Facilitating and Assessing Science Learning Within an Engineering Design-Focused, Project-Based Learning Curriculum

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Introduction

The new Framework for K-12 Science Education, developed by the National Academy of Sciences, proposes markedly increasing the profile of engineering practices and concepts within the domain of K-12 science education (NRC, 2011). The challenge for curriculum developers going forward is to create educational experiences that continue to ensure that students learn the identified core science concepts and practices, while concurrently exposing students to the central tenets of engineering design and making clear the links between engineering, technology, science and society. Though there are numerous commonalities between science and engineering, there are also significant points of departure that, if not addressed explicitly in the instructional materials, make it likely that "integrated" activities will instead end up focusing on either engineering or science, but not both. In these cases students may engage in engineering design without adequately answering the critical science questions of, *Why does it happen?* and *How does one know?* Conversely, students may learn science in a more traditional, didactic manner, never linking the core concepts to everyday applications and phenomena. That is to say, they will not experience the need to know and use science to solve a problem or improve conditions.

Science Learning Integrating Design, Engineering and Robotics (SLIDER) is an NSF-funded, DR K-12 project to create, implement and study the effects on student learning of an 8th grade physical science, project-based learning curriculum. Built upon the foundation developed as part of the NSF-supported *Project-Based Inquiry Science (PBIS)* (Kolodner, et al, 2009), the curriculum challenges students to solve engaging problems using engineering design practices and concepts, scientific inquiry, and LEGO Mindstorm™ robotic kits. Because the curriculum is being implemented within public schools in 8th grade physical science classrooms, the nonnegotiable first-level measure of student success is that students effectively learn physical science content and process skills spelled out in the Georgia Performance Standards. Prior research suggests that the engineering context and use of LEGO™ robotics might promote increased student engagement and self-efficacy (Brophy, et al, 2008). Studying these possible student outcomes is a significant part of SLIDER's research plan. Prominent among SLIDER's additional research questions is, "How should the learning that takes place [with the SLIDER curriculum] best be assessed in the classroom?"

The SLIDER curriculum developers have designed a progression of specific *SLIDER Curriculum Structures* (SCSs) that explicitly scaffold student learning: these ritualized activity structures (Kolodner, et al, 2003) move students back and forth from the engineering design process of defining problems and designing solutions, which serves to engage student interest, to the science skills of asking scientific questions, acquiring knowledge, and constructing explanations, which serves to develop conceptual understanding. The SCSs are systematically placed in the learning sequence and thus, over time, they can provide multiple embedded assessment opportunities (both formative and summative). They provide a window on students' conceptions of science content knowledge, reasoning, science process skills, collaboration, and engineering concepts. This paper describe these curriculum scaffolds, their development, the aspect of learning each can measure, how the metrics align with the new frameworks, and the preliminary use during classroom piloting.

The New Frameworks & Science and Engineering Practices

In December 2011, Bybee authored an article describing the *Science and Engineering Practices* (S&E Practices) that are now integral to the new frameworks and (presumably) the forthcoming Next Generation science standards. Bybee and the NRC Frameworks authoring committee make the case that science and engineering share these common practices (Bybee, 2011):

1. Asking questions and defining problems
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using math and computational thinking
6. Constructing explanations and designing solutions
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

For the past twenty years, inquiry-based instruction, as a pedagogical approach, was more central to the Benchmarks for Science Literacy (AAAS, 1993) and the National Science Education Standards (NRC, 1996) than it is in the new Frameworks. As Bybee points out, featuring inquiry birthed many cognitive benefits and increased the use of activities and investigations in science classrooms, but the inquiry perspective and methods never became the prevalent instructional approach in a majority of classrooms. The aim of the new focus on *practices* is "one of expanding and enriching the teaching and learning of science" (Bybee, 2011, p. 14). In this way, inquiry is simply part of a teaching strategy built on emphasizing engagement in the practices themselves, and thus inquiry can still be a valuable approach to helping students develop understanding and proficiency in science.

Engineering practices, though targeting a different goal than science, have overlapping behaviors and outcomes. As Bybee (2011) explains and advocates:

> *"The relationship between science and engineering practices is one of complementarity. Given the inclusion of engineering in the science standards and an understanding of the difference in aims, the practices complement one another and should be mutually reinforcing in curricula and instruction...*
>
> *... Science and engineering practices should be thought of as both learning outcomes and instructional strategies. They represent both educational ends and instructional means.*
>
> *... In brief, the practices represent one aspect of what students are to know, what they are able to do, and how they should be taught."* (p. 15)

Understandably, Bybee expresses concern that both pre-service and practicing teachers will need time to adjust to this view of teaching and learning, but that ultimately it will provide them with a path forward because the practices really will shape instructional curriculum design. This concern also seems mitigated by the fact that engineering design contexts have already been the basis for many curricula, inquiry and project-based ones in particular. Some of these curricula engage students in the engineering design process (iterative design; identifying criteria and constraints; evaluating multiple solution designs) because the design process can help drive engagement and reveal understanding of science content and skills (Kolodner, et al, 2003b).

In the next section, we highlight a curriculum approach and design that has for more than a decade made use of engineering design in conjunction with science inquiry. Not only does this approach help target the S&E Practices highlighted in the new frameworks, but a specific element of the model provides opportunities to assess student learning of both science and engineering. SLIDER curriculum units are modeled on this format.

The SLIDER Curriculum Model

SLIDER's curriculum design and instructional method is similar to the approach and protocol developed by the NSF-supported *Learning by Design* (LBD) project and the subsequent *Project-Based Inquiry Science* (PBIS) ™ project and series. These curricula are inquiry-based, problem-based learning (PBL) approaches to middle school science education founded in constructivist learning theory that aim to address the social and cognitive aspects of learning (Kolodner, et al 2003b, 2009). They incorporate the cognitive model of case-based reasoning where students learn from the lessons they formulated during previous experiences (Kolodner, 1993). The students work collaboratively to solve problems, thereby learning in a group setting as well as individually. Students identify what they know, what they need to learn more about, plan how they will learn more, conduct research, and deliberate over the findings all together in an attempt to move through and address a challenge or problem. There is a large amount of research extolling the benefits of inquiry, PBL curriculum and learning experiences (CTGV, 1997; Boaler, et al; Krajcik, et al, 1998; Bransford, et al, 1999; Kolodner, et al, 2003b; Hmelo-Silver & Pfeffer; Hmelo-Silver, et al, 2007). This research found that PBL can afford: more active learning of content; the development of problem-solving skills; increased ownership in learning; greater understanding of the nature of the scientific endeavor; more flexible thinking; improved collaboration skills; and opportunities for students to gain expertise in STEM.

In many PBIS units, students work with a design artifact as they attempt to meet a challenge. Students redesign the artifact or device multiple times during the course of the unit as they try to meet the criterion of the design problem. Through the design of these artifacts, students engage in the behaviors and activities of designers, engineers, and architects--they analyze a challenge, generate ideas to answer the challenge, investigate the science and math concepts governing the challenge, build or test models to obtain feedback, reflect, and then redesign the solution based on feedback to better meet the challenge. A significant emphasis is placed on the importance of iteration in design and problem solving. Figure 1 displays LBD's Cycles of Activities, illustrating the iterative engagement in design and investigation that helps students meet their design challenges in PBIS units.

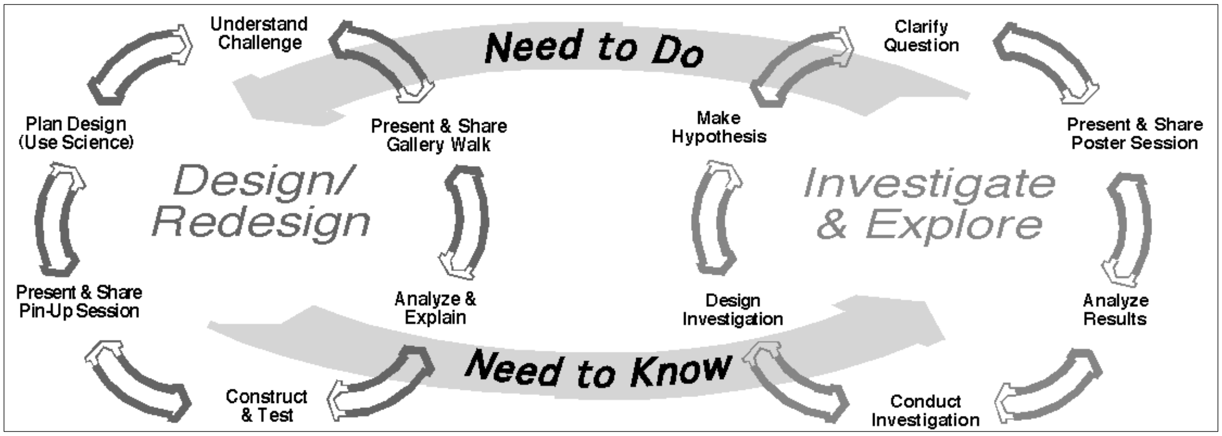


Figure 1: LBD cycles of activities (from Kolodner, Gray & Fasse, 2003a)

Figure 1 also provides a sense of how students in LBD/PBIS classrooms have to migrate back and forth between engaging in the practices of science and engineering while they pursue the challenge anchoring the unit. To be more illustrative, 8th-grade students beginning a 5-week unit in force and motion first encounter a challenge to build a better version of a self-propelled model vehicle that can climb many obstacles and travel far. Thus, students start atop the cycle on the left. As they create and consider design options, the need to learn more about various wheel-surface options arises. This shifts their work over to the right side cycle, where they design and run experiments with surfaces of different coefficients of friction. Through this inquiry into friction, the teacher targets the science content and skills included in typical science standards. Armed with their new knowledge, students shift back to the left side, and apply what they have learned about friction to their vehicle design. They iteratively build and test prototypes, presenting their new design and evaluating it against the challenge criteria. This back and forth occurs throughout the unit, covering a wide range of force and motion concepts that govern the various features and elements of the model vehicle.

Curriculum Structures

A key component in both the PBIS/LBD and SLIDER curriculum materials is the use of what Kolodner et. al. initially labeled as *Ritualized Activity Structures* (2003a). The current PBIS materials now refer to them formally as PBIS Practices. To provide a distinction between these structures and the S&E Practices mentioned earlier, the SLIDER project formally refers to its structures as the *SLIDER Curriculum Structures* (SCSs), and we will use the term *structures* for this paper.

The structures are intended to help students understand and participate in the science and engineering practices referenced in the standards, while providing a format that helps students see their usefulness in solving the challenge. For the most part, rituals can be divided into two general categories: action and discourse activities. Action-based activities help to habituate the skills and practices of science and engineering design. Discourse activities help students review and analyze their experiences (e.g., experiments, research, build and test sessions) to crystalize the content and skills they are learning and connect it to their challenge and goals.

Over time, the number of structures PBIS employs has increased, encompassing very specialized and uniquely named structures for very specific locations in the two cycles. SLIDER teachers have found this to be cumbersome and too difficult to differentiate with students. Our team reviewed the existing PBIS structures and created a smaller suite, where 3 or 4 unique PBIS structures are simply collapsed into one. For example, PBIS has a number of Practices where students share their work in a presentation. It could be an interim product design, the results of an experiment, their initial ideas about a design challenge, or the final artifact they have designed for the challenge. In PBIS, each of these presentations gets its own structure and protocol – in SLIDER all of these presentations are completed using the *Share Structure*. The nature of discussion and the goals of the moment certainly shift the Share Structure protocol details slightly, but the general sequence and method are the same.

SLIDER designs and employs curriculum using six distinct SCSs, each with its own general protocol and activity category (see Table 1).

Table 1: SCS Suite and Activity Categories

SLIDER Curriculum Structure	**Activity Category**
1) Organize the Challenge	Action & Discourse
2) Explore	Action
3) Share	Discourse
4) Add to Your Understanding	Discourse
5) Explain	Action
6) Reflect & Connect	Discourse

SLIDER Curriculum Structures & Assessment

The SLIDER Curriculum Structures are often collaborative, involving all members of the class, but each structure has dimensions that require individual student work. They happen at very specific places in the curriculum sequence, occurring in both of the cycles in Figure 1. They serve as moments for students to connect their more recent or smaller experiences to the challenge at-large: they help students share information, reflect on what they have learned, and develop new ideas and connections to pursue during the challenge. For the teacher, the structures reveal student understanding and conceptions – i.e., they serve as moments of formative assessment. As students iteratively engage in the structures over time within and across units, the nature of the assessment can be more summative. These structures, as such, become a way for teachers to assess and develop the S&E Practices the new Frameworks highlight. Table 2 displays where each SCS aligns with the S&E Practices.

Table 2: SCSs and Framework Practices

	Science and Engineering Practices from Framework							
SLIDER Curriculum Structures	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Organize the Challenge	■	■				■		■
Explore	■	■	■	■	■			■
Share				■		■	■	■
Explain				■	■	■	■	■
Add to Your Understanding				■	■		■	■
Reflect and Connect					■	■	■	■

1. Asking questions and defining problems
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using math and computational thinking
6. Constructing explanations and designing solutions
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

The SCSs are critical to helping sequence the learning within a unit, and they provide necessary opportunities for teachers to engage in formative assessment of student learning. Formative assessment has a variety of meanings (Young & Kim, 2010); we use formative assessment to refer to *the use of assessment for formative purposes, specifically to inform teachers' instruction of their students*. Previous research indicates formative assessment can create substantial student learning gains and empowers students as self-regulated learners, especially when used in conjunction with feedback that is timely, has a direct relation to specific pre-defined criteria, contains specific corrective advice, and can be assessed easily by both teacher and student (Black & William, 1998; Nicol & Macfarlane-Dick, 2006). The use of formative assessment and quality feedback can improve achievement of low performing students, potentially reducing achievement gaps between low and high performing students (Black & William, 1998; Stiggins & Chappuis, 2005). Additionally, regular use of formative assessment can enable teachers to move away from using assessment only to create grades (i.e. summative assessment), and towards using assessment to gauge student understanding (Sato, Wei & Darling-Hammond, 2008).

Despite these positive benefits, the majority of teachers do not systematically use formative assessment. When teachers do use data systems for formative purposes, they generally have difficulty with data comprehension and data interpretation (Young & Kim, 2010; U.S. Dept. of Ed, 2009). Instead, teachers rely on their own assessments--a mixture of informal measures like observations of perceived effort, and formal measures that emphasize recall of discrete facts. These assessments are often not systematically administered, have no paper trail, are administered only once, and are summative, not formative (Young & Kim, 2010). In the

SLIDER curriculum, the SCSs provide a sequence, schedule and roadmap for conducting formative assessment.

As part of SLIDER we have developed a series of rubrics that facilitate formative assessment by providing a list of criteria for evaluating student learning and for determining gradations in the quality of student work. For example, this type of rubric enables teachers to evaluate a student's explanation and content knowledge and to differentiate between content and pedagogical knowledge when assessing students' scientific explanations (Sevian & Gonsalves, 2008). Below we describe one of the SLIDER Curriculum Structures – *Explain* – and present samples of rubrics designed to assess student understanding and development across the practices through use of the SCSs.

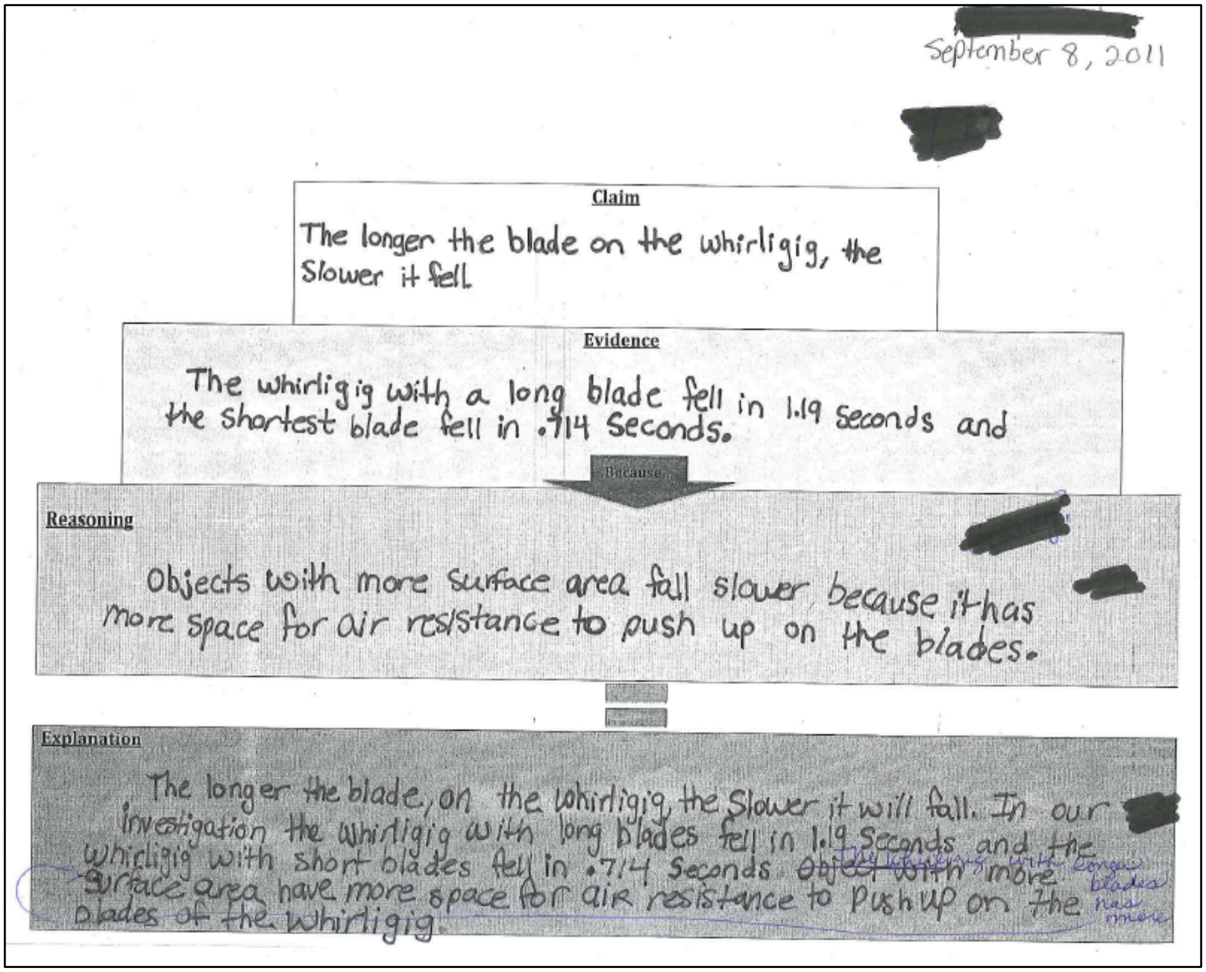
The *Explain* Structure

The NRC Framework for K-12 Science Education clearly describes the use of authentic science discourse and argumentation as a central practice in science education. Teachers enculturate students into science through quality inquiry experiences, exposure to experts, and use of science vocabulary. Engagement in scientific argumentation, discourse and explanation can be influential in this enculturation. At a larger scale, discourse of explanations and interpretations is what builds society's confidence in the agents and outcomes of scientific endeavor. As Driver, et al. (2000) suggest, "argument is thus the mechanism of quality control in the scientific community. Understanding argument, as used in science, is therefore central to any education *about* science" (p. 301). The engagement in scientific argumentation should be a prominent feature of the science classroom (Sutton, 1992; Kuhn, 1993; NRC, 1996, 2000; McNeill & Krajcik, 2009, 2012).

SLIDER's *Explain Structure* occurs iteratively and frequently throughout each curriculum unit. It allows students to explicitly connect their investigations and findings to the abstract science concepts governing those investigations and the challenge criteria that inspired the investigations. Iteratively throughout the SLIDER units, students develop scientific explanations through a Claim, Evidence, Reasoning (C-E-R) framework (McNeill, et al, 2006; McNeill & Krajcik, 2009, 2012). Students formulate claims throughout the curriculum to address both the smaller and greater challenges presented in each unit. The *claims* are generated from the analysis of the data and trends from investigations within the unit. Students identify pertinent and appropriate measurements and observations to use as *evidence* to support their initial claim. Students then apply science content knowledge learned through their investigation, reading material, or class discussions as their *reasoning*.

From their evidence and reasoning, students develop an explanation to validate their claim. Early in a unit, students might only develop one explanation, but iterate several times on this same explanation. With each iteration, teachers formatively assess the students' progress in establishing substantive claims, identifying appropriate and sufficient evidence, and applying accurate and appropriate reasoning. By the end of each unit, students have developed numerous explanations as design decisions, recommendations, or justifications to apply to the challenge. The SLIDER *Teacher's Edition* guides teachers through the process of assessing student explanations and their proficiency in applying specific content to either the activity at hand or the overall challenge, and includes suggestions for corrective advice for student misconceptions.

The Explain Structure's student materials scaffold student work and thinking via its C-E-R components. Below is a sample of student work from the *Whirligig Challenge* (Kolodner, et al, 2009) we had SLIDER students complete in the fall of 2011. The figure illustrates our C-E-R framework and student materials, where students draft and then assemble their *explanation*.


[redacted]
September 8, 2011
[redacted]

Claim

The longer the blade on the whirligig, the Slower it fell

Evidence

The whirligig with a long blade fell in 1.19 Seconds and the shortest blade fell in .714 Seconds.

Because...

Reasoning

[redacted]

Objects with more surface area fall slower because it has more space for air resistance to push up on the blades. [redacted]

Explanation

The longer the blade, on the whirligig, the Slower it will fall. In our investigation the whirligig with long blades fell in 1.19 Seconds and the whirligig with Short blades fell in .714 Seconds. ~~Object with~~ The whirligig with longer blades has more surface area have more space for air resistance to push up on the blades of the whirligig [redacted]

Figure 2: Student Sample Work: C-E-R Framework

Student proficiency in the *Explain* Structure is assessed through detailed rubrics that break down each of the components of the C-E-R framework. This targeted review of each component allows for a student who is proficient at making claims, but a novice at developing reasoning to receive appropriate feedback to create their explanation. Although the rubric does not provide a proficiency measure for the final explanation, the combination of the individual factors provides an overall assessment of explanation. Table 3 is a rubric to assess explanations formed following a set of investigations during a unit where students are challenged to improve the design of a paper helicopter, making it fall to the ground more slowly.

Table 3: Whirlygig Explain Rubric (*adapted from McNeill and Krajcik, 2012*)

Specific Rubric for Whirlygig Challenge Explain Event (Variable= # number of paperclips)			
	Claim	**Evidence**	**Reasoning**
Novice	**Does not interpret or analyze data. Does not communicate appropriate information.** ***or*** **Does not interpret or analyze data accurately, does not demonstrate computational thinking:** *The Whirligig should be dropped from higher heights.*	**Does not communicate data. Does not provide evidence to support argument or claim.** ***or*** **Communicates inappropriate data or vague analysis of data that does not support argument. May or may not demonstrate computational thinking.** *As the number of paperclips on the stem increased, the number of spins of the Whirligig.*	**Does not communicate or evaluate content to construct an explanation:** ***or*** **Communicates inappropriate or inaccurate content to construct an explanation. Content information does not support evidence in an argument.** *The Whirligig with more paperclips falls quicker due to increased air resistance.*
Emerging	**Interprets data accurately, but analysis and communication of information is incomplete. Does not demonstrate computational thinking.** *The number of paperclips on the stem affects the fall time of the Whirligig.*	**Communicates appropriate data to support argument, but not a sufficient analysis to construct an explanation. May or may not demonstrate computational thinking.** ***or*** **Includes inappropriate data to support argument, may or may not demonstrate computational thinking.** *As the number of paperclips on the stem increased, the number of spins decreased and the number of seconds it took to fall decreased.*	**Communicates accurate and appropriate content information, but is incomplete to construct an explanation. Does not communicate sufficient information to support evidence in an argument.** ***or*** *As the number of paperclips is increased, the Whirligig falls faster falls faster because of gravity.*
Proficient	**Communicates, interprets and analyzes data accurately. Demonstrates computational thinking.** *The more paper clips on the stem of the Whirligig of the blades decreases the fall time of the Whirligig.*	**Communicates appropriate data and a sufficient analysis to construct an explanation. Demonstrates computational thinking.** *As the number of paper clips on the stem increased, the number of seconds it took to fall decreased. The Whirligig with 5 paperclips on its stem averaged a fall time of 2 seconds, with 3 paper clips on its stem, averaged a fall time of 4 seconds, and with one paperclip averaged a fall time of 5 seconds.*	**Communicates accurate, appropriate, and sufficient content information to construct an explanation. Content information is communicated to support evidence in order to engage in an argument.** *As the number of paperclips increased, the mass of the whirligig increased. Mass and gravity have a direct relationship, and therefore objects with more mass have a greater gravitational force. Gravity is the force that pulls the Whirligig to the ground.*

The C-E-R components align with the Framework's S&E Practices, allowing us to assess for development and understanding along many of the S&E Practices (See Table 4).

Table 4: Practices Aligned with C-E-R Framework

	Claim	Evidence	Reasoning
Analyzing and interpreting data			
Using math and computational thinking			
Constructing explanation and designing solutions			
Engaging in an argument from evidence			
Obtaining, evaluating, & communicating information			

Students identify trends and patterns in their data to develop a qualitative statement that summarizes this information as they make **claims.** Students further analyze their data, use mathematical and computational thinking to provide observations, measures, and quantitative relationships to demonstrate how their **evidence** supports the claim. Their evidence along with their science content knowledge provides the **reasoning** to defend their claim and to develop a full explanation for the science phenomena they encounter in their investigation and challenges. The Explain Structure, and its C-E-R framework, provides students organization to construct coherent explanations that demonstrates their ability to link their observations and data with theory to explain scientific phenomena.

Conclusion

Though we only were able to present one of our structures here, the remaining five have similar rubrics, analysis, and (we believe) ability to develop and assess S&E Practices. There are many inquiry and PBL curricula available to teachers, none of which were designed with the new practices as a guide. This should cause little concern among teachers. Keep in mind the fact that the new standards are not a drastic departure from the content and skills targeted by the previous standards, such as the AAAS Benchmarks and the NRC's National Science Education Standards. Additionally, as Bybee stresses, a focus on the practices provides not only the ends, but also the means for developing student understanding and skill. Using curriculum structures to design and facilitate classroom activity perhaps provides an effective model for developers and practitioners to consider when the new standards are rolled out.

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