# Promoting Understanding of Three Dimensions of Science Learning Plus Nature of Science Using Phenomenon-Based Learning

by Maryam Saberi, Ministry of Education of Iran; & Noushin Nouri, University of Texas Rio Grande Valley

## Abstract

The utilization of phenomenon-based learning (PhBL) for science instruction remains limited despite its alignment with the goals outlined in the Next Generation Science Standards (NGSS; NGSS Lead States, 2013) due to the lack of exemplary materials and inadequate training opportunities for teachers. The aim of this article is to illustrate the steps of the PhBL method by providing an exploratory learning experience as it was implemented in a preservice setting. In this study, we provide an innovative perspective by illuminating how this kind of instruction can be used as a context to explicitly discuss the three dimensions of learning (i.e., Disciplinary Core Ideas, Science and Engineering Practices, and Crosscutting Concepts; NGSS Lead States, 2013) as well as the nature of science (NOS). Using PhBL to teach NOS is an answer to the concern of teachers who think teaching NOS would take time from their content teaching. Hopefully, this article provides a comprehensive guideline for science educators to facilitate the inclusion of PhBL in their science methods courses and use it to clarify the three dimensions of NGSS and the incorporation of NOS within these dimensions for preservice teachers.

## Introduction

According to the *Next Generation Science Standards* (NGSS; NGSS Lead States, 2013) and the *Framework for K-12 Science Education* (National Research Council [NRC], 2012), K–12 science education should be structured around three major dimensions—Disciplinary Core Ideas (DCIs), Science and Engineering Practices (SEPs), and Crosscutting Concepts (CCs) —and the nature of science (NOS) is integrated either by CCs or SEPs. The ultimate goal of these dimensions is to reflect "the importance of understanding the human-built world and to recognize the value of better integrating the teaching and learning of science, engineering, and technology" (NRC, 2012, p. 8). One of the most innovative aspects of the NGSS is the integration of three learning dimensions and the inclusion of NOS along with the emphasis on the importance of science instruction centered on natural phenomena:

The *NGSS* provides clear expectations for students studying natural phenomena as the basis of what they should learn (i.e., what they should know and be able to do) at the end of a grade or grade band. Past standards provided the isolated content and inquiry abilities but did not provide for the full integration of the science practices with the content. (Bybee & Pruitt, 2017, p. 109)

Phenomenon-based learning (PhBL) can serve as a responsive instructional method to address this innovation by focusing on a phenomenon and leveraging insights from different branches of science to explain it. However, teachers need support to acquire the skills necessary to effectively utilize PhBL and connect it to the expectations of the NGSS. Trauth and Mulvena (2021) mentioned the lack of materials and adequately prepared teachers as concerns about the implementation of PhBL. Smith (2020) warned only a few students have the opportunity to experience authentic phenomenon-based or problem-based science instruction and connected this issue to the insufficient availability of NGSS-based resources for teachers. Given this, it remains vital for science teacher preparation programs to offer chances for preservice teachers (PSTs) to become familiar with NGSS-based resources and acquire the skills to create lesson plans rooted in these resources. In this regard, the purpose of this article is to provide a procedure or routine for the successful implementation of PhBL, explain this routine through the use of a practical example to provide more clarification, and explicitly construct the connections between PhBL and the three dimensions of NGSS and NOS, thereby clarifying them for PSTs. Considering the time limitation within methods classes, the PhBL procedure can be used to effectively cover three important topics together: teaching science using PhBL, learning about NGSS and its dimensions, and learning about the elements of NOS.

## Phenomenon-Based Learning (PhBL)

PhBL is an active instructional approach in which learning takes place within an investigation of a real-world scientific phenomenon. According to Amplify Science (2018), “a scientific phenomenon is an observable event that occurs in the universe—one that we can use our science knowledge to explain or predict” (p. 6). PhBL is not just one but “an amalgamation of many different theories and best practices,” including social constructivism, situated cognition, phenomenology, and the theory of emergent learning “that together form a pedagogical structure that redesigns education and schooling completely” (Prakash Naik, 2019, pp. 24–25). Moreover, PhBL, as a larger umbrella, encompasses the elements of inquiry-based learning, problem-based learning, project-based learning, and other pedagogical models (Prakash Naik, 2019). PhBL in science begins with observing a real phenomenon (from the environment) and continues with asking questions, organizing the findings, making decisions, and trying to answer the questions (Silander, 2015). In this process, students try to use their own words and background knowledge to explain the phenomenon and the science behind it (Kubat, 2020). So, during the learning process, students are able to think and act like scientists and engineers (Bendici, 2019). Furthermore, in PhBL, learning objectives are not imposed; rather, they are created or emerge during the learning process (Kubat, 2020).

PhBL has several benefits for students. It “motivates students by providing them with a sense of purpose and agency, and by engaging their curiosity” (Amplify Science, 2018, p. 8). This engagement is essential for higher student achievement (Inkinen et al., 2019), more authentic learning experiences (Hoglund, 2020), higher content retention (Inkinen et al., 2019), and less off-task behaviors (Van Loo, 2017). PhBL is deeply collaborative and enhances students’ thinking skills through communication (Lehtonen et al., 2019). Students are motivated to participate with peers (Bobrowsky et al., 2014) and feel valued and respected (Hakkarainen, 2010). PhBL also helps students develop their creativity and critical-thinking skills while working on a real-world phenomenon (Makarova et al., 2020). This kind of instruction, in addition to increasing students’ knowledge of the content of science, increases skills like problem-solving, communication, and teamwork (Asahid & Lomibao, 2020). This approach also increases students’ flexibility in providing various solutions for solving science or math problems, which can promote students’ scientific and mathematical creativity (Asahid & Lomibao, 2020). In addition, teaching science with a PhBL approach increases the conceptual mastery of science. reduces the dominance of mathematics in solving science problems by students (Yuliati & Parno, 2018), and is effective in promoting students’ on-task behavior and motivation in science classrooms (Lefkowitz, 2020).

Considering all the benefits of PhBL for students, learning about it is crucial for PSTs because it will affect their future plans for daily science teaching (Hoglund, 2020). “This new tendency in education also has positive influences on the teaching of STEM subjects as it offers a better foundation for transdisciplinary studies” (Lee & Lee, 2022, p. 62). Several studies and scholarly sources support some benefits of learning PhBL for pre- or inservice teachers, which include (a) pedagogical preparation, (b) reflective practice, and (c) adaptation to diverse learners.

### *Pedagogical Preparation*

PSTs who engage with PhBL gain valuable insight into innovative teaching methods. According to Hongyim and Brunsell (2021), traditional lectures and presenting facts to passive students who remain motionless is an ineffective approach for promoting student learning and long-term retention of the material. In this regard, they propose PhBL as an effective, innovative method for science instruction.

### *Reflective Practice*

PSTs who engage with a PhBL approach are more likely to develop a reflective stance toward their own teaching methods, leading to ongoing improvement in their instructional strategies. As an example, Hongyim and Brunsell (2021) showed that after participating in a PhBL course, teachers were more likely to share strategies for PhBL with other teachers, allow colleagues to observe and reflect on their teaching, and discuss PhBL through social media with other instructors in other districts.

### *Adaptation to Diverse Learners*

PhBL encourages differentiation and adaptation of lessons to meet the diverse needs of students. PSTs who are trained in this approach learn that “The goal is to engage multiple times and multiple ways to create multiple chances to learn. The multimodal way of learning that takes place during this approach means it would benefit all the various types of learners” (Hoglund, 2020, p. 27).

### *Phenomenon-Based Learning (PhBL) and the Three-Dimensional (3D) Learning Approach*

When a PhBL approach is intertwined with the three-dimensional (3D) learning approach, a more authentic learning experience is created. The NGSS structures science learning around three integral dimensions – DCIs, SEPs, and CCCs. These dimensions work together in each standard to progressively build students’ comprehensive understanding of science (NGSS Lead States, 2013). According to Conant (1951), to be well-informed about science, one must have “some knowledge of the tactics and strategy of science” (p. 4). These tactics can be analogous to science and engineering practices, CCs, and, moreover, NOS.

Considering that the basic understanding of NOS is closely associated with SEPs and CCs (NGSS Lead States, 2013), elements of CCs, SEPs, and NOS can adequately be integrated with the PhBL approach to improve current PhBL frameworks or models for implementing it. In this regard, we focused on two PhBL frameworks, adopted some steps from each, and integrated 3D and NOS into those steps. The first framework is introduced by Trauth and Mulvena (2021) for using PhBL instruction in which they suggested the following implementation steps: (1) “introduce a phenomenon,” (2) “use a driving question board,” (3) “engage students in developing an initial explanatory model of the phenomenon,” (4) “coherently sequence investigations directly related to the phenomenon,” (5) “prompt students to track their learning in a summary table,” and (6) “develop a class consensus model and an explanation for the phenomenon” (pp. 7–8). The second framework from Hancock and Lee (2018) has three steps: (1) choosing a phenomenon, (2) identifying learners’ prior knowledge, and (3) designing the instruction (p. 43). When comparing these frameworks, the second framework introduces additional steps before introducing the phenomenon and is practical for designing the exploratory learning experience (ELE). The first framework offers a structure that is more comprehensive and easier to understand and, thus, more conducive to the replication and implementation of ELEs. It’s worth noting that neither of these frameworks includes integrated components aligned with the NGSS dimensions.

In this article, we designed and introduced the candle ELE to explain in detail how PhBL can be implemented for PSTs and how its connection to different dimensions of the NGSS can explicitly be discussed with them. Research shows many people have misconceptions while explaining the science behind the phenomenon of rising water in a jar inverted over a burning candle (Vera et al., 2011) and also have difficulties providing sound arguments for making testable predictive hypotheses about it (Lawson, 2002). So, the candle ELE was selected purposefully because the phenomenon potentially fulfills most of the specified criteria for designing effective PhBL instruction. We also share some primary data on implementing the ELE in a preservice setting.

## Implementing Phenomenon-Based Instruction

The ELE was designed and implemented in a science methods class for nineteen PSTs. The goal was for them to learn about using PhBL science instruction as a context to teach 3D learning (especially the science behind the phenomenon) and NOS. In this section, we first explain the steps of PhBL instruction by providing the candle ELE as an example. Some of the PSTs' responses in each step are included in the procedure. We also explain how we explicitly discussed the dimensions of NGSS and NOS with PSTs. Finally, we briefly share some data and an example of PSTs' final products.

### Step 1: Choosing a Phenomenon and Driving Question

In this step, the instructor seeks an attractive, question-raising phenomenon that will motivates students to investigate. A suitable real-world phenomenon is selected that will allow students to ask questions about and analyze the phenomenon, is appropriate to the learners' level of knowledge and understanding, and covers interdisciplinary concepts. Consistent with these criteria and based on our research purposes, we selected a high-potential learning experience, which we refer to as the candle ELE, to explicitly discuss 3D learning and NOS.

### *The Candle ELE*

Burning a candle in an inverted vessel partially immersed in water is a well-known, simple experiment with a long history that started in the third century BC by Philo of Byzantium (Vera et al., 2011). When the flame goes out, water starts to rise in the vessel, jar, or pitcher. However, most people do not know the scientific reasons behind this result. Philo had an incorrect explanation for the rise of water, attributing it to the four classical elements of ancient Greece, saying, "corpuscles of air were converted into small particles of fire and escaped from the vessel producing a partial vacuum that drove water to ascend" (Vera et al., 2011, p. 882). However, he was not the only one who explained it incorrectly; Birk and Lawson (1999) have cited some out-of-date chemistry texts and also several scientists as examples who have used the candle and cylinder demonstration to support the claim that oxygen makes up 21% of air volume. Because the whole amount of oxygen is consumed in the combustion process, it would create space for the water. So, the water rises and fills the bottom fifth of the jar. This is an explanation that is still a misconception for many people and can even be found in many scientific web sources. Eventually, Lavoisier was able to correctly explain that "the change of volume in the typical candle experiment was due to the thermal expansion of air" (Vera et al., 2011, p. 884). These days, people are using the candle experiment for different purposes. For example, Lawson (2002) used the experiment to examine sound and faulty arguments that biology PSTs generated when writing hypotheses. However, there are no records in the literature of using the experiment to teach PhBL or discuss elements of NOS.

In this innovative practice for introducing the phenomenon to PSTs, we conducted the experiment (depicted in Figure 1) and showed learners the phenomenon of water rising in a jar or a glass after the candle flame goes out. To begin the investigation, the PSTs were instructed to put on lab coats and safety goggles to follow appropriate science safety precautions. Materials, including matches and other equipment, were distributed to groups in limited quantities to prevent improper usage. Before the hands-on experience began, it was emphasized that students should only use materials when directed and follow specific safety guidelines in order to prevent accidents and promote a safe, productive learning environment. The instructor encouraged the learners to make observations and ask questions about the observed event. At this point, it was necessary to clarify the importance of precise observation in scientific processes and differentiate it from inference. For doing this, instructors asked questions such as: In what sense is this an observation, and how are observation and inference different?

**Figure 1**
*The Anchoring Phenomenon: The Candle ELE*

The instructor then wrote the learners' questions on the board for further discussion. Some common questions were: Why does the flame go out, why does the water rise, is there any oxygen left in the jar after the flame goes out, and what factors affect the rise of water inside the jar?

## Step 2: Identifying Learners’ Prior Knowledge

In this step, the instructor investigates the PSTs’ background knowledge about the desired phenomenon and the reasons for it happening. In our investigation, the instructor asked the learners to work in groups and discuss each of the aforementioned questions. Then, the class decided to focus on the second one to investigate the reason for the rise of the water. Here, the instructor pointed out that this is a cause-and-effect question and asked: What is the cause and what is the effect in this question? Then, explained the importance of cause-and-effect relationships in science. After that, the instructor asked groups to propose a hypothesis for answering the question. Because of the importance of alternative hypotheses in scientific research, the instructor also asked them to propose some alternative hypotheses. The instructor needed to clarify more about what a scientific hypothesis is with questions such as: How do we generate a scientific hypothesis, and how does it differ from an educated guess? Based on these additional explanations, the groups proposed various hypotheses, including the following.

1. Due to the consumption of oxygen inside the jar during the burning process, the air pressure inside the jar decreases, so the water rises.
2. The candle’s heat causes the air inside the jar to expand. Some of the air escapes from the mouth of the jar. Once the flame expires, the air begins to cool and contract. So, the air pressure inside the jar decreases, and the water rises.
3. The oxygen converts to carbon dioxide when the candle burns. Because the new gas can dissolve in water easier than oxygen, the air pressure inside the jar decreases, and the water rises.
4. The candle’s heat increases the temperature of the water, so the hotter water expands in the jar.

The first two hypotheses were more common among learners. So, we focused on these two; however, the instructor should be similarly prepared for the last two hypotheses. The rest of the ELE process was designed and carried out in accordance with the PSTs’ initial ideas.

## Step 3: Designing and Implementing the Instruction

We aligned the instruction with the four initial hypotheses suggested by the learners (mentioned above) that are expected based on our experience and the literature. Then, the instructor implemented the instruction discussed here to help students make sense of the phenomenon and explain the driving questions**.** The instructor gave each group a worksheet and the equipment necessary to make models and conduct various experiments to test their hypotheses. The instructor also emphasized that the learners should not change more than one variable in each experiment so that their results can be relied upon. The provided equipment included (a) candles of varying sizes, (b) glass jars or bottles of different sizes, (c) plates, (d) water, and (e) food coloring (optional). Then, the instructor encouraged and guided the groups to propose hypothetic-predictive models for testing their hypothesis using patterns such as *if*, *and*, *then*, *but*, and *therefore*. Table 1 shows some testing models that were proposed by learners for the consumed-oxygen hypothesis and the heated-air hypothesis and how they gathered evidence to support or reject each hypothesis. Before trying their models, the instructor asked questions such as the following. Why is it crucial to base our scientific explanations on empirical evidence rather than assumptions or beliefs? And why is it important to create models that are testable and predictive in scientific research? How do such models contribute to the advancement of scientific knowledge?

**Table 1**

*Some Sample Models for Testing the Hypotheses and Gathering Evidence to Support or Reject Each Hypothesis*

| | Testing model (*if*, *and*, *then*, *but*, and *therefore*) | Gathering evidence to support or reject the hypothesis |
|---|---|---|
| | The consumed-oxygen hypothesis | |
| Sample Model 1 | **If** the use of oxygen is the reason for the decrease in air pressure and the rise of water in the jar,<br>**And** the experiment is conducted with some additional burning candles,<br>**Then:** the water will rise to the same level.<br>**But**: if the water rises considerably higher,<br>**Therefore**: the hypothesis will not be supported. | To test this model, the learners compared the results of some experiments with different numbers of burning candles. The experiment showed that the water level was higher when using additional candles. So, this experiment did not support the consumed-oxygen hypothesis. |
| Sample Model 2 | **If** the use of oxygen is the reason for the decrease in air pressure and the rise of water in the jar,<br>**And** we watch the rising water carefully,<br>**Then:** we should see the water rise uniformly while the candle is burning, and the water will stop rising when the flame goes out.<br>**But**: if the water rises considerably after expiring the flame,<br>**Therefore**: the hypothesis will not be supported. | To test this model, the learners conducted the experiment again and observed carefully to measure (or compare) the rise of water before and after the candle flame went out. The experiment showed that the water level increased considerably <u>after</u> the flame went out. So, this experiment similarly did not support the consumed-oxygen hypothesis. |
| Sample Model 3 | **If** the use of oxygen is the reason for the decrease in air pressure and the rise of water in the jar,<br>**And** the experiment is conducted with some different sizes of jars,<br>**Then:** the water will rise to a fifth of the jar regardless of size.<br>**But**: if the water fills different volumes in dissimilar jars<br>**Therefore**: the hypothesis will not be supported. | To test this model, the learners compared the results of some experiments with different sizes of jars. The experiment showed that the water fills more volume of the jar when using smaller ones. So, this experiment did not support the consumed-oxygen hypothesis. |
| | The heated-air hypothesis | |
| Sample Model 4 | **If** the expansion of air and its escape from the opening of the jar is the reason for the decrease in air pressure after cooling,<br>**And** we observe the experiment carefully,<br>**Then:** we should see the escaping bubbles.<br>**But**: if no bubbles are seen,<br>**Therefore**: the hypothesis will not be supported. | To test this model, the learners conducted the experiment again and observed the mouth of the jar carefully to find out if they could see the bubbles escaping from the mouth of the jar. The learners saw the bubbles right at the moment of placing the glass on the burning candle. So, this experiment supported the heated-air hypothesis. |
| Sample Model 5 | **If** the expansion of air and its escape from the opening of the jar is the reason for the decrease in air pressure after cooling,<br>**And** we heat the jar from the outside without using the flame inside it,<br>**Then:** we should see the escaping bubbles and the water rise.<br>**But**: if no bubbles are seen and water does not rise,<br>**Therefore**: the hypothesis will not be supported. | To test this model, the learners heated the jar from the outside without using the flame inside it. The experiment showed the escaping bubbles and the water then rising. So, this experiment similarly supported the heated-air hypothesis. |

*Note*. When the PSTs were trying their models, the instructor asked the groups questions such as: What would happen if we used a smaller or larger vessel, is the amount of water affecting the phenomenon, and what about the size of the candle? These questions helped PSTs explore the concept of scale and proportion.

## Step 4: Connecting the ELE to 3D Learning and NOS

At this stage, with the help of pictures and videos, the instructor introduced the physical and chemical aspects of the experiment to explain the phenomenon of rising water, such asthe consumption reaction and its products,the air pressure, and the gas, and the interdependence of temperature and pressure for perfect gases at constant volume ($PV = nRT$). The instructor also briefly mentioned the history of this experiment and various hypotheses scientists have presented that were similar to the learners' hypotheses. In this historical context, the instructor asked questions such as the following. Are scientific ideas replaced very often? In what sense is scientific knowledge tentative? How does the need to make sense of data account for disagreement among you? How about disagreement among scientists?

Using questions such as these and many others asked during instruction, the instructor tried to discuss NOS, SEPs, and CCs explicitly and reflectively without mentioning their name. In addition, because our participants were teacher candidates, the workshop actually had a second section in which the instructor explained the foundation of PhBL, the three dimensions of NGSS, NOS, and the link between the discussions and questions during the ELE and these dimensions. For example, we might say the following: "Do you remember we discussed the role of creativity? Do you think this kind of discussion belongs to NOS, SEPs, or CCs? Why?" To help teachers differentiate between SEPs and NOS, we started by providing clear definitions of SEPs and NOS. We defined them as follows:

> SEPs are evident when students plan and conduct experiments, collect data, analyze patterns, and construct explanations during the investigation. NOS is highlighted when students discuss how scientific knowledge evolves over time, the role of empirical evidence in scientific inquiry, and ethical considerations related to scientific investigations.

Then, we used specific examples from the candle ELE to illustrate both SEPs and NOS. In addition, weengagedthePSTs in reflective questions to help them distinguish between SEPs and NOS in the context of the ELE and, via group discussions, allowed them to share their perspectives and insights on which aspects of the ELE align with SEPs and which pertain to NOS. Below, we discuss some of these explanations to make duplication of the ELE easier.

### *Dimension 1: Disciplinary Core Ideas (DCI)*

This experiment consists of two different aspects: burning and extinguishing the candle and rising water in the jar. The scientific explanation behind this phenomenon needs attention to some facts and laws in both chemistry and physics. Many students and teachers explain the rise of water by the chemical aspect of burning and the consumption of oxygen. From their point of view, when we cover the burning candle with a jar, oxygen from the air is consumed during the burning process, and all the oxygen disappears from the air inside the jar, and because "the oxygen content in the atmosphere is 21%," around one-fifth of the initial gas volume will be reduced and replaced by water (Vera et al., 2011, p. 883). Contrary to this viewpoint, Lavoisier conducted experiments and showed that changes in the gas volume due to combustion are negligible. In a similar experiment that involved burning a piece of paper, Vitz (2000), showed that just 44% of the oxygen content had been consumed during the burning process. So, the idea of consuming all the oxygen and the air pressure decreasing because of that is incorrect. If complete combustion happens, oxygen ($O_2$) and paraffin ($C_nH_{2n+2}$) will react, which would result in producing water ($H_2O$) and carbon dioxide ($CO_2$). Assuming that the candle wax consists of the hydrocarbon pentacosane ($C_{25}H_{52}$), the equation would be balanced based on the conservation of mass: $38O_2 + C_{25}H_{52} = 25CO_2 + 26H_2O$ (Birk & Lawson, 1999). Based on the equation, some oxygen is used up, but it would be replaced by the products. So, the chemical aspect of the phenomenon alone cannot be responsible for the rise of water inside the jar. Instead, the physical aspect, which may be unknown to many people, can explain the scientific reason for the phenomenon.

The physical aspect, which is the main contributing factor, is related to the thermal expansion of air during the burning process. The candle's heat causes the air around the flame to expand, and the bubbles escape from the bottom of the jar. After the flame goes out, the temperature and the pressure of air decrease, "so the water is pushed in by greater air pressure outside" (Lawson, 2002, p. 241). We use the ideal gas model to explain the behavior of the air inside the container. In this model, it is assumed that the particles of the system are very small spheres that are completely rigid. These particles do not interact until they collide with each other. The parameters, or quantities, of the perfect gas state that represent the state of the system at equilibrium include pressure, volume, temperature, and the number of moles (or molecules). These quantities are related through the equation of state for ideal gas law (i.e., $PV = nRT$). According to this equation, if we change any of the parameters of the ideal gas system, the other parameters must be changed in such a way that this relationship is still maintained between them. In the candle experiment, when we light the candle and place the jar on top of it, the temperature of the air inside the glass rises. According to the ideal gas law, because the volume is constant, the pressure increases. This increase in pressure causes air bubbles to move outside the jar and reduce the number of air molecules inside. When the candle is extinguished, the temperature of the air inside the glass starts to decrease. This reduction continues until the temperature becomes the same as the outside temperature because on the right side of the equation, in addition to the temperature, the number of molecules (the number of moles) has also decreased, while the volume of the container has remained constant. Therefore, it can be easily concluded that in the new equilibrium condition, the pressure value will be lower than the initial pressure. In fact, due to the removal of some of the air inside the container, a relative vacuum is created inside it. This pressure difference between the inside and outside air causes the water to be pushed into the container and rise. These explanations can be experimentally verified by the candle–cylinder demonstration in which the air is trapped and will not escape from the container (for more details, see Vera et al., 2011). The final level of water inside the cylinder shortly after the flame goes out is exactly the same as its initial level. So, this experiment supports the heated-air hypothesis. In addition, the candle experiment can be covered by mass and energy conservation law and also by the kinetic molecular theory.

In summary, this ELE can effectively cover DCIs related to both the combustion reaction and the gas laws (*PV* = *nRT*). Learners can investigate some important DCIs, including the construction and explanation of a chemical reaction (HS-PS1-2), conservation of mass (HS-PS1-7), and conversion of energy forms (HS-PS3-3) that are related to the combustion reaction. They can also explore the concept and the application of the gas laws to learn about some critical DCIs connected with developing models for energy atthe macroscopic scale (HS-PS3-2), changing the temperature of particles (HS-PS1-5), and making a computational model for energy change in system components (HS-PS3-1).

## *Dimension 2: Science and Engineering Practices (SEPs)*

There are eight practices that NGSS (NGSS Lead States, 2013) demands from our learners: (1) *asking questions and defining problems*, (2) *developing and using models*, (3) *planning and carrying out investigations*, (4) *analyzing and interpreting data*, (5) *using mathematics and computational thinking*, (6) *constructing explanations and designing solutions*, (7) *engaging in argument from evidence*, and (8) *obtaining, evaluating, and communicating information*. PhBL instruction of the candle ELE covered almost all of them.

In this stage of the workshop, the eight NGSS practices requires from learners were introduced, and the PSTs were asked to discuss how we addressed each SEP during the candle ELE. This type of discussion helps PSTs learn about these SEPs and also generates ideas for incorporating the SEPs into their future PhBL lesson plans. Here, we provide some examples of the PSTs' discussions on covering each SEP during the ELE.

**Asking Questions and Defining Problems**. The PSTs pointed out how they needed to ask appropriate and answerable questions after observing the phenomenon and when they wanted to find reasons behind the rising water.

**Developing and Using Models**. Considering that this SEP is the main goal of PhBL science instruction, the PSTs mentioned how they suggested different models to support their hypothesis. They discussed the concept of modeling by discussing how diagrams or physical models can represent the candle, vessel, water, and air system. They also discussed the model used to explain the behavior of perfect gases in the gas laws. In this model, it is assumed that the molecules making up the perfect gas are very small spheres that have no internal structure and are completely rigid. These particles do not interact until they collide with each other.

**Planning and Carrying Out Investigations**. Participants mentioned how they planned and conducted controlled experiments to investigate factors affecting the phenomenon, such as varying the number of candles, changing the amount of water, or altering the vessel size. They also emphasized the importance of systematic data collection and accurate measurement techniques.

**Analyzing and Interpreting Data.** The PSTs pointed out how they recorded and organized their data, such as water level measurements over time, temperature changes, or observations of the candle flame. They discussed how their interpretation of the analyzed data guided them to refine their hypotheses.

**Using Mathematics and Computational Thinking.** The PSTs pointed out several opportunities for mathematics, for example, measuring the amount of the water rising to compare it with the 21% expectation for oxygen and balancing the equation for a complete combustion reaction. They also mentioned how they utilized computational tools during the PhET visualizations.

**Constructing Explanations and Designing Solutions**. The PSTs discussed how they constructed explanations after trying each hypothesis based on the data and understanding of scientific principles. They also addressed the challenges they encountered while designing solutions for questions or problems identified during the investigation.

**Engaging in Argument From Evidence.** The PSTs highlighted how they engaged in scientific arguments based on the evidence they collected by creating *if–then* models and examining them. They also discussed their use of evidence to support claims and counterarguments.

**Obtaining, Evaluating, and Communicating Information.** The PSTs highlighted how group sharing and discussing the obtained results with the class ensured the learning of the material.

In addition, many other science-process skills, such as inferring, measuring, controlling variables, and hypothesizing, were utilized and discussed with the PSTs. We also encouraged students to see how asking questions, modeling, and data analysis, for example, are interrelated and contribute to a holistic understanding of the phenomenon.

### *Dimension 3: Crosscutting Concepts (CCs)*

CCs are overarching themes that bridge different areas of science and help students develop a coherent and scientifically based view of the world. Here, we saw that both chemical and physical reasoning were needed to explain what was happening. During the investigation of gas laws and the exploration of relationships among volume, pressure, and temperature, especially during PhET visualizations, we had a substantial opportunity to talk about several CCs, including energy and matter, cause and effect, energy and stability, and systems and system models. We explicitly discussed the transfer and conversion of energy. When the candle burns, it consumes oxygen and produces carbon dioxide and heat. This process illuminates the intricate interplay of energy and matter in the phenomenon. Moreover, the heat generated by the candle affects the air pressure within the vessel, causing some of the air to move outward and resulting in a noticeable change in the water level. This dynamic interaction exemplifies the concept of matter and energy flow within the system, highlighting the transformative nature of energy and matter as they contribute to the overall phenomenon. We discussed the cause-and-effect relationships when discussing the question that PSTs asked in the beginning and when discussing changes in physical quantities (i.e., $P$, $V$, and $T$). In addition, we talked about how changes in these variables can affect the stability and equilibrium of a gas system. Ultimately, considering the inputs, outputs, and relationships between these variables, we were able to talk about the behavior of gases that can be described and modeled as a system.

## *Nature of Science (NOS)*

During the ELE, the instructor's role was to pose NOS questions and redirect PSTs' answers by asking further questions or offering illustrative examples and detailed explanations. After the ELE, the instructor was able to explain what NOS is and clearly mention elements of it.This part was thoughtfully integrated into the workshop because it was imperative for the PSTs to transition into this new role after experiencing the phenomenon as students. Because the NOS elements of NGSS are broad, the instructor broke them down and explained in which part of our ELE the aspects of NOS were discussed. During the concluding explanation of NOS, the instructors also referenced back to the NOS related questions discussed through the instruction ***Observation vs. Inference***. The whole ELE relied on observation and inference, so it was critical that the instructor ask questions to bring PSTs' attention to the distinction between observation and inference. The PSTs made lots of observations throughout the process. For example, two main observations that were critical for correct inferences or explanations include noticing bubbles coming out and the rise of water, which occurs mostly after the flame goes out not during the burning process. We asked the PSTs to compare and contrast qualitative and quantitative observations in science, and we asked them questions such as: How do they contribute differently to our understanding of the natural world, and to what extent is scientific knowledge based on or derived from observation of the natural world?

**Creativity and Imagination.** *When* suggesting different hypotheses until finding a model or trying hypotheses and then finalizing their answers, the PSTs used their creativity. To point this out, the instructor asked questions such as the following. In which steps of your work did you use your creativity? In what ways do you think scientists use creativity in their work? Scientists have to formulate ideas to account for data; how does this show that science is creative? What factors moderate imagination and creativity in the development and justification of scientific ideas?

**Subjectivity.** During the ELE, a group happened to choose a jar with a specific thickness that resulted in the water coincidentally rising to fill the bottom fifth of the jar. Because this appeared to correspond so closely with the oxygen content of the atmosphere (21%), the group was convinced that the consumed-oxygen hypothesis was correct and did not try other alternatives. This accident provided us with an opportunity to bring PSTs' attention to the role of bias and not accepting other explanations. Also, the candle experiment was a great example illustrating how identical observation historically led to different scientific explanations, and even the PSTs themselves had varying hypotheses observing the same phenomenon. Examples of guiding questions include the following. To what extent are scientists and scientific knowledge objective and subjective? To what extent can subjectivity be reduced or eliminated? How do personal bias and prior knowledge influence the way scientists approach their research and interpret their findings? In what ways can data collection and experimental design be influenced by subjective choices? How can scientists minimize these influences?

**Role of Background Knowledge.** Knowing the process of a burning candle, its chemical equation, expansion and contraction, and the gas laws may have affected PSTs' inferences. There was also thechance that they had previously seen a video or supporting materials. These conditions can help the educator to pose questions about the role of background knowledge. It was also discussed that if they knew the process of burning but not the part where oxygen would be replaced by carbon dioxide, this background knowledge would actually work against them. *For example, we asked the following questions.* How did your prior knowledge and experience influence your observations and interpretations during the candle ELE? Can you identify specific instances during the ELE where your background knowledge or assumptions affected your understanding of the process or results? How do scientists differentiate between valid background knowledge and unsupported assumptions? What strategies can they use to ensure their prior knowledge is accurate and relevant?

**Difference Between Scientific Law and Theory.** *When discussing* the science behind the experiment, we explained gas laws and kinetic molecular theory and then asked: Why do we call the first one a law and the second one a theory, and what is the difference between them? After summarizing the PSTs' answers, we added our explanation and clarified that gas laws are mathematical descriptions of gas behavior under specific conditions, whereas the kinetic molecular theory explains molecular gas behavior. Gas laws are established and validated, making them laws. Kinetic molecular theory is a conceptual framework, categorizing it as a theory. Both are vital for understanding gas behavior and complement each other at varying levels of detail.

**Importance of Empirical Evidence.** As it was mentioned in the ELE, we brought PSTs' attention to the difference between a hypothesis and an educated guess. In addition, PSTs observed and engaged in the process of suggesting testable solutions. We asked PSTs the following questions. Why is testing your hypothesis important? Is there any way we can answer our main question without trying different hypotheses? What types of empirical evidence can you gather during the candle ELE, and how do these observations contribute to your understanding of the process?

We also asked broader NOS questions such as: How might this candle ELE be similar to and different from real science? However, because all the elements were not highlighted in our ELE, we did not address all of them. Science educators can play around with NOS elements depending on the phenomenon. For example, if the phenomenon is culturally relevant, there is space to pose questions about the relationship between science and culture.

### Step 5: Summarizing the Final Knowledge and Completing the PhBL Concluding Table

After a group discussion and exchange of opinions, the PSTs created their final explanatory model of the phenomenon and wrote their final answers to the initial question: Why does water rise in a jar inverted over a burning candle standing in water? Ultimately, the PSTs' knowledge was deepened in two ways: (1) through demonstrations or videos of similar phenomena—e.g., pulling an egg into a bottle (https://www.youtube.com/watch?v=28TIyWdfxxc) or lifting a lemon pyramid (https://www.youtube.com/watch?v=3KTDS6HbH24)—or using toys called "hand boilers" and "drinking bird" (http://scientificsonline.com/) and explaining the similar scientific idea behind them and (2) through the use of PhET (https://phet.colorado.edu/) virtual activities—i.e., Gas Properties (https://phet.colorado.edu/en/simulations/gas-properties) and Gases Intro (https://phet.colorado.edu/en/simulations/gases-intro)—to explore the relationships among volume, pressure, and temperature. These visualizations provided an opportunity to discuss how changes in these variables can affect the stability and equilibrium of a gas system.

Trauth and Mulvena (2021) introduced a summary table to help learners conclude the PhBL lesson. We adopted their table and modified it based on our innovation (integrating dimensions of NGSS) to reflect both the PhBL steps and the dimensions of NGSS and NOS. An example of a completed PhBL concluding table for another phenomenon is provided in Figure 2, and an editable template is included as a supplemental file. PSTs worked in groups under the instructor's guidance to complete this table based on the explanations and procedures they had followed for the candle ELE.

## Implementation

We have implemented the candle ELE in a secondary methods class with nineteen PSTs with the following goals: (1) introducing PhBL and its procedure, (2) teaching the three dimensions of NGSS, (3) helping PSTs to develop an informed understanding of NOS, and, eventually, (4) assisting PSTs in designing PhBL instruction that reflects the achievement of the previous goals. In order to have clear criteria for evaluating the PSTs' achievements, we gave them a certain phenomenon and asked them to design their PhBL science instruction and complete the PhBL concluding table. In other words, we asked PSTs to write a lesson plan to make sure they have learned about designing a PhBL lesson plan and using it as a context to teach NOS and SEPs in particular. In Figure 2, we present one of the best-designed lessons as evidence of the effectiveness of our instruction. Furthermore, we include this lesson plan as an example and our criteria for evaluating it to help science educators in designing their assessment. The criteria for assessing PSTs' instructional designs and the number of PSTs who met those criteria are shown in Table 2.

**Figure 2**

*The Phenomenon-Based Learning (PhBL) Concluding Table Completed by a Participant for Crumpling a Tanker Phenomenon*

**Introducing the Phenomenon**

Figure A shows a tank that was used to move products from a factory. Every evening, this tank was washed for ready use the next day. One morning, upon arrival, the factory workers encountered the scene shown in Figure B.

Figure A

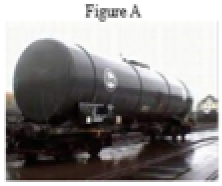
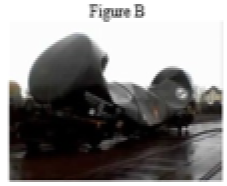


Figure B



If you face this event, what questions arise in your mind?

**Anticipated Phenomenon Question**

What factors have led to the crumpling (or the collapse) of the tanker?

| Anticipated student questions | Anticipated student ideas/observations |
|---|---|
| 1. What has happened?<br>2. How did this happen?<br>3. Why was the tanker crushed (or collapsed)?<br>4. What factors have led to the crumpling (or the collapse) of the tanker?<br>5. Has there been an explosion?<br>6. Has a heavy object fallen on the tanker?<br>7. Did the people who were there hear a loud noise last night?<br>8. Is there a smell of smoke or burning in the area?<br>9. Was the tanker crumpled all at once or slowly?<br>10. Was the temperature too low last night?<br>11. Is it possible to see what happened last night by viewing the CCTV recordings? | • The middle of the tank is crumpled, but the two ends are not crumpled.<br>• The surroundings are wet, and the weather is cloudy. It seems that last night was cold, and it rained.<br>• No large object can be seen around the tanker.<br>• There are no signs of damage caused by an explosion |

**Devise a Model for the Phenomenon**

| Initial model | First revision | Second revision |
|---|---|---|
| **Students' initial hypotheses of the reasons for crumpling**<br>• There has been an explosion.<br>• A heavy object fell on the tanker and crushed it.<br><br>**Gathering more evidence**<br>• In this step, more evidence is needed. Examining CCTV films shows that the tanker was crushed at once without an explosion or a heavy object falling on it. So, the initial hypotheses are rejected. | **Students' revised hypothesis of the reasons for crumpling**<br>• The cold air has caused the contraction of the hot air trapped in the tanker. As a result, the air pressure inside the tanker is lower than the air pressure outside, and this has caused the tanker to crumple.<br><br>**Gathering more evidence by conducting experiments**<br>• To test this hypothesis, an experiment can be conducted with an empty soda can that is heated and put downward into cold water. By doing this experiment, the students observe that very little compression will occur in the body of the can. So, probably a more important factor than the contraction of the air inside the tanker has led to its crumpling. | **Students' final hypothesis of the reasons for crumpling**<br>• The cold weather has caused condensation of water vapor trapped in the tanker. As a result of condensation, the air pressure inside the tanker is lower than the air pressure outside, and this has caused the tanker to crumple.<br><br>**Gathering more evidence by conducting experiments**<br>• To test this hypothesis, an experiment can be conducted with a soda can (with a little water inside) that is heated until you can see the vapor come out of the can and then quickly placed downward into cold water. By doing this experiment, the students observe that the can will crumple suddenly with a loud noise. So, this evidence may confirm the final hypothesis. |

**NGSS Physical Sciences Performance Expectations (PEs) Aligned With This Phenomenon**

**MS-PS1: Matter and Its Interactions**

- "MS-PS1-4. Develop a model that predicts and describes changes in particle motion, temperature, and state of a pure substance when thermal energy is added or removed" (p. 56).
- "Develop a model to predict and/or describe phenomena. (MS-PS1-1), (MS-PS1-4)" (p. 56).
- "Develop a model to describe unobservable mechanisms. (MS-PS1-5)" (p. 56).

**MS-PS3: Energy**

**NGSS Dimensions of Learning Covered in This Phenomenon-Based Education**

| Disciplinary Core Ideas (DCIs) | Science and Engineering Practices (SEPs)[a] | Crosscutting Concepts (CCs)[a] |
|---|---|---|
| **MS-PS1: Matter and Its Interactions**[a]<br>• Gases and liquids are made of molecules or inert atoms that are moving about relative to each other. (MS-PS1-4)<br>• In a liquid, the molecules are constantly in contact with others; in a gas, they are widely spaced except when they happen to collide. In a solid, atoms are closely spaced and may vibrate in position but do not change relative locations. (MS-PS1-4)<br>• The changes of state that occur with variations in temperature or pressure can be described and predicted using these models of matter. (MS-PS1-4)<br><br>**PS3: Energy**<br>• PS3A: Definitions of Energy<br>• PS3B: Conservation of Energy and Energy Transfer | 1. Asking questions and defining problems<br>2. Developing and using models<br>3. Planning and carrying out investigations<br>4. Analyzing and interpreting data<br>5. Using mathematics and computational thinking<br>6. Constructing explanations and designing solutions<br>7. Engaging in argument from evidence<br>8. Obtaining, evaluating, and communicating information | • Patterns<br>• Cause and effect<br>• Systems and system models<br>• Energy and matter in systems<br>• Stability and change of systems |

**Nature of Science (NOS) Elements Covered in This Phenomenon-Based Education**

- Scientific investigations use a variety of methods (not everyone followed the same steps)
- Scientific knowledge is based on empirical evidence (we examined every idea)
- Scientific knowledge is open to revision in light of new evidence (when we saw our idea was not working, we looked for new evidence and changed our plan based on that evidence)
- Scientific models, laws, mechanisms, and theories explain natural phenomena (as we used some of them here)
- Science is a human endeavor (role of creativity, subjectivity—different ideas for the same phenomenon—and role of background knowledge)

*Note*. a The Science and Engineering Practices (SEPs) and Crosscutting Concepts (CCs) are found on p. xx. b The Disciplinary Core Ideas (DCIs) on the “Structure and Properties of Matter” listed here can be found on pp. 56–57.

**Table 2**

*Criteria for Evaluating the Phenomenon-Based Learning (PhBL) Concluding Tables and the Number of Preservice Teachers Who Met Each Criterion (N = 19)*

| Criteria | Lower than expectation (10 points) | *n* | Meets expectations (15 points) | *n* | Exceeds expectations (20 points) | *n* |
|---|---|---|---|---|---|---|
| Anticipated student questions | Less than 3 questions are anticipated, or questions are not meaningful | 2 | Between 3 to 6 questions are anticipated, and most of the questions are reasonable | 11 | More than 6 questions are anticipated, and questions are relevant and meaningful | 6 |
| Anticipated student ideas/ observations | Few observations have been mentioned and lack details | 2 | Some observable and essential details inside the image are mentioned | 11 | Precise observations of the details inside the image have been stated | 6 |
| Devise a model for the phenomenon | The model is not reasonable, or it is not clear how it should be examined | 1 | Only one model has been proposed, and it is clear how it should be examined | 12 | At least 2 models have been proposed, and it is clear how they should be examined | 6 |
| NGSS performance expectations (PEs) aligned with this phenomenon | Could not find any standard | 0 | Standard is somehow related | 5 | Correct and related standards have been identified | 14 |
| Disciplinary Core Ideas (DCI) | Only some part of the science behind the phenomenon is mentioned, or the explanation is not accurate | 6 | Science content is mentioned but not explained in detail | 7 | All science content behind the phenomenon is mentioned correctly (including changes of state and pressure) | 6 |
| Scientific and Engineering Practices (SEP) | Less than 3 items are mentioned, or connections are not explained | 0 | 3–5 items are mentioned with clear explanations | 3 | More than 5 items are mentioned with clear explanations | 16 |
| Crosscutting Concepts (CCs) | Could not find a relation or explanation that is not related | 1 | Items are mentioned, but the connection is not clear | 17 | Items are mentioned, and the connection is clear | 1 |
| Nature of science (NOS) | Only 1 or 2 elements are mentioned, or connections are not explained | 2 | 2 to 4 elements are mentioned, and all are explained properly | 11 | More than 4 elements are mentioned, and all are explained properly | 6 |

*Note*. There was a total of 160 points possible for this rubric (20 points per criterion).

Based on our data, the concluding tables of six PSTs were reasonable in almost every aspect. Anticipating students' questions and observations seemed difficult for many of our PSTs; however, this difficulty can be overcome by showing the phenomenon to random individuals (e.g., family members) and collecting their ideas. It was not surprising that some of the PSTs struggled to connect the concluding tables to NGSS, considering that our state has not yet adopted NGSS and that the PSTs also learned about NGSS during our instruction. Because our methods class had previously completed discussions about NOS, and we referred to them in our questions during the ELE and in our explanations that followed, we thought that the way our PSTs used the PhBL to cover NOS was reasonable, and they correctly mentioned at least three elements of NOS. The problem with the SEPs' connection was that although all the PSTs mentioned the covered items, they rarely explained in detail how they integrated the specific SEPs into their instruction.

## Conclusion

NGSS is based on *A Framework for K-12 Science Education* (NRC, 2012) and puts forth universal goals for science education in the United States. PhBL is an appropriate method to address the three dimensions of NGSS. As a result, it is very important to prepare materials for teaching different scientific concepts using PhBL and explicitly explain its relation to science dimensions. In our methods classes, we try to help PSTs learn about innovative pedagogies to teach science, science standards, science process skills, and NOS, and we believe that PhBL instruction is a step in the right direction.

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### Supplemental Files

Saberi_Nouri_supplement.docx

### References

Amplify Science. (2018). *What's so phenomenal about phenomena? An introduction to phenomenon-based learning*. The Lawrence Hall of Science, University of California, Berkeley.

Asahid, R. L., & Lomibao, L. S. (2020). Embedding proof-writing in phenomenon-based learning to promote students' mathematical creativity. *American Journal of Educational Research*, *8*(9), 676–684. https://doi.org/10.12691/education-8-9-9

Bendici, R. (2019). World of wonder: Curiosity drives phenomena-based learning, which stresses investigation, collaboration, and discovery. *District Administration*, *55*(3), 32–35.

Birk, J. P., & Lawson, A. E. (1999). The persistence of the candle-and-cylinder misconception. *Journal of Chemical Education*, *76*(7), 914–916. https://doi.org/10.1021/ed076p914

Bybee, R. W., & Pruitt, S. L. (2017). *Perspectives on science education: A leadership seminar*. NSTA Press.

Bobrowsky, M., Korhonen, M., & Kohtamäki, J. (2014). *Using physical science gadgets & gizmos, grades 6–8: Phenomenon-based learning*. NSTA Press.

Conant, J. B. (1951). *Science and common sense*. Yale University Press.

Hakkarainen, K. (2010). Learning communities in the classroom. In K. Littleton, C. Wood, & J. Kleine Staarman (Eds.), *International handbook of psychology in education* (pp. 177–225). Emerald.

Inkinen, J., Klager, C., Schneider, B., Juuti, K., Krajcik, J., Lavonen, J., & Salmela-Aro, K. (2019). Science classroom activities and student situational engagement. *International Journal of Science Education*, *41*(3), 316–329. https://doi.org/10.1080/09500693.2018.1549372

Kubat, A. E. (2020). *Embedding phenomena-based learning practices into a middle school science curriculum* [Master's capstone project, Hamline University]. DigitalCommons@Hamline. https://digitalcommons.hamline.edu/hse_cp/602/

Lawson, A. E. (2002). Sound and faulty arguments generated by preservice biology teachers when testing hypotheses involving unobservable entities. *Journal of Research in Science Teaching*, *39*(3), 237–252. https://doi.org/10.1002/tea.10019

Lefkowitz, C. (2020). *The use of phenomena based learning to promote student on-task behavior and motivation in an eighth grade physical science classroom* (Publication No. 27956500) [Master's thesis, Caldwell University]. ProQuest Dissertations & Theses Global.

Lehtonen, A., Salonen, A. O., & Cantell, H. (2019). Climate change education: A new approach for a world of wicked problems. In J. W. Cook (Ed.), *Sustainability, human well-being, and the future of education* (pp. 339–374). Palgrave Macmillan. https://doi.org/10.1007/978-3-319-78580-6_11

Makarova, T. S., Matveeva, E. E., Molchanova, M. A., & Morozova, E. A. (2020). Phenomenon-based approach to teaching Russian as a foreign language in the cultural context. *European Proceedings of Social and Behavioural Sciences*, *95*, 541–552. https://doi.org/10.15405/epsbs.2020.11.03.58

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. National Academies Press. https://doi.org/10.17226/13165

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. National Academies Press. https://doi.org/10.17226/18290

Prakash Naik, R. (2019). *Phenomenon-based learning in Finland* [Master's thesis, University of Jyväskylä]. University of Jyväskylä JYX Digital Repository. https://jyx.jyu.fi/handle/123456789/64611

Silander, P. (2015). Digital pedagogy. In P. Mattila & P. Silander (Eds.), *How to create the school of the future: Revolutionary thinking and design from Finland* (pp. 9–25). University of Oulu, Center for Internet Excellence. http://www.phenomenaleducation.info/school-of-the-future.html

Smith, P. S. (2020). *Obstacles to and progress toward the vision of the NGSS*. Horizon Research. https://horizon-research.com/NSSME/wp-content/uploads/2020/04/NGSS-Obstacles-and-Progress.pdf

Trauth, A. E., & Mulvena, K. (2021). Supporting inservice teachers' skills for implementing phenomenon-based science using instructional routines that prioritize student sense-making. *Innovations in Science Teacher Education*, *6*(3). https://innovations.theaste.org/supporting-inservice-teachers-skills-for-implementing-phenomenon-based-science-using-instructional-routines-that-prioritize-student-sense-making/

Van Loo, B. J. (2017). *The effect of model-based inquiry teaching on student engagement, and the NGSS science practices in high school biology* [Master's capstone project, Montana State University]. Theses and Dissertations at Montana State University. https://scholarworks.montana.edu/xmlui/handle/1/13701

Vera, F., Rivera, R., & Núñez, C. (2011). Burning a candle in a vessel, a simple experiment with a long history. *Science & Education*, *20*(9), 881–893. https://doi.org/10.1007/s11191-011-9337-4

Vitz, E. (2000). Paradoxes, puzzles, and pitfalls of incomplete combustion demonstrations. *Journal of Chemical Education*, *77*(8), 1011–1013. https://doi.org/10.1021/ed077p1011

Yuliati, L., & Parno, P. (2018). Exploration of physics problem-solving skills within phenomenon-based learning in senior high school students. *Proceedings of the International Conference on Education*, *4*(1), 97–103. https://doi.org/10.17501/icedu.2018.4111