largest food available to them and how this might affect the populations of other organisms in the lake. I thought that the activity we participated in would be useful in the instructional sequence that I am building about ecology.*

Another VSTEM participant reported learning a multi-stage sequence for teaching science from watching environmental science faculty move from engaging students through videos, to using small toys to represent key concepts, to conducting hands-on experiments to solidify learning. Other participants reported learning from geology faculty on the use of student drawings of rock faces to teach Steno's laws of stratigraphy and how to test for calcite to demonstrate the connection between chemistry and geology content.

There were several instances in which the teaching strategies that participants reported learning during the program also appeared in the projects they designed. For example, two high school science teachers collaborated in the development of an NGSS-aligned project that focused on the impact of non-point source pollution on stream health. The project entailed students collecting, analyzing, and comparing data from water and macroinvertebrate samples at multiple local stream sites over time. Similarly, a middle school teacher designed a project that utilized local hiking and mountain bike trails as a context for teaching the topic of erosion. The fundamental idea that underlies this project is that wind and water can change the shape of the land, a concept that first appears in her summer institute journal following the VSTEM geology field trip. In both projects, students in these classes designed potential solutions to each problem. Teachers used these designs to assess students' understanding of underlying science content and scientific practices as suggested by the NGSS.

Another example where a teacher applied topic-specific teaching strategies learned during the program to their project design involved an elementary teacher who participated in VSTEM for 2 years. This participant designed a project for elementary students that applied the concept of biomimicry to mutualism between humans and natural systems—a strategy the teacher reported learning from VSTEM engineering faculty during a summer institute workshop. In this project, students are invited to use their observations of seed dispersal in nature to design innovative solutions to human problems associated with mobility and transportation.

### *Classroom Observations as Evidence of PCK*

Classroom observation data provided additional evidence of knowledge of instructional strategies for teaching science for the 10 teachers who participated in both years of VSTEM. As summarized in Figures 1 and 2, the mean of all the DCO indicators shifted from moderate levels at the initial observation conducted in fall 2015 toward consistent levels by the third observation conducted in spring of 2017.

**Figure 1**

*Classroom Observation Data – DCO Implementation Indicators*

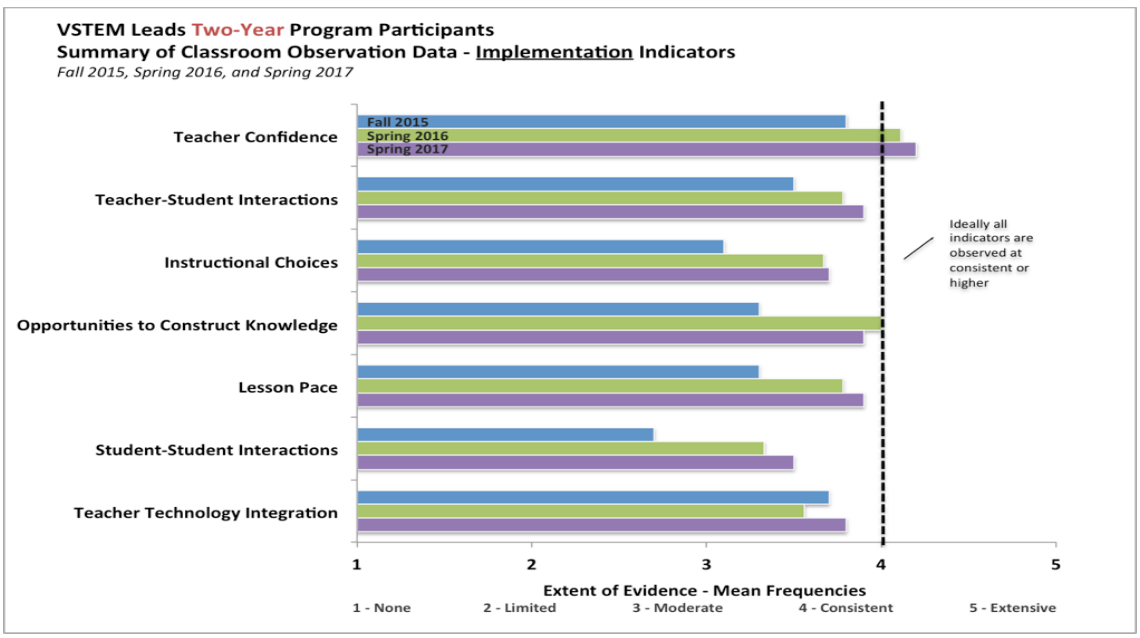
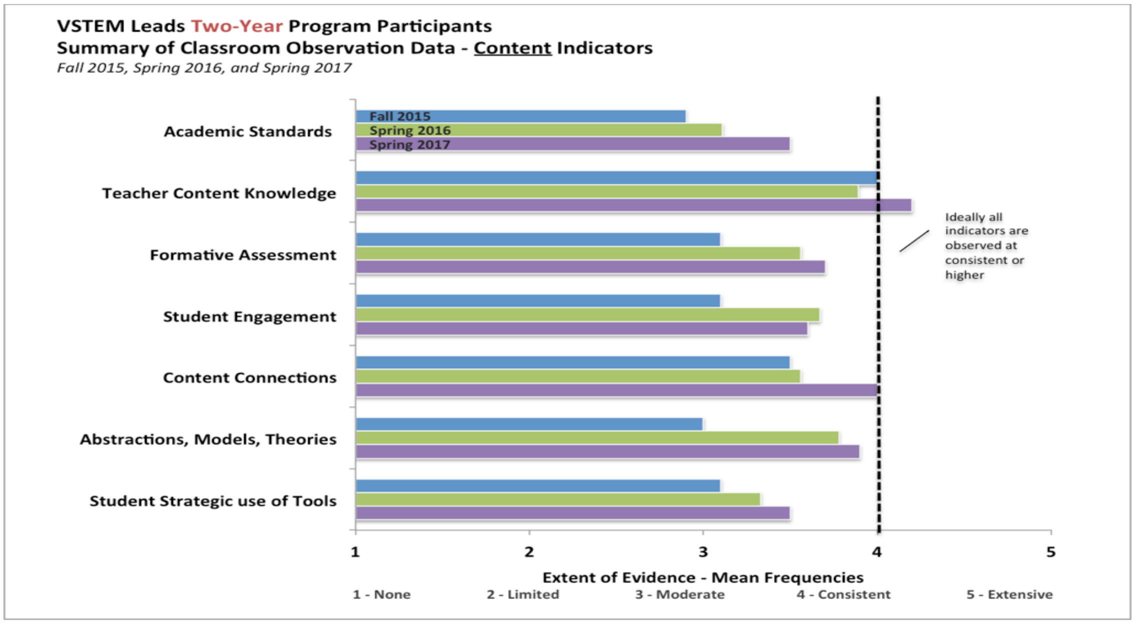


**Figure 2**

*Classroom Observation Data – DCO Content Indicators*




A paired sample t-test for each of the 14 DCO indicators (see Table 6) revealed statistically significant increases in the mean ratings for four of the DCO indicators including implementation indicators (instructional choices, opportunities to construct knowledge and student-student interactions) and content indicators (abstractions, theories, and models).

**Table 6**

*Results of Yr. 2 Paired Samples T-Test on DCO Indicators*

| DCO Indicator | *t* | Sig. (2-tailed) |
|---|---|---|
| Teacher Confidence | -1.406 | .193 |
| Student-Teacher Interactions | -1.406 | .193 |
| Instructional Choices | -3.000 | .015 * |
| Opportunities to Construct Knowledge | -4.583 | .001* |
| Lesson Pace | -1.861 | .096 |
| Student-Student Interactions | -2.250 | .051* |
| Teacher Technology Integration | 1.000 | .343 |
| Academic Standards | -1.500 | .168 |
| Teacher Content Knowledge | .557 | .591 |
| Formative Assessment | -1.078 | .309 |
| Student Engagement | -1.861 | .096 |
| Content Connections | -.231 | .823 |
| Abstractions, Models, Theories | -2.333 | .045* |
| Student Strategic Use of Tools | -1.000 | .343 |

Demonstrated growth between the first and third classroom observations related to teacher instructional choices, student opportunities to construct knowledge, and productive student-student interactions reflects VSTEM's emphasis on scientific inquiry. While factors within school systems unrelated to VSTEM may have encouraged or inhibited change in teacher PCK, this shift suggests that teachers who participated across two years of the program embraced the STEM constructivist strategies modeled and supported throughout the VSTEM program.

At the time of initial observations, approximately two months after the week-long summer institute, most teachers were beginning to implement place-based or project-based learning strategies and some had already begun teaching the NGSS-aligned projects that they had developed during the previous summer. Most teachers were already familiar with the NGSS practices and some were skilled at engaging students in active and collaborative learning at the onset of the program. Much of the observed lesson content was linked to local place-based issues such as Lake Champlain conservation and energy efficiency in the local community.

Regardless of the instructional content, many of the initial observed lessons were didactic in nature characterized by explicit instruction and steps for engaging in STEM investigations by the teachers. In these instances, students were provided little opportunity to construct their own understanding of science concepts or collaborate in their scientific investigations with one another. Students generally followed teacher directions, and in some classrooms, they appeared far more compliant than engaged in their learning. The majority of the teachers tended to give direct answers to student questions rather than probe for understanding or respond with questions designed to encourage and motivate students to arrive at their own answers. Teachers were also more likely to present models than have students generate them. For example, this approach was evident in an elementary classroom where the teacher presented a model of a living cell and then demonstrated how a pizza and its various ingredients represented cell structures or organelles. Students were primarily engaged in observing the process but seemed more focused on tasting the pizza rather than how the various ingredients might represent cell organelle structure and function.

By the final observation point, lesson content continued to emphasize place-based and project-based learning with a shift towards more student-directed investigations. For example, one elementary class was engaged in an engineering design project that involved testing various materials for a new helmet design. During the first observation point, students were instructed in every phase of the project by the teacher, with little room for exploration and surprise. During the final observation, however, after testing materials that students chose and dropping helmet prototypes from the roof of the school, the teacher appeared to demonstrate genuine enthusiasm and surprise at some of the prototype results.

In a middle school classroom, teams of students worked at stations to investigate the movement of sound waves through various substances. Students made predictions and recorded observations that were later utilized as evidence in a claim-evidence-reasoning discussion. Similarly, in a high school biology class, students gathered evidence from experiments, readings, and mini-lectures to prepare for a debate on the use of genetically modified organisms in local agriculture.

Teachers at all levels were also more likely to engage students in developing and revising their own models in response to essential questions (e.g. How is the Earth organized? How does sound travel?) posed in the initial stages of the unit of study. The elementary teacher who had earlier modeled a cell by building a pizza was now using a story board to record and track students' evolving conceptions and representations about waves and energy transfer.

At the end of Year 2, participating teachers were more likely to ask probing questions such as "How do you know that?" "What tells you that?" "What is your evidence?" or "Is this type of graph a useful representation for this type of data?" When students raised content or process questions, teachers were more likely than at the initial observation point to respond with probing questions and reminders to utilize other resources such as their fellow students, thereby encouraging students to socially construct their own understanding of scientific concepts. By the third observation point, many teachers had created more contexts for students to ask their own questions, use evidence to make claims, and engage in genuine discussion and reasoning about their findings.

### *Online Surveys as Evidence of PCK*

Detailed reports of teacher responses to an anonymous online program survey documented teacher perceptions of the ways in which program participation changed and improved their STEM classroom practice. See Table 7 for a sample of survey comments.

**Table 7**

*Post-program Teacher Survey Data*

| Teacher | Comment |
|---|---|
| 1 | I think more about the scientific practices and what skills I want the students to master and therefore what projects I am going to have them demonstrate their proficiency in those skills. |
| 2 | I feel that I have assimilated the learning from VSTEM directly into my everyday teaching both with daily lesson structure and overall unit design. |
| 3 | I have always wanted this (projects and place) to be part of my practice but now I see how doable it is. |
| 4 | I have worked to make my class much more project-based and I present a great deal less information as ‘an expert’ and allow ideas to emerge from data and evidence. |

Most teachers reported moderate to large changes in how they supported student learning that included the development of clearer learning targets, new attention to real-world connections, implementing place-based units, incorporating engineering design, and focusing on all three dimensions of the NGSS. They also reported facilitating new opportunities for students to develop their own experiments and engage in scientific discourse with each other. In the surveys, teachers also reported numerous challenges associated with implementing curricular and pedagogical changes that included insufficient planning time, limited time for science instruction, the amount of time needed for inquiry and engineering design, limited supplies and physical space, and uncertainty when facilitating student-led investigations.

## Discussion and Conclusions

Creating multiple opportunities for teachers to experience authentic scientific research through place and project-based models was foundational to changes in teaching practice in this study. Comprehensive analysis of VSTEM program data and artifacts revealed that teachers’ science content knowledge and pedagogical content knowledge were enhanced by VSTEM program participation with moderate to strong indications about place-based education, project-based learning, and the importance of engaging students in authentic scientific research. Evidence from a variety of data sources demonstrated that VSTEM participants learned new content-specific teaching strategies and implemented standards-based lessons and projects that aligned with constructivist theories of teaching and learning. The VSTEM touchstones—authentic inquiry, place-based and project-based learning, NGSS standards, personal connection, and backward design—served as guiding principles for these shifts in teachers’ thinking, content knowledge, pedagogical content knowledge, and overall teaching and practice over time.

Interactions with VSTEM faculty during the summer institute and throughout the school year provided inspiration and technical support for the teachers as they continued to apply their STEM content and pedagogical content knowledge to their evolving NGSS projects and lessons. Faculty facilitated sessions during the VSTEM summer institute and school year workshops were readily available as a resource to participants throughout the academic year. In turn, university VSTEM faculty gained new understandings about the NGSS, as well as the school and cultural context for K-12 STEM education. Project leaders reported a higher volume of communication between university faculty and teacher participants in Year 2 compared to Year 1. This included requesting clarification about specific content and pedagogical questions, suggestions for accommodating special needs students, feedback on project plans, or sharing articles and information about other STEM professional development opportunities. As a direct outcome of their VSTEM participation, two middle school teacher participants collaborated with one of the project leaders to mentor a teacher intern during their student teaching experience.

Professional relationships within higher education and between the participating teachers were also reinforced. A strong synergy between project leaders from The College of Education and Social Services and The College of Engineering and Mathematical Sciences has been extended beyond the life of the program as these individuals continue to develop new projects and mentor and challenge each other to become ardent leaders for STEM education. Participants, too, were reaching out to each other directly to share lessons, projects, and units or to share information about upcoming STEM education events. Within each school district team, teachers continued collaboration beyond the timeframe of the VSTEM project.

The variety of professional learning opportunities such as those described in this study have worked to build teachers' capacity to offer more authentic and engaging STEM education to their students. As Vermont and other states increasingly aim to provide high-quality STEM education for *all* students, the VSTEM Leadership Program offers a framework, through its touchstones, curriculum, and modeling, to advance and support these conversations.

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## Appendix A

## Vermont STEM Leadership Institute
## Goals, Objectives and Outcomes

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**Course Description and Goals:**
**The VSTEM Leadership Program (VSTEM Leads) will** engage K-12 teachers in an exploration of the Next Generation Science Standards through authentic research and investigations pertaining to Vermont's ecology and geology and related energy issues, as well as an exploration of engineering design principles and projects. Coupled with these experiences will be opportunities to reflect upon ways to meaningfully integrate project-based, proficiency-based, and place-based experiences into formal and informal learning environments.

VSTEM Leads program activities are aligned with the Next Generation Science Standards (NGSS), the Common Core State Standards (CCSS) in ELA and Mathematics, and the Vermont Transferable Skills Standards. Workshops and activities will commence with the VSTEM Leads Institute (July 11-15$^{th}$) and continue throughout the school year with follow-up workshops and lesson studies (dates to be determined with input from teachers). During the academic year, teachers will work in school-based teams to lead NGSS Professional Learning Communities (PLCs) at their schools. Teachers will participate in the VSTEM Conference to share and present the results of their project implementation and NGSS PLC work.

**VSTEM Learning Objectives:**
VSTEM professional learning experiences will emphasize three primary learning objectives:
1. Teachers will demonstrate an understanding of STEM knowledge and concepts necessary to respond to the learning needs of all students. This includes a deep understanding of:
   - NGSS core knowledge and practices and VT Transferable Skills Proficiencies.
   - Common misconceptions that students hold in regard to fundamental science concepts.
   - Science as a way of thinking by engaging in Science and Engineering Practices.
   - Engineering as the practical application of mathematics and science.
   - Ways to integrate the knowledge of content, instruction, assessment, and technology.
   - Ways to integrate CCSS in Math and ELA into meaningful science learning opportunities.
2. Teachers will demonstrate improved teaching skill and effectiveness with a focus on project, place, and proficiency-based teaching and learning.
3. Teachers will develop leadership skills that include an understanding of the effective use of resources and tools to support the implementation of the Next Generation Science Standards.

**Program Outcomes:**
As part of VSTEM Leads program outcomes and requirements, participating teachers will:
1. Develop a project and instructional sequence with appropriate performance assessments aligned to NGSS, CCSS in Math and ELA, and VT Transferable Skills standards.
2. Develop and present a poster of project implementation at the VSTEM Leads Conference.
3. Participate in 3 lesson studies at participating schools followed by a critical friends reflection and discussion.
4. Draft and implement a plan for conducting a monthly PLC at their school about NGSS

implementation with monthly online reporting/discussion board of the successes/challenges during the academic year.

**Essential Question for the VSTEM Institute:**
**How can authentic research, local investigations, and scientific and engineering design practices inform my pedagogy and deepen my students' understanding of key STEM principles and concepts?**

**Driving Questions:**
1. How do local ecosystems, watersheds, and landscapes change over time?
2. How are evidence and data analysis used in the research and teaching process?
3. How are models used in the research and teaching process?
4. How do key educational theories and practices (i.e. project-based, proficiency-based, inquiry-based, and placed-based practices) inform my developing curriculum and pedagogy?
5. How do the NGSS, CCSS in Math and ELA, and the VT Transferable Skills Standards inform my ability to develop curriculum?
6. How does an emphasis on responsive teaching, student efficacy, and issues of equity promote success for ALL K-12 students?

**Module Objectives:**

**Exploring Vermont Geology**
A field trip to Lessor Quarry will provide participants with the opportunity to explore how the geology of Vermont can be used to teach some basic concepts in the geosciences. Participants will examine sedimentary rocks with fossils and engage in an investigation on determining relative geologic timing. Activities include making observations about the type of rocks and geologic structures, fossil identification, making sketches of a rock face, and using a geologic compass.

**Moving Energy**
Energy comes in many forms and is transferred in numerous, often subtle ways. Participants will examine how different forms of energy are transferred to and from common substances. Using temperature, participants will investigate relationships between energy transfer, average kinetic energy, mass, and types of matter.

**Optimal Forging**
Optimal foraging theory explains how animals effectively gather resources given tradeoffs of the time it takes to search and capture food, uncertainty in food location, and energetic value of food. Participants will become familiar with basic experimental design, understand the different tradeoffs animals face when trying to secure resources, apply math to animal behavior concepts, and collect, analyze, and graphically represent data.

## Appendix B

## VSTEM PROJECT PLANNER[1]

GOAL: To apply your knowledge of science content and pedagogical practices as you develop a place-based education (PBE) project to be implemented in your classroom during the academic year.

| |
|---|
| DESCRIPTION AND GOALS OF PBE PROJECT: What is the background and context of the project and instructional sequence? What is the relevance and importance of the project? What is the authentic problem being addressed? How are the principles and practices of PBE incorporated in your project? |
| |
| STANDARDS/PROFICIENCIES: Identify the essential content standards and proficiencies that drive your project. (Consider multiple subjects and standards). |
| |
| Big Ideas/Enduring Understandings (EUs): What big ideas or enduring understandings will students know and understand over time and drive your place-based project? Write the EU's in student friendly language. |
| |
| Essential/Driving Questions: What essential questions will drive the project/sequence? Be sure to address how societal and cultural issues (preferably local issues that are meaningful to students) will be integrated into the place-based project. |
| |

| OBJECTIVES: KNOWLEDGE, PRACTICES & DISPOSITIONS: What key knowledge, practices and dispositions will students know, understand and do (KUDs) as a result of engaging in this place-based project? | | |
|---|---|---|
| Content & Concepts: What will students know and understand about the place of study and PBE? | Practices: What specific practices/skills will students develop and be able to do over time? | Dispositions: What important attitudes, habits of mind, ethics, and/or beliefs will students develop over time about place and PBE? |
| | | |

| |
|---|
| PROJECT DESIGN - Develop a hand-out for students that describes the following:<br>What are the project goals? How will the project be developed and sequenced over time? What are the milestones and due dates for completion of various project activities and investigations? How will the project be assessed? |
| I. Project Description: Describe the goals, objectives and outcomes of the place-based project. **In your project description, consider the following elements:**<br><br>1. Authentic Research and Place-based Learning: What research questions and practices or inquiry skills are integral to the project? How does the project incorporate a sense of "place"?<br><br>2. Anchoring Events: How will you hook and sustain student interest? Develop an **anchoring event** that engages students in a motivating activity that can be referred to throughout the project.<br><br>3. Fieldtrips and Experts: What experts can students contact? What kinds of fieldtrips directly align with project goals? What businesses, non-profits, agencies**, experts,** and colleges can inform project goals?<br><br>4. Pedagogical Considerations: What kind of skills and practices do you intend for the students to learn? How will you differentiate and accommodate for various student needs? How will you integrate the background and culture of your students in the project? How does your project apply to the real world and life beyond secondary education? |

[1] Adapted from the Buck Institute of Education (n.d.) Project Design Rubric and Wiggins and McTighe (2005). *Understanding by Design. Expanded Edition*. Association for Supervision and Curriculum Development.

- Discussion and Argumentation: How will you hold students accountable to the project tasks and each other? What kinds of discussion protocols (e.g. pair-share, four corners, listening triads, fishbowl) will support students in the project?
- Differentiated Instruction/IEP/504/SST: How will the project accommodate various student needs and interests? Consider ELL and special-needs students as well as the diverse learning styles/interests of all students.
- Social Justice and Multicultural Considerations: How is the background, culture, gender and SES of all students integrated into the project? What strategies will you implement so that all points of view are heard throughout?
- College and Career Readiness: What transferable skills will you emphasize that prepare students for life after high school? What careers will you highlight that pertain to the project?

II. Design a Project Timeline: Outline specific lessons, tasks, and milestones that students will complete throughout the duration of the project that align to your goals and objectives for the project:

- <u>Pre-Project:</u>
- <u>Project:</u>
- <u>Post-Project</u>

III. Reflection and assessment strategies: How will you and your students reflect on and assess (formative and summative) understanding <u>over time</u>? (e.g. Class discussion, fishbowl, surveys, student-facilitated formal debrief, peer/group evaluations).

Develop tasks, activities and rubrics that assess learning outcomes and proficiencies.

| PROJECT RESOURCES | | |
|---|---|---|
| Student Literature | Materials & Field Trips | Web sites & Technology |
| • What texts (fiction, non-fiction), newspapers & journal articles will support student learning? | • What materials do you need?<br>• Who will you contact?<br>• Where will you go?<br>• What support do you need?<br>• What are the logistics and for the field trip or activities? | • What technology and web resources will you utilize? |
| PLAN LEARNING OPPORTUNITIES AND SEQUENCE INSTRUCTION: Outline the essential learning experiences that sequence the key knowledge and practices for this project? | | |
| Week 1<br>Standards:<br>EUs/EQs:<br>Objectives:<br>Activities/Tasks: | Week 2<br>Standards:<br>EUs/EQs:<br>Objectives:<br>Activities/Tasks: | Week 3 (or more)<br>Standards:<br>EUs/EQs:<br>Objectives:<br>Activities/Tasks: |