Lucas Education Research
GEORGE LUCAS EDUCATIONAL FOUNDATION

Making Project-Based Learning Actionable with Ambitious Instruction

David Stroupe
Michigan State University

Angela Haydel DeBarger and Nathan Warner
George Lucas Educational Foundation

Making Project-Based Learning Actionable with Ambitious Instruction

David Stroupe
Michigan State University

Angela Haydel DeBarger and Nathan Warner
George Lucas Educational Foundation

The emergence of various standards revisions in K-12 education, including the Common Core and Next Generation Science Standards, represent an exciting effort to reimagine expectations for teaching and learning in classrooms. Across reform efforts, multiple goals describe a different view of education than exists in many classrooms, including,

- an emphasis on deeper learning in and across disciplines,
- a broad recognition that teachers need to do more to prepare learners to be ready for college, and for bringing innovation to the workforce, and
- reimagining of expectations for teaching and learning since we know that the intellectual work students are capable of now outstrip what many teachers do and how they are prepared.

In order to achieve these goals, classrooms need to become welcoming environments for the kind of learning that extends beyond achievement on high-stakes standardized assessments such as standardized tests. When schools "fixate on conceptual content" (Rudolph, 2014) for the purpose of test scores, the potential for learning to be authentic and meaningful to students can be lost. Rather, learning in schools should provide multiple opportunities for students to connect to their communities and engage in authentic practices of various disciplines (Polman, 2012).

Project-based learning (PBL) is one promising way for students to engage in authentic disciplinary work that presses them to deepen their understanding of core concepts, while supporting social and emotional growth as part of the learning process. Recent efforts to define a more rigorous model PBL and to develop research-based curricula are underway. These new PBL curricula aim to demonstrate how learning goals can be realized and still provide engaging learning experiences for students.

The work of teaching must fundamentally change to meet these pedagogical expectations. PBL requires that teachers and students actively develop and shape the courses to enhance meaning and relevance of their work for themselves and their communities. This requires a different set of skills and pedagogical practices than typically occur in classrooms. Our work in trying to unpack the pedagogical possibilities in PBL is in part to address this dominant image of teaching in American classrooms, of which the primary activity is an individual's delivery of subject matter information to students (Saywer, 2008).

The norm of "teacher dominated" instruction appears in large-scale observational studies in American classrooms, which note, "teacher discourse, textbook based lessons, and coverage [are] the main curricular principles" shaping instruction (Sykes, Bird, & Kennedy, 2010, p. 465). For example, in many science classrooms, instruction focuses on the completion of numerous activities rather than sense making, rarely takes into account students' prior knowledge, seldom presses for explanations, and treats students' ideas as incongruent with canonical science (Alexander, Osborn, & Phillips, 2000; Banilower, Smith, Weiss, & Pasley, 2006; Barton & Tan, 2009; Horizon Research International, 2003; Maskiewicz & Winters, 2012; Roth & Garnier, 2007; Weiss, Banilower, McMahon, & Smith, 2001; NRC, 2011; Warren, Ballenger, Ogonowski, Rosebery, & Hudicourt-Barnes, 2001).

The push for students' recitation of correct information and the teacher's delivery of facts does not align with literature about teacher and student learning, learning sciences, disciplinary practices, and teacher education. Drawing on sources such as research in learning science, teacher learning, and equity studies, several related themes emerge that signal a new direction for teaching.

Theme 1: Redefining learning

Multiple lines of literature suggest that deep learning is not the memorization of discrete facts learned in a linear progression. Instead, learning is a process in which students change their understanding and participation in practices over time. Learning is best anchored by a puzzling event or problem that students (and the teacher) work to solve over time (Magnusson & Palincsar, 2005; NRC, 2007).

Theme 2: Redefining teaching

As researchers and practitioners have taken a new view of learning, examinations of effective teaching suggest that instructors should view students as active sense-makers rather than passive recipients of information. Therefore, a new vision of teaching is emerging in which four important elements of professional work stand out. First, pedagogical practices are not static and fixed, but are fluid and change based on context and research-practice partnerships (e.g. Coburn et al., 2013). Second, pedagogical practices are supported by an ever-expanding set of linked tools that both reify theories of teaching and learning and provide support for teachers' planning and reflection. Teachers, researchers, and instructional coaches can use such tools to support a common vision of teaching and learning (Windschitl et al., 2012). Third, teachers can take action daily action to transform the learning community in their classroom (Paris & Alim, 2014). Fourth, teachers (as well as students and researchers) should study their instruction and adapt based on evidence of learning (Franke et al., 2001). Taken together, these elements suggest that teachers take on a new level of responsibility for ensuring that all students have robust learning opportunities.

Theme 3: Building a safe and collaborative learning community

One important implication of the movement to redefine teaching and learning is that the classroom environment must shift from positioning students as passive listeners to active participants in knowledge construction. Students should have an important voice in shaping a rigorous and equitable learning community as they bring in their ideas, experiences, and stories from their life (Moll et al., 1992). To help students use their lived experiences as foundational for classroom work, teachers shift responsibility for participation and learning to students over the course of the school year (Bransford et al., 2000). Ideally, teachers and students treat each other as intellectuals and co-learn about difficult topics (Warren et al., 2001).

Implied in the list of principles is that to move beyond the teacher-dominated framework of most classroom instruction, some researchers are working to redefine "what counts" as teaching and learning. For example, Smylie and Wenzel (2006) constructed a report to improve Chicago's public schools, noting that "intellectually ambitious instruction" – teaching that fostered deep student learning – changed the role of the teacher from information delivery system to facilitating students' opportunities to engage in disciplinary work. Recent studies from mathematics, literature, and science education have continued the work of Smylie and Wenzel (2006), framing the teaching profession around *ambitious instruction*. Teachers enacting ambitious instruction provide rigorous and equitable learning opportunities to all students using specialized practices and tools that are learned, developed, and adapted over time.

This perspective of ambitious instruction appears to be aligned with the vision set forth for rigorous PBL, one in which students and teachers engage in projects of consequence. This paper explores ambitious instruction as one framework to inform the design and enactment of PBL. We need to figure out how to create generative and meaningful learning environments through projects.

A New Model of Project-Based Learning

Lucas Education Research is working toward defining a model of PBL that clearly articulates design principles that promote active student and teacher voice as well as connections to civic engagement (Baines, DeBarger, De Vivo, Warner, Brinkman, & Santos, 2016). Our aim in PBL is to develop students' agency to become engaged in their communities. To do so requires intentionality with the design of PBL courses that foster students' identity development as sensemakers as they engage with challenges that are personally relevant. While elements of this design work may be part of the "core" PBL curriculum, teachers will need to have an active role in making further refinements and adaptations to support their students' personal growth trajectories and interests.

Principles to Inform the Design and Enactment of PBL

The Lucas Education Research model of PBL currently identifies four core areas, each of which contain several principles that are necessary for realizing a vision of rigorous PBL (see Figure 1). In this model, students participate in purposeful and authentic project experiences that promote civic purpose and engagement and also demand critical, thinking, problem solving and application of interdisciplinary content knowledge and skills. Rigor is evident in the process through which learning occurs, as well as in the artifacts that students produce to address the driving questions or challenges. Classroom interactions support a culture of student agency, promote collaboration that intentionally builds on the diverse strengths and voices of learners, and include multiple opportunities for reflection on growth toward the learning goals. Thus, these dimensions and the corresponding principles work in a coordinated fashion in PBL classrooms.

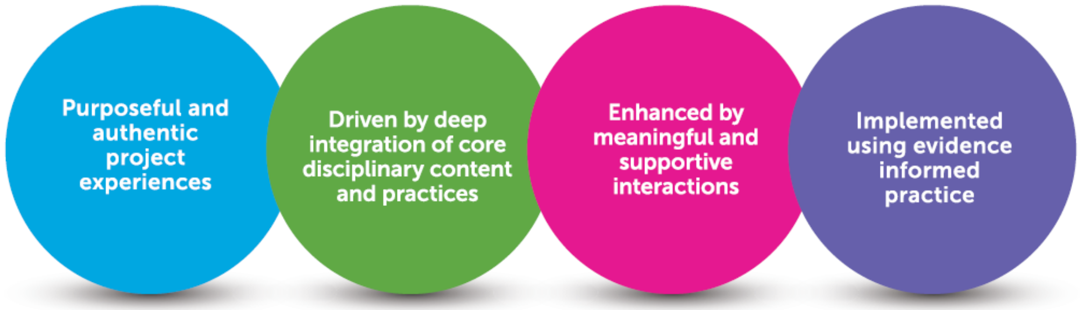


Figure 1. Rigorous Project-Based Learning (Baines et al., 2016)

This perspective recognizes PBL as a dynamic process in the classroom, as projects are enacted. PBL is jointly shaped by the interests and experiences of the teachers and students. Beginning with core course materials that reflect key design principles, such as the incorporation of a challenging driving question that when answered will result in artifacts that reflect significant learning goals, much work remains for teachers and students to "own" the projects. For example, there may be ways in which the driving question is tailored to address a particular need in the local community. Different students and groups may require unique supports when creating their artifacts, and how and when feedback and reflection occur will be driven by the questions and challenges that emerge throughout the learning process.

In recognition of these educational needs, PBL core course materials should be accompanied by educative features that support teachers in making choices and adaptations that simultaneously support their students and maintain the integrity of the course in relation to learning goals (e.g., Ball & Cohen, 1996; Davis & Krajcik, 2005). These educative features may include content connections and applications, practices for initiating lessons and engaging students, representations and analogies to make content more meaningful for learners, and techniques to notice and build on student ideas. In addition, core practices for PBL enactment are emerging.

Instructional Approaches for PBL Enactment

In PBL classrooms, a wide range of teaching practices are necessary to effectively support and guide student learning. In many ways, good teachers of PBL employ many of the same practices and strategies that good teachers, generally speaking, employ. However, the PBL curriculum context—with its emphasis on student collaboration, choice, relevance, sustained inquiry, reflection and revision—creates the conditions whereby certain teaching practices and strategies are necessary in order to support student learning in project-based learning classrooms.

A recent PBL literature review by Condliffe, Visher, Bangser, Drohojowska, & Saco (2015) found in the research a set of broad instructional approaches associated with PBL enactment. They are: promote construction of knowledge, cultivate student engagement, use scaffolds to guide student learning, encourage student choice, and support collaborative learning. Additionally, the review uncovered certain assessment approaches used in PBL contexts: create a product that answers a driving question, provide opportunities for student reflection and teacher feedback, and present products to authentic audiences.

These PBL approaches, while helpful guideposts for understanding what project-based enactment looks like in the classroom, require more work to define the high-leverage principles and practices associated with this type of pedagogy. Only once broad approaches are broken down into smaller sets of principles, practices and strategies that are high-leverage and core to their successful implementation will they be ready to be learned, practiced and enacted by teachers.

Ambitious Instruction

Ambitious instruction could be a powerful pedagogical framework that not only aligns with the goals of PBL, but also provides guidance about tools and practices for PBL teachers. A key feature of ambitious instruction, which adds to PBL research, is that teachers' work is guided by a repertoire of instructional practices that enable them to *adapt and innovate pedagogical routines and tools to meet students' emerging needs* (Ball, Sleep, Boerst, & Bass, 2009; Duschl, 2008; Kazemi, Franke, & Lampert, 2009; Lampert & Graziani, 2009). In other words, teachers enacting ambitious instruction provide themselves with opportunities to understand what students know and where they need help. As teachers learn about students' needs they constantly revisit and reshape their pedagogical actions to better serve all students. While many approaches to teaching emphasize the importance of adapting instruction to meet students' needs, ambitious teaching is different because of the purpose of pedagogical adaptations. Teachers enacting ambitious instruction use students' ideas as resources to deepen the learning opportunities they offer students over time rather than positioning students' ideas as misconceptions to be fixed over time (Stroupe, 2016). We propose that teachers enacting ambitious instruction frame their professional work differently than teachers who view teaching as information delivery and the assessment of students' conceptual understanding.

Studies show that teachers enacting ambitious instruction provide opportunities for students to engage in multiple features of disciplinary work (Windschitl et al., 2012), that teachers and students negotiate the knowledge and practice of a classroom community (Stroupe, 2014), that novice teachers can adapt and innovate tools and pedagogical routines to provide students with science learning opportunities (Thompson, Windschitl, & Braaten, 2013), and that teachers can make use tools and pedagogical routines to press students for deeper and more complex explanations of natural phenomena (Braaten & Windschitl, 2011). Each of these findings suggest that during moment-to-moment interactions with students, teachers enacting ambitious instruction actively shift the expectations of student learning away from information acquisition and recitation, and towards participation in disciplinary practices.

Seven principles of ambitious instruction

Ambitious instruction reifies literature arguing for rigorous disciplinary expectations for students, as well as literature focused on equity and responsiveness (see Levin et al., 2012; Michaels, O'Connor, & Resnick, 2008; Sherin et al., 2011). There are few examples from classrooms or the literature that provide a clear vision of teaching that simultaneously promotes rigorous disciplinary activity and is responsive to all students.

In one of the few large-scale studies that examined similar constructs, researchers found only 13 percent of the K-12 math and science lessons observed were highly respectful of students' ideas while also encouraging "serious learning" (Horizon Research International, 2003). Examples from the literature suggest that classrooms can be responsive, yet lack rigor in terms of addressing core content and practices; students can have meaningful conversations but not build substantive disciplinary understandings. Alternatively, classrooms can aim solely for rigorous standards (i.e., holding students accountable for canonical vocabulary and knowledge, yet be restrict to students' ideas. Students might "sound like" a scientist, historian, or mathematician, but there is little room for them to fit these understandings into the contexts of their own lives.

Therefore, the simultaneous attention to rigor and equity inherent in ambitious instruction results in seven principles of teaching, which are listed below (from http://www.ambitiousscienceteaching.org). There are three features of the principles to note. First, each principle inherently involves teacher actions. The experiences advocated by the principles, such as talk and writing, only occur if the teacher provides opportunities for students to engage in such work. Second, the principles are bound together, and collectively provide students with deep learning opportunities. In other words, no one of these principles is effective unless coupled with the others. Third, the principles promote the stance that all students can learn complex disciplinary ideas and practices. Teachers help all students participate by constantly "problem solving" about who is, and is not, taking part in the activities of the classroom community. The teacher makes strategic pedagogical decisions during planning, instruction, and reflection to ensure all students have opportunities to participate.

Seven Principles of Ambitious Instruction

1. *Anchor learning* – Teachers anchor students' on-going learning experiences in the press to understand complex and puzzling phenomena

2. *Use students' ideas and experiences as resources* – Students' everyday ideas, experiences, and questions are treated as resources within the classroom community to advance everyone's thinking

3. *Authorize students to use science practices for a purpose* – Students are apprenticed into using ensembles of disciplinary practices to test ideas they believe are important to their developing explanations and models

4. *Foster productive discourse* – Teachers provide daily opportunities for students to reason through talk

5. *Scaffold talk, writing, and participation* – Students have access to specialized tools and routines that support their attempts at discipline-specific forms of writing, talk, and participation in activity

6. *Make thinking visible in other to "work on ideas" together* – Student thinking is regularly made public and subject to critique by the classroom community

7. *Build complex and cumulative understandings over time* – Learning experiences are sequenced to help students integrate ideas together and revise understandings of "big science ideas"

Figure 2. Seven principles of ambitious instruction

These seven principles illustrate a core stance of ambitious teaching, that practitioners continually analyze their instruction to improve over time. The stance of continual improvement distinguishes ambitious teaching from many other instructional models that promote a static image of effective teaching.

High-Leverage Practices: The Core of Ambitious Instruction

As noted above, the principles of ambitious instruction indicate that teachers make pedagogical decisions during planning, instruction, and reflection to provide rigorous and equitable learning opportunities for students. However, such pedagogical reasoning is difficult, particularly since teachers must often make decisions in the face of uncertainty about what students might say or do in response to particular actions. While ambitious instruction provides a framework for teachers, the seven principles do not describe a blueprint for how, why, and when teacher should make decisions that lead to powerful learning opportunities for students. Therefore, multiple subject matter areas, such as mathematics, science, English, and history, are working to define and articulate the particular practices teachers should enact to make instructional decisions that align with seven principles of ambitious instruction.

Teachers engage in many daily practices around planning, enactment, and reflection that are intended to support student learning. For example, teachers can ask students to recite information, teachers can plan an activity, and teachers can use student data to adapt instruction. While it could be a useful exercise to identify all of the practices teachers engage in, such a task seems daunting when given the enormous amount of work teachers enact daily. Across subject matter domains, there are common patterns of effective ways for teachers and students to engage. The language of *high-leverage practices* (HLPs) is often used to describe these principles and pedagogical routines teachers enact to provide students with powerful learning opportunities. In this section, we will further define high-leverage practices, using examples from science, mathematics, English, and history, and will give an elaborated example from a science classroom in which a teacher enacting ambitious instruction constructs and enacts a unit using high-leverage practices.

Defining high-leverage practices for ambitious instruction

To articulate how teachers should enact ambitious instruction, researchers across subject matter areas are working to identify and articulate high-leverage practices (HLPs). By HLPs, we mean specific interactions between teachers and students around subject matter that have greater potential than others to engage learners in productive intellectual work. Windschitl et al. (2012) synthesized research from the fields of mathematics, science, and teacher education (i.e., Ball et al., 2009; Franke & Chan, 2007; Hatch & Grossman, 2009) to describe six criteria for an instructional practice to be considered high-leverage:

- Practices must be applicable to the everyday work of teaching and are used frequently.
- Practices must be conceptually accessible to learners of teaching, meaning that novice teachers must be able to understand what the practices entail, and how and why they are important for teaching.
- Practices must be able to be articulated and taught by more knowledgeable instructors so that the practices can be named, unpacked, and explained.
- Practices must be able to be practiced by beginners in their university and field-based settings, and in the process be revisited in increasingly sophisticated and integrated acts of teaching. In addition, these HLPs should have features that readily allow novices to learn from their own teaching.
- Clusters of practices should build upon one another instructionally and play recognizable roles together in a coherent system of ambitious teaching.
- HLPs should be few in number to reflect priorities of equitable and effective teaching and to allow significant time for novices to develop and receive feedback on approximations of each of these practices.

Note that the criteria for HLPs press on teachers, and teacher educators, to constantly learn from their instruction to provide students with increasingly sophisticated learning opportunities.

Examples of high-leverage practices

Despite the conceptual agreement about HLPs across subject matter areas, scholars differ here about "what counts" as a practice and at what grain size novices should begin to approximate teaching activities. Below is a brief summary of four fields engaged in work around HLPs. Note that for each example, the teacher educators consider disciplinary work along with pedagogical moves when defining "what counts" as a HLP.

Science education: Windschitl et al. (2012) provide the only articulation of possible HLPs in the field of science education. Their framework hinges on the planning for a science methods course, which can be organized the course around the four sets of HLPs. They are: 1) planning a unit around a "big science idea", 2) eliciting and activating students' ideas about a puzzling phenomenon (for the purpose of adapting instruction), 3) helping students make sense of science activities, and 4) pressing students to construct evidence-based explanations. The grain sizes of these practices extend over 2-3 days of instruction in a unit. Each practice, then, allows for teachers to adapt the specific components of instruction as needed for the students and school context.

Mathematics education: Multiple research teams are investigating HLPs in mathematics education. For example, Boerst and Sleep (2007) refer to whole-class discussions as a "domain", which can be broken down into "practices" such as eliciting students' ideas, which are themselves composed of smaller scale "techniques for teaching" such as revoicing or using wait time. Like Windschitl et al. (2012), Ball et al. (2009) are using HLPs to frame a methods course and provide opportunities for preservice teachers to try out the practices in a safe setting. The grain size for practices in mathematics education is smaller than in science education. HLPs in mathematics education tend to focus on specific kinds of interactions between teachers and students that may occur during a class session (for example, here is a video from the Teaching Channel highlighting one HLP - "counting collections" in a kindergarten classroom: https://www.teachingchannel.org/videos/skip-counting-with-kindergarteners).

English education: An early advocate of HLPs, Grossman uses HLPs in the context of secondary English instruction. For example, Hatch and Grossman (2009) consider orchestrating class discussions as a practice. They conceptualize smaller scale actions, such as modeling features of academic discourse, as "teaching moves."

History and Social Studies education: The first mention of HLPs in history education emerged from the Stanford History Education Group. For example, Fogo (2014) described a Delphi Panel survey in which experts reached consensus on nine practices for history teachers. These practices are: 1) use historical questions, 2) select and adapt historical sources, 3) explain and connect historical content, 4) model and support historical reading skills, 5) employ historical evidence, 6) use historical concepts, 7) facilitate discussion of historical topics, 8) model and support historical writing, and 9) assess student thinking about history. The grain size of these practices is difficult to describe for two reasons. First, the field of social studies education is considering how the practices relate to other endeavors to engage students in inquiry. Therefore, the field is still considering how the practices should be used in classrooms. Second, social studies educators have not yet published research about HLPs in classrooms or teacher preparation programs. Therefore, there are a limited number of publications available to understand how they conceptualize the grain size of HLPs.

An example of ambitious instruction and high-leverage practices in science

Here we provide a concrete example of a middle school science teacher - Maria - enacting ambitious instruction through the use of HLPs and planning and face-to-face tools. Maria has a bachelor's degree in biology, and participated in a university-based teacher preparation program focused on ambitious instruction. Note how Maria's use of HLPs enabled her students to work on science ideas over time. Such work made Maria reimagine the unit in a way she could not have predicted when planning. Also take note of how Maria learned *with* and *from* her students because of her enactment of HLPs.

HLP1: Planning a unit around a "big science idea"

Maria taught seventh grade in a high-needs district (45% free/reduced lunch). In this unit, Maria planned a two-week long unit about energy transfer in the context of a roller coaster using the planning tools from her university science methods course. In the roller coaster unit, Maria presented students with a video of a puzzling scenario of how a roller coaster could go through the same loop twice on a track – once forward, and once backward after traveling up a small hill. Though Maria tried to shape the unit around students' interests and lived experiences, she acknowledged that "this puzzling phenomenon is not really new – scientists know how roller coasters work." However, working on roller coasters was unique for Maria and her students in their localized classroom context.

HLP2: Eliciting and activating students' ideas about a puzzling phenomenon (for the purpose of adapting instruction)

To begin the unit, Maria showed students a video of a roller coaster going through a loop twice – once forward and again backward. Maria chose this video because students expressed interest in roller coasters during a prior unit about Newton's Laws of motion. During the video, students recorded observations of where they thought energy existed in the roller coaster and how energy transformations might occur. Maria also asked the students to create hypotheses about why the roller coaster could go through the loop twice.

After recording observations and hypotheses, Maria and her students moved to "idea space" – a physical location at the back of the room in which students shared their own science ideas as Maria inscribed them on poster paper. By utilizing "idea space", Maria provided opportunities for students to share science ideas in a safe environment. In turn, Maria provided herself with opportunities to hear student thinking that she would not have access to if she shut down students' public theorizing (see Appendix A for a photo of students' ideas generated in "idea space" about energy).

During this time in "idea space" Maria reflected: "[I] was listening mostly for talk about height being an indicator of energy and movement being an indicator of energy. I was also listening for talk about other types of energy that exist here (heat from friction, sound, etc.). I was also listening for any talk about how potential energy (height energy, gravity energy) turns into kinetic energy (motion energy, moving energy, speed energy). Now that I know what my students are thinking, I know what to do tomorrow." In other words, Maria wanted to hear and record how students talked about relationships between energy types in order to know what pedagogical decisions to make for the next class period.

HLP3: Helping students make sense of science activities

After the roller coaster video, Maria decided to enact a practice from her methods class – creating an explanatory model on a poster during a whole class discussion. Maria decided to try the tool because "I wanted an ongoing visual of what we have explained, what we have questions about…It also 'forces' students to come to a consensus using data and evidence and then discuss their ideas as a class." After a whole class discussion, Maria drew the initial roller coaster model and placed it at the front of the room. It is important to note that Maria drew the first whole class model based on her interpretation of students' science ideas.

For the next class, Maria decided that students should test the model she drew by recreating a physical model. By allowing students to use materials to make a physical model using pipe insulation and a marble acting as the car, Maria provided students with opportunities to share science ideas while working together to test the whole class model.

Subsequently, Maria heard science ideas from students who rarely spoke in class, thus providing her with more resources to shape her practice. One critical conversation for Maria's teaching occurred between two students, José and Anthony, who rarely spoke in class. While attempting to recreate Maria's roller coaster model, José and Anthony noticed that the marble kept "flying off of the tracks" and that they "can't make it stay on." When they summoned Maria to their table and she observed several trials, she concluded that José and Anthony's data problematized her model. Maria decided in-the-moment to recast her unit by leveraging the students' evidence, and asked José and Anthony to share their results with the class. After José and Anthony shared their findings, Maria told the class, "Well, there goes my model. Even though you think teachers are always right, this time, your data proves otherwise." When asked why she allowed José and Anthony to publicly disprove her model, she replied, "correcting the class model is a good way to give credence to their [students'] ideas - it lends even me to revisions….I want to go where they want to go." Note that Maria both recast her plan given José and Anthony's evidence, and set herself up as someone who needed to learn from students' science ideas during the remainder of the unit.

HLP4: Pressing students to construct evidence-based explanations

Since Maria's model acted as the sole representation of a roller coaster thus far, the class now faced a scientific challenge. Maria asked students to generate a better model since her representation no longer held up against the evidence students compiled in class. Eventually, the students determined that the problem with Maria's roller coaster model was that the roller coaster car started too high up on a ramp; therefore, the car had too much kinetic energy to remain on the track. The students lowered the height of the ramp, thus reducing the kinetic energy of the car, and successfully revised both the physical and conceptual model. In addition, this work served as an opportunity for formative and summative assessment. Maria created an assessment task in which students had to form groups and explain parts of the model to each other (see Appendix B for photos of the task instructions and student work).

Generating and testing these new models, as well as completing the assessment task, required two extra days of work that took Maria off of the curriculum pace. She decided to provide students with the opportunity to construct a better model because "lots of students who rarely talk are leading groups, like José and Anthony. I want them to feel empowered to be scientists." Maria paid particular attention to this talk because it gave her *access to new resources – typically silent students' science ideas – that could inform "my planning for the next lessons*."

At the end of the unit, Maria told students how much *she learned from them*: "When I say we revise our ideas in this class, I don't just mean you [students]. I mean me too. You showed me that my model was wrong, and I wouldn't have known that without your help and hard work" (observation notes). Maria thus thanked students publically for helping her learn, and showed students their role as agents who can shape the practices of the classroom community.

Exploring Intersections of Rigorous PBL and Ambitious Instruction to Inform Enactment

To systematically explore conceptual and practical connections between PBL and Ambitious Instruction, we examined the relationship between the core principles of the Lucas Education Research framework for rigorous PBL and the seven principles of Ambitious Instruction. We note that there is a high degree of overlap among the principles. In this section, we describe the relationship among the principles as they correspond to the four dimensions of PBL and draw on the educational research literature to support these connections. For areas that reflect a high degree of overlap, we identify tools research-based tools developed to support ambitious instruction practices and discuss how these tools can also support PBL enactment.

Creating Purposeful and Authentic Project Experiences

Rigorous PBL and ambitious instruction value the perspective that projects drive the learning. Projects go deeper than merely presenting a context to apply ideas. They present meaningful ways for students to engage and learn the core knowledge and practice of a discipline.

Both perspectives reflect the importance of creating learning experiences to engage students in making sense of relevant phenomena. Relevant phenomena are important in relation to the "big ideas" of science and to students' everyday lives. Authenticity reflects making connections to the disciplinary community, as well as among students' communities, interests and experiences (Polman, 2012; NRC, 2011). However, ambitious instruction does not go so far as to "require" civic engagement on the part of students. From the ambitious instruction lens, enactment of purposeful and authentic project experiences can be operationalized as students participate in intentionally sequenced disciplinary activities (Parker & Lo, 2016) as well as, such as writing and discourse to answer the driving question. These activities require extended planning and research for students (Larmer, Mergendoller, & Boss, 2015). Learning develops and is reinforced through conversations among the classroom community, as ideas are made public (and challenged) and students collectively revise understandings.

The **Big Idea Planning Tool** (http://ambitiousscienceteaching.org/wp-content/uploads/2014/08/Practice-Tool-Planning-for-Engagement.pdf) is one resource to help teachers craft projects that incorporate purposeful and authentic experiences. To construct a Big Idea, teachers first identify a topic (such as force and motion or homeostasis) then look at their curriculum and the standards to select related ideas with the greatest explanatory power. Students will spend significant time developing these key ideas during the unit. In the next stage of planning, teachers determine a relevant and puzzling phenomenon for the students to explain, and construct a gapless causal explanation for the event. For example, a teacher planning a unit about sound could focus on energy and waves as fundamental ideas. They could then select a puzzling phenomenon, perhaps asking why windows shake when a car playing loud music drives by. The teacher constructs a causal explanation, using unobservable events, processes, and structures, in this case molecules hitting each other as energy is transmitted via compression waves. Finally, the teacher anticipates what students might think about sound, considering both everyday and instructed experiences students may have had about this phenomenon.

Learning Experiences Driven by Deep Integration of Core Disciplinary Content and Practices

Another set of connections between rigorous PBL and ambitious instruction is the value both frameworks place on emphasizing the integration of disciplinary ideas and practices as the foundation for all learning experiences. The activities and ideas students engage with maintain the most complex and deep features of disciplinary work (Krajcik & Czerniak, 2013).

There are two intersections between rigorous PBL and ambitious instruction related to this dimension. First, both frameworks ask that teachers build units and lessons backwards from significant learning goals and standards. Teachers identify "big ideas" of the curriculum and discipline, then plan maximize exposure to such ideas with a variety of ways for students to "confront and resolve conflicting ideas (Darling-Hammond et al., 2008, p. 214-216; Windschitl et al., 2012). Second, teachers enacting rigrous PBL and ambitious instruction do not march through curricular content at a rapid pace with the goal of "getting through" the standards. Instead, rigorous PBL and ambitious instruction emphasize the need for students to revisit concepts with increasingly sophisticated applications to deepen understanding and support critical thinking, to engage in problem solving, and to participate in the construction of content knowledge (Parker et al, 2013, p. 1433; Larmer, Mergendoller, & Boss, 2015). In addition, teachers intentionality make students' thinking visible and pay attention to how students' ideas develop and evolve over time, constantly looping back to content and ideas core to the discipline.

To support disciplinary rigor, teachers could use two kinds of tools from AI. First, all of the **planning tools on the ambitious science teaching** website (http://ambitiousscienceteaching.org/tools-planning/) are examples of tools that press teachers and students to unpack foundational concepts in science, to increase intellectual expectations for all students, and to help teachers and students apply content to solve emerging problems in the classroom and community. Second, the **face-to-face tools** (http://ambitiousscienceteaching.org/tools-face-to-face/). This family of tools was developed to help students to construct and revise evidence-based explanations and models for complex phenomena. Face-to-face tools are used with students to represent and work on ***their*** current ideas. These representations are often put on the walls of the classroom so that students' current thinking can be ***made public and revised*** over time. These tools do not just display thinking, they help organize and refine student reasoning as well.

Meaningful and Supportive Interactions

Eliciting meaningful conversations about phenomena and pressing students for reasoning to develop deep understandings over time would not be possible without thoughtful consideration of how to establish a community wherein these types of conversations are valued. Both rigorous PBL and ambitious instruction reflect the fundamental importance of building a culture of agency to promote rigorous discourse about disciplinary learning (Thompson, Hagenah, Kang, Stroupe, Braaten, Colley & Windschitl, 2016). In these classrooms, students are recognized as "authors and producers of knowledge" (Darling-Hammond, 2008, p. 216). These opportunities to develop and exchange diverse "funds of knowledge" can enhance learning because they offer an authentic way for students to connect with and contextualize the content (Gonzalez, Andrade, Civil, & Moll, 2001). In this way, equity becomes more than just an issue of access to content; students are positioned as able to shape and make meaning of disciplines.

In addition, both ambitious instruction and rigorous PBL encourage teachers to be reflective about the culture of their classroom. Teachers may be asking themselves questions such as: Are my students collaborating productively? What are the multiple ways and forms that students can express what they are learning (through discourse, writing, drawing, etc.)? Do my students and I have enough time to reflect on our learning and growth? Have I created opportunity for students to own and feel ownership about their learning?

In considering tools to support this practice, we focus on classroom discussions. Teachers are likely to navigate some of these questions explicitly in their conversations with students. And moreover, the core of ambitious teaching is that students and teachers make sense of the world by engaging in multiple forms of discourse in the classroom. To support these interactions, a primary resource for teachers can be the **discourse primer** (http://ambitiousscienceteaching.org/wp-content/uploads/2014/09/Discourse-Primer.pdf). This resource explains what productive talk sounds like, how teachers can support such talk, and why such talk is important for student success. These examples are important because unfortunately, they are not common in classrooms. This resource also provides guidance about norms to create a safe classroom environment for conversation and strategies to reinforce norms.

Evidence-Based Teaching and Assessment Practices

Both the rigorous PBL and ambitious instruction frameworks emphasize the importance of using multiple forms of evidence to shape instruction. While a dominant narrative about "evidence" focuses on assessment data (particularly standardized test scores), rigorous PBL and ambitious instruction press teachers to look at more types of evidence, including students' emerging, developing, and shifting disciplinary ideas. Since a core feature of rigorous PBL and ambitious teaching is the elicitation and revision of ideas, we propose that teachers need opportunities to "notice" and use students' ideas as resources to make instructional adaptations (Sherin et al., 2011). Opportunities for teachers to notice students' thinking could include multiple kinds of formative and summative assessments, including class discussions, revisiting representations of thinking, and allowing students to propose and carry out investigations. Such assessments also link back to the driving question, helping students see connections between the tasks and the disciplinary work (Krajcik and Shin, 2014).

In addition, teachers enacting rigorous PBL and ambitious instruction prompt students to self-assess and reflect on learning. Such opportunities provide teachers with a rich source of evidence about student learning. For example, students have opportunities to engage in metacognition about their thoughts and actions in a classroom, building a powerful foundation for students to take ownership in their learning by understanding how their thinking changes over time. The feedback that students get about their learning is also oriented toward students' reasoning and practices in the subject matter (Coffey, Hammer, Levin, & Grant, 2011). Such work supports "generative learning" - teachers' continued use of students' ideas as resources opens up learning opportunities not available if teachers shut down student thinking (Fennema et al., 2001).

To support the use of evidence to shape instruction, teachers could use two kinds of tools from ambitious instruction. First, **scaffolding tools** (http://ambitiousscienceteaching.org/tools-scaffolding/) support students' writing and talk as they engage in rigorous disciplinary work. They also provide teachers with opportunities to assess student thinking and make instructional adaptations for upcoming lessons and units. Second, **face-to-face tools** (http://ambitiousscienceteaching.org/tools-face-to-face/) provide teachers with formative assessments both in-the-moment (teachers can track student thinking in real time) and during reflection (teachers can analyze student thinking on the tools individually and in professional learning communities).

Summary

We propose that rigorous PBL and ambitious instruction offer complementary messages about teaching and learning. We think that each pedagogical approach brings unique strengths to bear on conversations and professional learning opportunities focused on improving teaching. We also note that rigorous PBL and ambitious instruction reify important principles about teaching and learning from converging lines of literature. Specifically, they anchor learning opportunities around a puzzling problem, promote rigorous and equitable learning opportunities for all students, position students as the co-constructors of knowledge and classroom practices, and emphasize the importance of using multiple forms of evidence to shape instruction.

While our excitement about the intersections of rigorous PBL and ambitious instruction builds, we note that reading and writing about the pedagogical connections does not automatically result in better instruction and supports for teachers. We recognize three families of questions that emerged from the analysis and synthesis of research. First, how do teachers learn the practices and tools associated with complex instruction? In particular, how do teachers learn to coordinate the practices and tools so that they are using such resources to achieve larger unit and year-long goals rather than treating the resources as separate entities? Second, we cannot expect teachers, schools, and districts to take up such complex instruction without support. Therefore, we wonder what kinds of learning opportunities do teachers, schools, and districts need to shift instructional goals and learning expectations to meet the vision of rigorous PBL and ambitious instruction? Finally, we know that researchers and practitioners need stronger relationships. Since teachers use practices and tools daily, researchers should be willing to learn with and from the teachers' innovations to meet their students' needs. How do we promote a norm of co-learning about rigorous PBL and ambitious instruction among researchers, teachers, schools, and districts?

Future Research

In light of these larger questions, we propose five lines of research to collect evidence of developing teacher practice.

Research line 1: How do we support growth in ambitious instruction practices in PBL over time?

The Lucas Education Research model of PBL provides a unique opportunity to study teacher practice over time within well-specified PBL curricular contexts. Current LER projects involve practicing teachers, who may participate in projects to pilot early versions of materials or who implement and adapt developed projects. As described earlier, the practices promoted through ambitious instruction are consistent with those of PBL. A study of inservice teacher learning would be an opportunity to pinpoint specific points of intersection, incorporate ambitious instruction tools and practices into existing projects, and capture implementation data to evolve effective practices. Studies may focus on systematic adaptations based on ambitious instruction and how teachers develop sophistication in these practices over the course of a year.

Research line 2: How do we prepare preservice teachers to enact ambitious instruction and PBL?

Ambitious teaching and project-based instruction are different from the typical vision most people imagine of classroom teaching. Therefore, it is difficult for preservice teachers—many of whom experienced high school recently—to imagine teaching beyond lectures and confirmatory activities. If we want teachers to anchor instruction around a puzzling phenomenon that emerges from students' lived experiences, we must provide preservice teachers with opportunities to plan, rehearse, and receive feedback about their efforts to learn such work. Therefore, future studies could examine how teacher educators can better teach novices what complex instruction looks like, how such instruction unfolds over time, and why such instruction provides students with deep learning opportunities.

Research line 3: How do we collaborate with administrators to create protocol to provide insight into ambitious instruction and PBL practices?

While teachers play the most vital role in creating learning opportunities for students, school and district administrators have an increasing influence on the pedagogical decisions teachers make (Ingersoll, 2006). Therefore, any initiatives and interventions designed to support teachers' learning must also consider the role of various administrators in the school context. For example, Kirchgasler et al. (2015) examined how a cohort of their novice teachers attempted to enact ambitious science teaching in several schools. They found that the novice teachers had difficulty in enacting any features of ambitious instruction given the school and district administrators' insistence that teachers improve students' standardized test scores.

Such findings indicate that the role of administrators is vital, but undertheorized, in research about the daily work of teachers. If teachers and researchers want rigorous PBL and ambitious instruction to become more entrenched in classrooms, we need to help conversations of administrators so that such instruction is valued, and so that administrators become change agents to support this kind of work. For example, administrators could shape teacher instruction given the annual review process. During this process, an administrator observes a teacher using an observation protocol, and uses the rating as part of the teacher's yearly performance review. However, the most popular observation protocols are not necessarily designed to capture the elements of student learning inherent in rigorous PBL and ambitious instruction. Therefore, future research could consider how administrators, researchers, and teachers can co-design an observation protocol aimed at illuminating students' deep learning during rigorous PBL and ambitious instruction.

Research line 4: How do we engage students in community based problems through PBL and ambitious instruction practices?

Research shows that instruction building on students' lived experiences provides a conceptual anchor for students to learn complex disciplinary concepts and practices (Barton & Tan, 2009; Ladson-Billings, 1995; Moje et al., 2004; Paris, 2012). Thus, rigorous PBL and ambitious instruction aim to use students' communities as sites of learning opportunities, as well as an audience to listen and take up the work students and teachers engage in over time. However, there are few examples that specify how teachers and students engage in instructional activities that substantively connect learners with their communities.

Research around community-based learning and action with rigorous PBL and ambitious instruction could take parallel paths. First, we need to better understand how to leverage students' lived experiences in classrooms. Students enter school with prior knowledge and experiences that should be used as resources for learning during sense-making talk, however the degree to which teachers allow students to learn from a familiar cultural base and to connect new knowledge to their own narratives varies (Bergeron, 2008; Menchaca, 2001). Second, we need to consider how teachers and students can work on complex disciplinary (and interdisciplinary problems), emerging in their communities. Rather than view the community as merely an audience for students to share their work done in a classroom, the community could become a place in which the walls of school and home and blurred. Teachers, students, and community members could work together to identify problems, solve them, and share their ideas.

Research line 5: How can PBL and ambitious teaching practices support equitable participation in projects?

Calls for schools to become places in which *all* students served have been well publicized. Gay (2000) calls for teachers and schools that 1) assume a non-deficit perspective toward students' capabilities and their lived experiences, and 2) take a critical perspective towards the structural ways knowledge is reproduced in and through classroom interactions. Both rigorous PBL and ambitious teaching feature instructional principles promoting equity in classrooms as students are positioned and scaffolded competently to learn from one another as they engage in disciplinary talk and tool use, and as classroom exchanges are part of larger sets of social and institutional discourses (Gee, 2001; Gutiérrez, Rymes, & Larson 1995).

The research challenge lies in understanding how and why teachers and students design and maintain equitable classrooms over time. Tensions may exist as teachers, currently positioned as instructional authorities, adjust to redistribute the intellectual work to students. Moving forward, we need to better understand how and why rigorous PBL and ambitious instruction provide students with opportunities to help create a community in which the disciplinary and pedagogical work shapes, and is shaped by, students' lived experiences.

These lines of research suggest a strategy for establishing principles and practices rooted in ambitious instruction to address known challenges of project-based teaching. In order to develop and sustain PBL, we need to attend to supports for novice and experienced teachers as well as contextual factors that can support or inhibit these practices taking hold.

References

Alexander, R. J., Osborn, M., & Phillips, D. (Eds.) (2000). *Learning from comparing: New directions in comparative educational research, Volume II: Policy, professionals and development*. Oxford, England: Symposium Books.

Baines, A. DeBarger, A. H., De Vivo, K., Warner, N., Brinkman, J. & Santos, S. (2016). *What is rigorous project-based learning?* Lucas Education Research Position Paper 1. San Rafael, CA: George Lucas Educational Foundation.

Ball, D. L.. & Cohen, D. K. (1996). Reform by the book: what is – or might be – the role of curriculum materials in teacher learning and instructional reform? *Educational Researcher, 25*, 6 - 8, 14.

Ball, D., Sleep, L., Boerst, T., & Bass, H. (2009). Combining the development of practice and the practice of development in teacher education. *The Elementary School Journal*, *109*(5), 458–474.

Banilower, E., Smith, P. S.,Weiss, I. R., & Pasley, J. D. (2006). The status of K-12 science teaching in the United States: Results from a national observation survey. In D. Sunal & E. Wright (Eds.), *The impact of the state and national standards on K-12 science teaching* (pp. 83-122). Greenwich, CT: Information Age.

Barton, A. C., Tan, E. (2009). Funds of knowledge and discourses and hybrid space. *Journal of Research in Science Teaching, 46*(1), 50-73.

Bergeron, B. S. (2008). Engaging a culturally responsive curriculum in a novice teacher's classroom: Encountering disequilibrium. *Urban Education, 43*(4), 4-28.

Boerst, T., & Sleep, L. (2007). Uses and meanings of practice in learning to do the work of mathematics teaching. Paper presented at the annual meeting of the American Educational Research Association, Chicago.

Braaten, M. & Windschitl, M. (2011). Working towards a stronger conceptualization of scientific explanation for science education. *Science Education, 95*, 639-669.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (2000). *How people learn: Brain, mind, experience, and school.* Washington, D. C.: National Academies Press.

Coffey, J. E., Hammer, D., Levin, D. M., & Grant, T. (2011). The missing disciplinary substance of formative assessment. *Journal of Research in Science Teaching*, *48*(10), 1109–1136.

Condliffe, B., Visher,M. G., Bangser, M. R., Drohojowska, S., & Saco, L. (2016). Project-Based Learning: A Literature Review. New York, NY: MDRC.

Darling-Hammond, L., & Barron, B., Pearson, P. D., Schoenfeld, A. H., Stage, E. K., Zimmerman, T. D., Cervetti, G. N., & Tilson, J. L. (2008). *Powerful learning: What we know about teaching for understanding*. San Francisco, CA: Jossey-Bass.

Davis, E. A., & Krajcik. J. S. (2005). Designing educative curriculum materials to promote teacher learning. *Educational Researcher, 34*(3), 3-14.

Duschl, R. (2008). Science education in three-part harmony: Balancing conceptual, epistemic, and social learning goals. *Review of Research in Science Education, 32*, 268-291.

Fogo, B. (2014) Core practices for teaching history: The results of a delphi panel survey. *Theory & Research in Social Education, 42*(2), 151-196.

Franke, M. L., & Chan, A. (2007). Learning about and from focusing on routines of practice. Paper presented at the annual meeting of the American Educational Research Association, Chicago.

Franke, M., Carpenter, T., Levi, L., & Fennema, E. (2001). Capturing teachers' generative change: A follow-up study of professional development in mathematics. *American Educational Research Journal*, *38*(3), 653–689.

Gay, G. (2000). *Culturally responsive teaching: Theory, research, & practice.* New York, NY: Teachers College Press.

Gee, J. P. (2001). Identity as an analytic lens for research in education. *Review of Research in Education, 25*, 99-125.

Gonzalez, N., Andrade, R., Civil, M. and Moll, L. (2001). Bridging funds of distributed knowledge: Creating zones of practices in mathematics. Journal of Education for Students Placed At Risk, 6(1 & 2), 115-132.

Gutierrez, K., Rymes, B., & Larson, J. (1995). Script, counterscript, and underlife in the classroom: James Brown versus Brown v. Board of Education. *Harvard Educational Review, 65*, 444-471.

Hatch, T., & Grossman, P. (2009). Learning to Look Beyond the Boundaries of Representation: Using Technology to Examine Teaching. *Journal of Teacher Education, 60*, 70-85.

Horizon Research International. (2003). Special tabulations of the 2000—2001 LSC teacher questionnaire and classroom observation data. Chapel Hill, NC: Horizon Research.

Ingersoll, R. (2006). *Who controls teachers' work? Power and accountability in America's schools*. Cambridge, MA: Harvard University Press.

Kazemi, E., Franke, M., & Lampert, M. (2009). Developing pedagogies in teacher education to support novice teachers' ability to enact ambitious instruction. In R. Hunter, B. Bicknell, & T. Burgess (Eds.), *Crossing divides: Proceedings of the*

32nd *annual conference of the Mathematics Education Research Group of Australiasia* (Vol. 1, pp. 11-21). Palmerston North, NZ: MERGA.
Kirchgasler, K., Braaten, M., Barocas, S., & Bradford, C. (2015). Why science educators should care about the educational data movement. Paper presented at the annual meeting of the National Association for Research in Science Teaching (NARST). Chicago, IL.
Krajcik, J.S., & Czerniak, C., (2013). *Teaching Science in Elementary and Middle School Classrooms: A Project-Based Approach*, Fourth Edition. Routledge: London.
Krajcik, J. S., & Shin, N. (2014). Project-based learning. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (2nd ed.) (pp. 275-297). New York, NY: Cambridge University Press.
Ladson-Billings, G. (1995). But that's just good teaching!. *Theory Into Practice 34*(3), 59-65.
Lampert, M., & Graziani, F. (2009). Instructional activities as a tool for teachers' and teacher educators' learning. *The Elementary School Journal*, *109*(5), 491-509.
Larmer, J., Mergendoller, J. R., & Boss, S. (2015). *Setting the standard for project based learning: A proven approach to rigorous classroom instruction*. Alexandria, VA: ACSD.
Levin, D. M., Grant, T., & Hammer, D. (2012). Attending and responding to student thinking in science. The American Biology Teacher, 74 (3), 158-162.
Magnusson, S. J., and Palincsar, A. S. (2005). Teaching and learning inquiry-based science in the elementary school. In J. Bransford and S. Donovan (Eds.), *Visions of teaching subject matter guided by the principles of how people learn* (pp. 421-476). Washington, D.C.: National Academy Press.
Maskiewicz, A. C., & Winters, V. A. (2012). Understanding the co-construction of inquiry practices: A case study of a responsive teaching environment. *Journal of Research in Science Teaching*, *49*(4), 429–464.
Menchaca, V. D. (2001). Providing a culturally relevant curriculum for Hispanic children. *Multicultural Education, 8*(3), 18-20.
Michaels, S., O'Connor, C., & Resnick, L. (2008). Deliberative discourse idealized and realized: Accountable talk in the classroom and in civic life. *Studies in Philosophy and Education* 27, 283-297.
Moje, E. B., Ciechanowski, K., Kramer, K., Ellis, L., Carrillo, R., & Collazo, T. (2004). Working toward third space in content area literacy: An examination of everyday funds of knowledge and discourse. *Reading Research Quarterly, 39*(1), 38-71.
Moll, L., Amanti, C., Neff, D. and Gonzalez, N. (1992). Funds of knowledge for teaching: Using a qualitative approach to connect homes and classrooms. *Theory Into Practice, 31, 2*, 132-141.
National Research Council. (2007). *Taking Science to School: Learning and Teaching Science in Grades K-8*. Committee on Science Learning, Kindergarten Through Eighth Grade. R. A. Duschl, H. A. Schweingruber, and A. W. Shouse (Eds.). Board on Science Education, Center for Education, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.
National Research Council. (2011). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Committee on a Conceptual Framework of New K-12 Science Education Standards. Board on Science Education. Division of

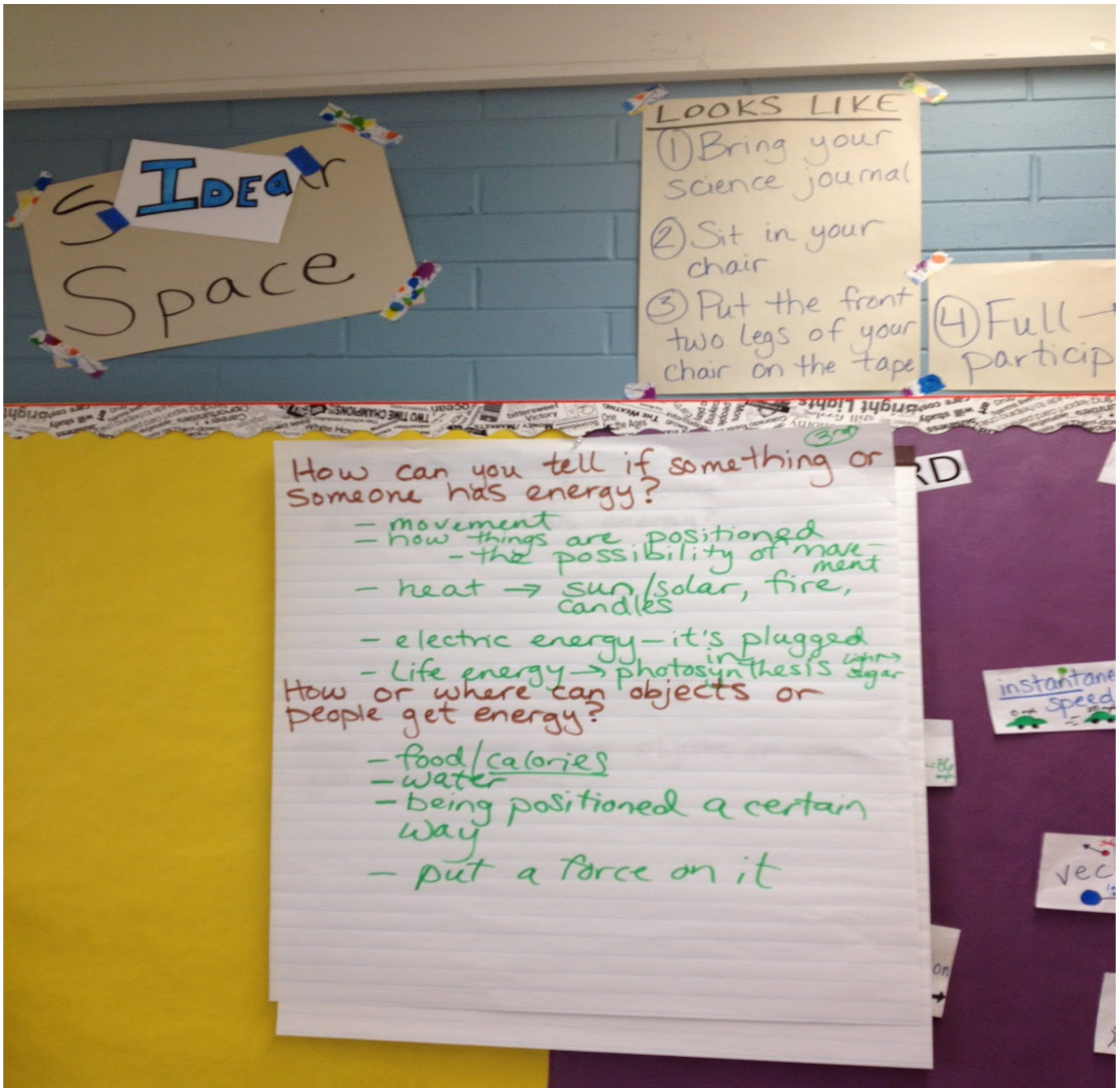
Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.
Paris, D. (2012). Culturally sustaining Pedagogy: A needed change in stance, terminology, and practice. *Educational Researcher, 41*(3), 93-97.
Paris, D., & Alim, H. S. (2014). What are we seeking to sustain through culturally sustaining pedagogy? A loving critique forward. *Harvard Educational Review, 84*(1), 85-100.
Parker, W. C., & Lo, J. C. (2016). Reinventing the high school government course: Rigor, simulations, and learning from text. *Democracy and Education*, *24(1)*, 1-10. Retrieved from http://democracyeducationjournal.org/home/vol24/iss1/6/
Parker, W. C., Lo, J., Yeo, A. J., Valencia, S. W., Nguyen, D., Abbott, R. D., Nolen, S. B., Bransford, J. D., & Vye, N. J. (2013). Beyond breadth-speed-test: Toward deeper knowing and engagement in an advanced placement course. *American Educational Research Journal, 50*(6), 1424-1459.
Polman, J. L. (2012). Trajectories of participation and identification in learning communities involving disciplinary practices. In D. Yun Dai (Ed.), *Design research on learning and thinking in educational settings: Enhancing intellectual growth and functioning* (pp. 225-242). New York: Routledge.
Roth, K., & Garnier, H. (2007). What science teaching looks like: An international perspective. Educational Leadership, 64(4), 16-23.
Rudolph, J. (2014). Dewey's "Science as method" a century later: Reviving science education for civic ends. *American Educational Research Journal*, *51*(6), 1056–1083.
Sawyer, R. K. (2008). Optimizing learning: Implications of learning sciences research. *Learning in the 21st century: Research, innovation, and policy* (pp. 1–14). Presented at the OCED/CERI International Conference, Paris, France: Centre for Educational Research and Innovation.
Sherin, M. G., Jacobs, V. R., & Philipp, R. A. (Eds) (2011). Mathematics teacher noticing: Seeing through teachers' eyes. New York, NY: Routledge.
Smylie, M.A., & Wenzel, S.A. (2006). Promoting Instructional Improvement: A Strategic Human Resource Management Perspective. A Report of the Chicago Annenberg Research Project. Consortium on Chicago School Research: University of Chicago.
Stroupe, D. (2016). Beginning teachers' use of resources to enact and learn from ambitious instruction. *Cognition and Instruction, 34*(1), 51-77.
Stroupe, D. (2014). Examining classroom science practice communities: How teachers and students negotiate epistemic agency and learn science-as-practice. *Science Education, 98*, 487-516.
Sykes, G., Bird, T., & Kennedy, M. (2010). Teacher education: Its problems and some prospects. *Journal of Teacher Education, 61*(5), 464–476.
Thompson, J., Hagenah, S., Kang, H., Stroupe, D., Braaten, M., Colley, C., & Windschitl, M. (2016). Rigor and responsiveness in classroom activity. *Teachers College Record, 118* (5), 1-58.
Thompson, J., Windschitl, M., & Braaten, M. (2013). Developing a theory of ambitious early-career teacher practice. *American Educational Research Journal, 50*(3), 574-615.

Warren, B., Ballenger, C., Ogonowski, M., Rosebery, A., & Hudicourt-Barnes, J. (2001). Rethinking diversity in learning science: The logic of everyday sense-making. *Journal of Research in Science Teaching*, *38*(5), 529-552.

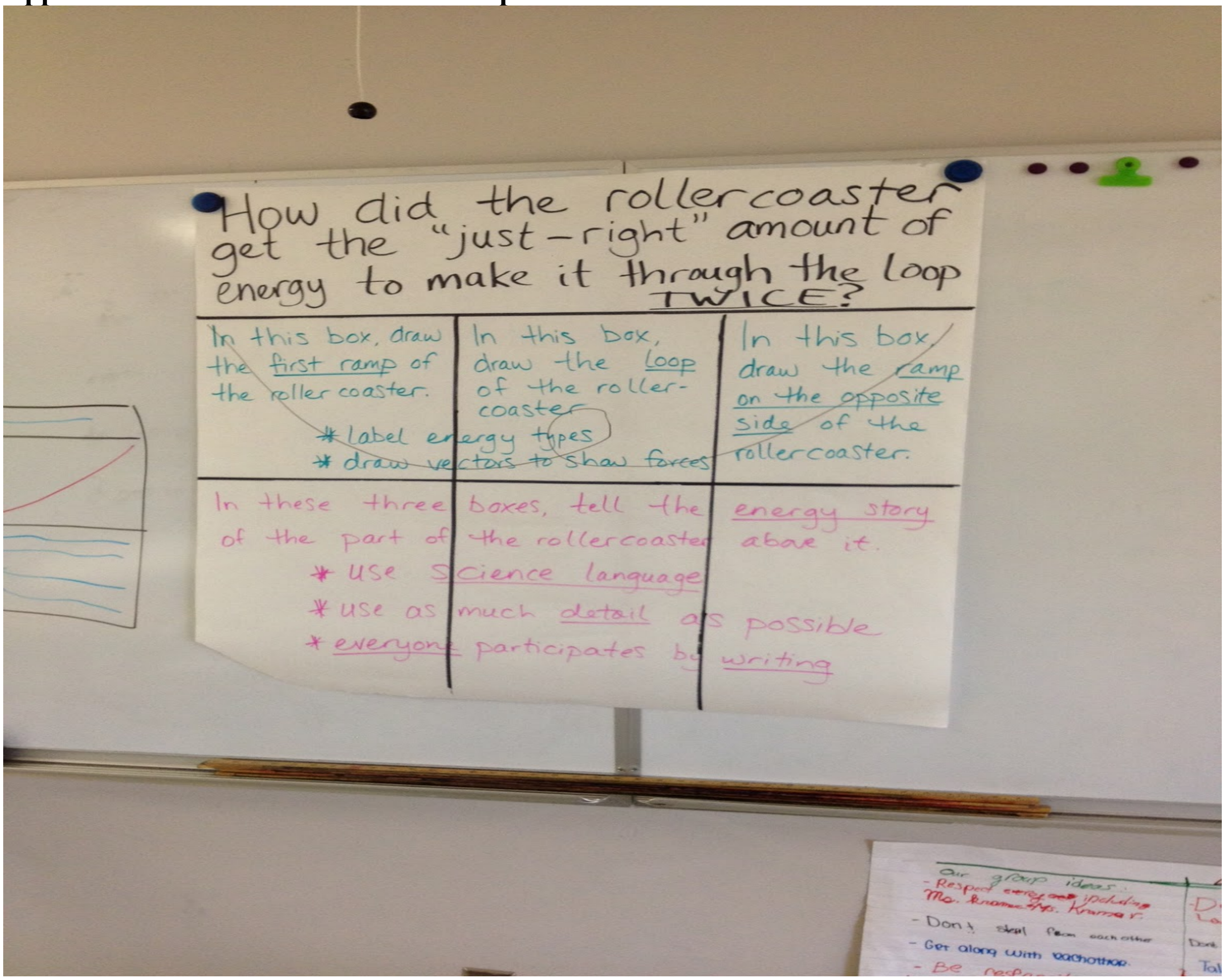
Weiss, I. R., Banilower, E. R., McMahon, K. C., & Smith, P. S. (2001). Report of the 2000 National Survey of science and mathematics education. Chapel Hill, NC: Horizon Research Inc. Retrieved from www.horizon-research.com.

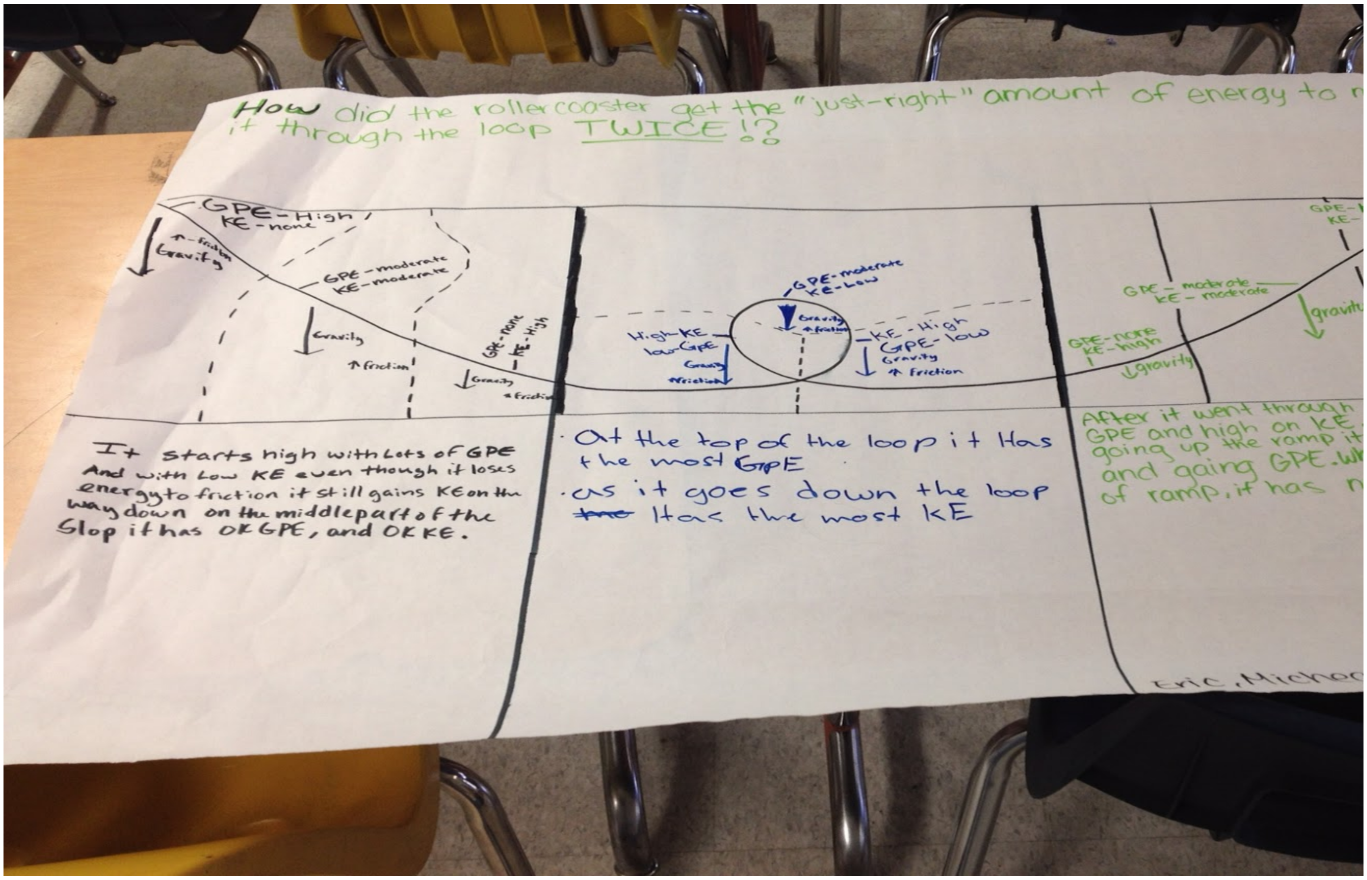
Windschitl, M., Thompson, J., Braaten, M., & Stroupe, D. (2012). Proposing a core set of instructional practices and tools for teachers of science. *Science Education*, *96*(5), 878-903.

Appendix A. Students' ideas about energy generated in "idea space"



Appendix B. Assessment task and example of student work




How did the rollercooster get the "just-right" amount of energy to
it through the loop TWICE!?
GPE-High
KE-none
Gravity
GPE-moderate
KE-moderate
Gravity
Friction
GPE-none
KE-High
GPE-moderate
KE-Low
Gravity
High KE
low GPE
KE-High
GPE-low
Gravity
Friction
GPE-none
KE-high
gravity
It starts high with Lots of GPE And with Low KE even though it loses energy to friction it still gains KE on the way down on the middle part of the Slop it has OK GPE, and OK KE.
· At the top of the loop it Has the most GPE
· as it goes down the loop Has the most KE